Microplastics
in the marine environment:

Sources, Impacts & Recommendations

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Foreword

Plastic pollution in the marine environment has been consistently reported since the late 1960s, however, recent evidence of global widespread microplastic pollution has led to an exponential increase in both research and policy efforts.

This report reviews recent publications on the effects and impacts of microplastics in the marine environment with the aims to provide useful information for decision-makers, stakeholders, researchers working in this field, and the general public. Every effort has been undertaken here to verify valid sources of information, while interacting with marine litter and microplastic experts to ensure that the most recent and reliable information available is part of this report.

It is common to refer to the topic of microplastics with prudence due to the many uncertainties associated with the lack of common definitions or standardised methodologies for sampling, processing, data analysis and reporting. However, it is important to take stock of the multiple efforts conducted thus far by many researchers throughout the world. This report does not intend to diminish the contribution that plastic as a material has made to the socio-economic development of our species or the immense added value it has contributed to several research fields including medicine and computing.

The future challenges associated with plastic pollution lie on the distinction between essential and non-essential single-use items; on efficient and adequate global solid waste and wastewater management; and on eco-design approaches that follow universal circular economy principles. The combination of responses to these challenges will lead to the reduction of the enormous quantities of plastic that are accidentally or intentionally disposed in the marine environment, every year.

For this report, two main definitions are of particular importance. The first one is **marine litter**, defined by the Marine Strategy Framework Directive (2008/56/EC) as: "any persistent, manufactured or processed solid material that is deliberately or unintentionally discarded, disposed of, abandoned or transported by winds, rivers and animals into the marine and coastal environment". The second definition is **microplastics**, here following

Frias and Nash, 2019, and defined as "any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water". This report focuses on both primary and secondary microplastics, meaning, plastic items that are produced to have microscopic dimensions or that result from the fragmentation and degradation of larger items, respectively.

This report focuses on the marine environment and is divided into four chapters which address the (1) scale of the marine microplastic pollution through its sources and pathways, (2) the known and most important impacts, (3) future monitoring based on expert opinion and a final chapter on (4) recommendations to minimise and mitigate the plastic problem.

It is the authors' intention that the report stimulates dialogue among stakeholders and decision-makers, and that by doing so, this will lead to awareness raising and prompt action, particularly towards phasing out non-essential single-use items and intentionally added microplastics in personal care and other relevant consumer products; as well as promoting eco-design approaches that allow plastics to fully move towards a circular economy paradigm.

It is time to flatten the plastic curve.

João Frias

Executive Summary

This report on marine microplastics provides an overview on the sources and pathways (routes of entry) of microplastics into the marine environment, while exploring the effects and impacts on 1) vulnerable marine ecosystems, on 2) the climate, and on 3) marine wildlife. The basis of this report is an extensive analysis of scientific peer-reviewed research papers and scientific reports from a wide range of institutions that have been studying this topic for decades. In addition, marine litter and microplastic pollution experts from diverse academic, governmental, non-governmental and industry sectors worldwide were interviewed on microplastic monitoring in environmental matrices. Their contributions and opinions are included in a dedicated chapter that explores the biggest environmental concerns associated with plastic pollution, which environmental compartments should be monitored and with which frequency.

Based on research available at the time of writing, a set of policy recommendations, including market-based instruments, are proposed here to reduce and minimise plastic emissions, and consequently the impacts of microplastics into the marine environment. The definition of microplastics follows the peer-reviewed publication of Frias and Nash, 2019 where microplastics are defined as "any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water".

Sources

The majority of plastic and microplastic pollution in the ocean, approximately 80%, is derived from land while marine & maritime sources account for the remaining 20%. As such, sources in this report are divided by their origin into these two main categories, where land-based covers diverse sectors from agriculture, tourism and personal care products to textiles, plastic production and road transport. Marine & maritime-based sources range from fisheries and aquaculture to shipping.

Land-based sources

The agriculture sector is a significant source of microplastics through 1) direct use of plastic coatings added to seeds; 2) the spreading of sludges derived from wastewater treatment plants (WWTPs) and 3) the use of plastic in silage and hay bales. Plastic coatings added to the seeds are released into the soil after sowing. Secondary microplastics resulting from degradation or fragmentation of larger plastics can be washed into nearby water bodies rains. Plastic mulching, a technique used to grow crops, identified as having the highest coverage area in Europe, was also targeted as having a high probability of releasing microplastics, in comparison to low tunnels or greenhouses.

Tourism, a socio-economic activity of high importance in Europe, generates high revenue due to the increase in the transient population in coastal areas, particularly in Mediterranean countries during summer. As a consequence, plastic pollution increases, and the abundance of plastic items is often linked to items forgotten or purposely left behind in beaches and coastal areas. The presence of plastics and microplastics constitutes an increased impact on local water bodies, particularly in the Mediterranean basin, which has been identified as one of the most polluted basins in the world, when it comes to plastic litter. Furthermore, tourists increase the pressure on the solid waste and wastewater management systems in coastal areas. Cruise ships are another significant portion of waste generated at sea (24%), within the tourism sector. Nonetheless, not all the waste generated in cruise ships are plastics and there are strict regulations in place (e.g., MARPOL annex V), in relation to disposal of waste at sea. Ports and harbours play a vital intermediary role, ensuring that waste generated at sea is transported to appropriate facilities in land for adequate treatment and disposal.

Personal care products represent a multibillion-euro market, and microbeads intentionally added to such products represent an important source of primary microplastics. With more than 500 microplastics ingredients identified in personal care products, it is estimated that approximately 4,130 tonnes of microbeads are used in cosmetic and exfoliant products in European countries every year. The microbeads are included in products such as toothpastes, exfoliants and makeup and estimates show that about 210 trillion microbeads are released into the environment every year. Despite the several initiatives to ban the introduction of microplastics in these products, several further steps are needed to ensure that products currently available in the market do not contain any microplastics in its composition. Overall, microplastics in personal care products account for 2% of all microplastic sources.

On average, textiles lose 2% of microfibres during their lifetime, through washing. This percentage is variable by material type (mixed fibres, garments made entirely of synthetic fibres, etc.) or washing conditions (temperature, spin speed, use of fabric conditioners, etc.). For reference, a pair of jeans, usually made of 100% cotton, can release 56,000 microfibres per wash, which shows the high number of fibres that can be released during washing. This reference number is particularly concerning in the case of fully synthetic garments. Because most stretch materials have synthetic fibres in its composition, it is necessary to find solutions (e.g., removable filter installed directly in the washing machine, etc.) to reduce the amount of microplastics in greywater, at its source. Overall, microplastics from textiles account for 35% of all microplastic sources, being the number one source of marine microplastics identified in this report.

Plastic pellets, also known as pre-production pellets, beads, mermaid's tears or nurdles, are the most widely used raw material to produce plastic products, having a diameter that ranges between 1 and 5 mm, with a regular round shape. Plastic pellets, whose production in the EU ranges between 58 and 70.6 million tonnes annually, are regularly and unintentionally lost to the open environment, at each stage of the supply chain, from manufacturing to transportation. Pellet loss is a consistent concern associated with plastic production, and examples from Sweden show that between 3 and 36 million pellets are released annually from one single production site. Solutions to minimise pellet loss require low technological investments from the industry and can contribute to significant reductions in the number of pellets lost annually to the environment. Overall, pellets account for 0.3% of all microplastic sources.

Transportation, particularly road transportation, has been highlighted as a significant source of microplastics by many research centres, particularly associated to the wear and tear of tyres and to the friction caused by acceleration and braking. Current models predict annual tyre wear emissions per capita to range between 0.23 and 1.9 kg per country, with Europe generating 1.3 million tonnes of tyre wear waste annually. Many studies refer to tyre wear as the number one source of microplastics derived from land-based sources, however such particles are difficult to quantify. Research into tyre wear particles is likely to continue in upcoming years to find innovative solutions to identify quantitatively and qualitatively tyre wear particles.

Marine & maritime-based sources

The loss of containers at sea by the shipping industry, is of two-fold concern due to its financial and ecological implications. Containers lost at sea will accumulate in the seafloor, while the products within, depending on their density, can also be deposited in the ocean floor or float to the surface. The World Shipping Council estimates that between 2008 and 2019, an average of 1,382 containers were lost, every year. However, this figure is likely to reach a maximum of 10,000 containers lost at sea every year. Containers lost at sea are hard to retrieve, particularly in the open ocean. As the container sinks, the pressure of the ocean can cause them to open, releasing its contents (e.g., ink cartridges, rubber ducks, tennis shoes, plastic toys, etc.) directly into the ocean. Oceanic currents can then transport the materials released from the containers into coastal areas several thousands of kilometres away.

Fisheries and aquaculture represent a multibillion-euro market in Europe, with aquaculture considered a priority growth sector in Europe. In both sectors, macroplastics, particularly abandoned, lost, or otherwise discarded fishing gear (ALDFG) are a significant portion of what is released into the environment. Most of the ALDFG derives from the fishing industry itself, and in case studies conducted in the Faroe Islands and in the Norwegian continental shelf, ALDFG was found to represent more than 75% of the plastic litter in that region. Furthermore, it is estimated that 5.7% of fishing nets, 8.6% of traps and 29% of long lines used in fishing activities are lost annually worldwide. These macroplastic items will continue to fragment under environmental conditions, driven by solar radiation (ultraviolet radiation), salinity, temperature, abrasion, etc.; and producing secondary microplastics.

Pathways

Several pathways, or routes of entry of microplastics into the marine environment, were identified here, such as atmospheric deposition, river input, ocean circulation, and waste management, including import and export of goods internationally.

Atmospheric deposition of microplastics is a relatively new field of research, and it is estimated to be an important long-distance transport pathway of microplastics. Experiments on microplastic fallout have been recorded in mountains and urban areas with variable concentrations ranging from 275 - 718 MPs m^{-2} day^{-1}. The fallout variations are dependent on many atmospheric factors, such as wind speed and direction, temperature, precipitation, etc. Preliminary studies generally show that urban areas have higher fallout concentrations when compared to sparsely populated areas. Atmospheric deposition of microplastics has already been recorded in the Arctic subcontinent.

Rivers have consistently been identified as one of the most important microplastic pathways, with plastic waste both accumulating and being influenced by several geographic and demographic factors. Spatial and temporal changes, and extreme climatic events play an important role in the abundance of floating microplastic concentrations in rivers, particularly after periods of high rainfall resulting in flooding. Asian rivers account for a large percentage of plastic inputs into the ocean, however it is likely that the import and export of waste to these countries are influential. Furthermore, plastics have accounted for a significant proportion of all items deposited in and alongside riverbanks, e.g., 30.5% in Germany.

Gyres are convergence zones where large quantities of floating plastic litter are known to accumulate. According to recent estimates, the North Pacific Gyre accumulates between 1.1. and 3.6 trillion plastic plastics weighing 79,000 tonnes. Consistent efforts to monitor other gyres, such as the North Atlantic Gyre, close to the Azores archipelago in Portugal, has been undertaken in recent years, and results show that gyres represents an important pathway of microplastics in the region and a possible input for other areas further north, where transport is promoted by ocean currents.

Extreme events such as cyclones, tsunamis, tropical storms, and hurricanes, can generate millions of tonnes of debris, including large quantities of plastic. This plastic can be transported great distances from its origin, carrying species which can threaten the local biodiversity of their destination. The transportation of pathogen species, such as *Vibrio spp.*, to new geographical areas have consequences that are not fully understood. The Fukushima earthquake and tsunami, in 2011, identified species native to Japan settling and becoming invasive in North America, just a few months after the event.

Waste management

Wastewater treatment plants (WWTPs), although not originally designed to handle microplastics, mitigate their spread through their high removal efficiencies (> 65%) of these pollutants. Nonetheless, WWTPs themselves can be a source of microplastics through paint chips from old pipes, which are likely to be removed within the treatment, or a pathway via the sludge used on agriculture fields. It is estimated that the microplastic concentrations in sludge that can end up on agricultural land can range between 63,000 to 430,000 tons annually.

Waste generation is higher within developed economies when compared to developing countries or countries with emerging economies. In the EU28, the average waste generation is 30 kg per capita, with Ireland and Estonia being the two countries generating the most waste per capita. Global waste generation is expected to grow to 3.4 billion tonnes by 2050, and a significant part of this waste is plastic (38.2 million metric tons annually in Europe). Consequently, by 2016, the plastic waste entering the oceans annually in Europe was already equivalent to 66,000 waste collection trucks. To ensure that waste generation is reduced, and that materials are reused a circular economy approach is essential.

Import and export of waste is another relevant aspect associated with waste management, as many developed countries export waste (including plastic waste) to countries with emerging economies, mostly in Asia. Since the Chinese ban on imported waste started at the end of 2017, much of the European waste has been diverted to other countries in Western Europe or Asia, intensifying the pressure on countries where waste management might not follow the same European standards.

Vulnerable ecosystems

Vulnerable ecosystems worldwide, such as coral reefs, estuaries, mangroves, salt marshes, seagrass beds and the deep sea, have all been impacted by microplastic pollution. Even polar regions, once considered pristine, have recorded microplastics entrapped in ice or commonly found in the scat of local fauna.

Coral reefs and associated reef species in the Mediterranean Sea, particularly in Italy, Spain, France, Croatia, Greece, Malta, Cyprus, Montenegro, and Morocco have all been identified as having impacts associated to plastic marine litter and microplastic pollution. Corals are non-selective feeders, which makes them particularly vulnerable to microplastic ingestion, due to the size range of the food (0.2 to 1,000 μm) they consume. Due to its ecological and economic importance, it is fundamental to ensure that coral reef systems are not endangered by microplastic pollution.

Estuaries, mangroves, and salt marshes, due to their geographic location are already vulnerable to diverse natural and anthropogenic pressures, and experience similar impacts as coral reefs, as a result of the accumulation of plastics and microplastics. Studies in the Douro Estuary, in Portugal, revealed that there were more microplastics present in water than fish larvae. Similarly, mangroves have been identified as a major sink and hotspot for microplastic pollution, with concentrations 8.5 times higher than the surrounding shores. Furthermore, concentrations of microplastics in saltmarshes are relatively high when compared to intertidal zones. Regular clean ups can contribute to minimise the risk, but are not efficient on the long term, and other solutions to prevent the input of microplastics into these systems need to be considered. Seagrass meadows play a crucial role in coastal protection, climate change mitigation, biodiversity maintenance and production of food and raw materials used in medicine. Seagrass meadows are experiencing negative effects from plastic pollution, as they are prone to plastic and microplastic accumulation. Microplastics have been found to influence growth and development of seagrasses, just by their presence. Similarly, to estuaries, mangroves and saltmarshes, underwater clean ups can be a short-term solution, not economically viable on the long term, and other viable options to minimise risk are required.

The ultimate sink for microplastics is the deep sea, as it is estimated that 94% of plastics will accumulate there. In 2016, it was estimated that between 19 and 23 million tons of plastic waste entered aquatic ecosystems, with 10 million metric tonnes entering the ocean annually, the equivalent to approximately 990 times the weight of the Eiffel Tower. Microplastics will eventually reach the deep sea through a variety of media from marine snow or submarine landslides to whale falls and containers lost at sea. Video records of the deep sea in the North Atlantic Ocean and in the Mediterranean show that more than 89% of the identified plastics are either non-essential single-use plastic items or large plastic items (e.g., plastic chairs, etc.). Due to the low solar radiation in the seafloor, these items are likely to have low fragmentation and degradation rates, therefore remaining there for longer periods of time, when compared to floating plastic litter at the ocean surface.

Once considered pristine regions, both the Arctic and Antarctica are now facing consequences of plastic accumulation. In the Arctic, microplastics have been identified in all environmental compartments, with concentrations within the sea ice reported to be higher than concentrations in surface oceanic waters. Reports from an island in the Bering sea reported that concentrations of plastic marine litter had more than doubled between 1972 and 1974, from 2,221 to 5,367 items km^{-1}. Microplastics have been found to be ingested by a wide range of organisms from the Arctic (Northern Fulmar, Polar cod) to the Antarctic (Gentoo and King penguin). The consequences of the presence of microplastics in both polar regions is not yet fully understood, but several research teams are investing efforts to proper assess microplastic concentrations in both regions and ensuring low risk to these vulnerable ecosystems that are already experiencing consequences due to climate change.

Impacts on Climate

Once exposed to solar radiation, plastic undergoes chemical changes which contribute to gradual degradation and fragmentation processes. Such processes have been proven to release greenhouse gases (GHG), such as methane and ethylene to the atmosphere. As such, the presence of plastics and microplastics have consequences in carbon sequestration and on the release of GHG. Among several polymer types tested, Low Density Polyethylene (LDPE) released the highest concentrations of methane and of ethylene when exposed to solar radiation. This polymer produced approximately twice as much methane gas and 76 times more ethylene gas than LDPE fragments submerged in seawater. Methane is 25 times more potent at trapping heat in the atmosphere, when compared to carbon dioxide. Plastic degradation accounts for 76 Million tonnes of methane released annually worldwide, which is equivalent to all the CO_2 released annually from 435 coal-fired power plants or to charging a smartphone 210 trillion times. This means that plastic in the ocean might have the ability to contribute to climate change. Morphologic impacts have been shown in phytoplankton, zooplankton, the basis of the ocean food chain, as well as impacts in seagrass meadows.

Impacts on Marine wildlife

All marine life, from plankton to large marine mammals have now been affected by microplastic pollution, either by ingestion, entanglement, or both. Organisms are affected differently, depending on their feeding strategy, habitat, geographical location, type of prey consumed, etc. Microplastic ingestion has been shown to affect growth, morphology, photosynthetic activity, feeding ability, etc. Some species have shown signs of bioaccumulation of plastics while others are showing higher levels of toxins which can be caused by the particle itself, by the additives introduced during manufacturing or by the persistent organic pollutants available in the water or sediments that are absorbed at the surface of microplastics.

Planktonic organisms have been shown to ingest microplastics which can be transferred up the food chain to higher trophic levels. Many commercial invertebrate and fish species consumed by humans have been shown to consume microplastics. From a total of 323 species of fish that have been found to ingest microplastics, 262 are commercially relevant. The Norwegian lobster (*Nephrops norvegicus*), the blue mussel (*Mytilus edulis*) and the pacific oyster (*Crassostrea gigas*) are among those organisms, which have been shown to have concentrations up to 2 microplastics per individual. In the case of fish and crustaceans, where the gut is removed, the exposure through human consumption is minimal.

It is estimated that plastic ingestion currently affects 180 seabird species with predictions stating that by 2050, about 99% of all seabirds will have plastic in their digestive systems. Plastic ingestion is known to cause a wide range of effects, from gut obstruction to appetite loss, and in extreme cases, death. The Northern fulmar is one of the seabird species with data available to allow it to be classified as an indicator for floating plastic debris in the North Sea.

All seven sea turtle species on the planet are impacted by both plastic marine litter and microplastics. Turtles in the Mediterranean Sea were observed to have the highest abundances of plastic when compared to their Atlantic and Pacific counterparts, due to the relatively high abundances of plastic debris within the Mediterranean basin. Once a turtle has 14 pieces of plastic within their gut, the probability of mortality increases by 50%.

Charismatic animals such as seals and whales are threatened by large plastic items such as plastic bags and drift fishing gear (ALDFG or ghost nets). The large items cause entanglement of marine mammals, and furthermore microplastics are often ingested while eating. Injuries such as fin cuts or neck entanglements, have impacts on the hydrodynamic movement of such species in the ocean. Ingestion and entanglement can cause behavioural changes and in extreme cases, particularly in relation to entanglement, it can lead to death by starvation.

Impacts on Human health

The two main pathways of microplastics into the human body are ingestion or inhalation. Microplastics are prevalent in commercial seafood and although risk is minimal once guts are removed, estimates show still those consumers are expected to ingest up to 11,000 microplastic particles every year. Inhalation of microplastics can occur via airborne contamination, but it is thought to have minimal risk. Furthermore, to the authors knowledge, there is not enough research to date to assess the impacts on human health and it is not the primary focus of this report, as we are targeting marine microplastics.

Nonetheless there are some studies underway and preliminary research which shed some light into potential human health impacts, which are referenced within the report.

Future Monitoring

A panel of marine anthropogenic litter and microplastic pollution experts from academic, governmental & non-governmental institutions and of the industry recommended that invertebrates, seabirds, fish, and sea turtles should be monitored to assess microplastic concentrations over time. Based on their opinions, seawater and marine fauna are recommended to be sampled seasonally to assess microplastic concentrations, while seafloor sediments require longer periods of time between sampling due to the low sedimentation rates in the ocean. The atmosphere and road run-off were new environmental or urban compartments mentioned to be of particular interest for monitoring in upcoming years. A set of 5 common cross-sector recommendations can be summarised from the interviews to the 23 experts, which are:

1. Addressing the macroplastic issue will significantly decrease the occurrence, concentration and impacts of microplastics,
2. Reusing products, reducing waste, and repairing equipment are more effective strategies than recycling single-use products,
3. Recycling plastic is currently not effective, feasible or economically efficient. Circular economy approaches need to be applied to reduce impacts,
4. Implementing extended producer responsibility and corporate social responsibility schemes while redesigning plastic products in a true circular economy approach is fundamental to reduce plastic pollution and,
5. Banning non-essential single-use plastics wherever sustainable and carbon-neutral alternatives are available are fundamental to ensure long term reduction of plastic pollution in the ocean.

Policy recommendations

This report provides several policy recommendations based on the review of scientific peer-reviewed publications and reports, and on the dialogues with the experts.

Recommendations follow market-based approaches, circular economy approaches, or approaches collected from outreach and awareness education campaigns.

Policy recommendations are divided by expected implementation timeline, into three categories, short- (S), medium- (M) and long-term (L), meaning 2-3 years, 3-8 years, and more than 8 years, respectively.

The set of recommendations reflect the sectors discussed within the report, namely: Agriculture, Tourism, Personal care products & consumer goods, Textiles and Fashion industry, Plastic supply chain, Packaging, Transport' Fisheries and aquaculture, Shipping and Cruise industry, Water and wastewater treatment plants, Import and export of waste, Recycling, Solid waste management, Monitoring and research and Education and outreach.

Examples of short-, medium-, and long-term recommendations, without a specific order of importance or relevance, range from the introduction of legislation and tax incentives to change behaviour; the systematic identification of single-use products on the market with the aims to tackle those that need to be banned; the reduction of excessive packaging in daily products; and the increase in funding efforts to sample, monitor and conduct outreach and education campaigns targeted at microplastics. Some recommendations aim at setting reduction targets to release of microplastics in water treatment plants, wastewater treatment plants or agriculture fields; while other recommendations focus on phasing out potentially toxic additives added to plastic packaging.

Ensuring reusability and repair over recycling is also recommended, as well as the creation of fees to fund infrastructures in ports and harbours targeted at Fishing for Litter schemes throughout Europe.

In conclusion, this report provides a simple yet deep insight into the current state of the art concerning microplastic pollution research, while providing recommendations that stimulate research-led debate among decision-makers and stakeholders at local, national, European, and international level.

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Acronyms

GDP Gross Domestic Product

GHG Greenhouse gases

HDPE High-density polyethylene

LDPE Low-density polyethylene

PA Polyamide

PE Polyethylene

PET Polyethylene terephthalate

PLA Polylactic acid

PP Polypropylene

PS Polystyrene

PUR Polyurethane

PVC Polyvinyl chloride

WTP water treatment plant

WWTP wastewater treatment plant

UNCLOS United Nations Convention on the Law of the Sea

IMO International Maritime Organisation

MARPOL he Convention for the prevention of Pollution from ships

IOC International Oceanographic Commission

UNEP United Nations Environment Programme

MSFD Marine Strategy Framework Directive

GES Good Environmental Status

CEAP Circular Economy Action Plan

Glossary of important concepts

Marine litter is any persistent, manufactured or processed solid material that is deliberately or unintentionally discarded, disposed of, abandoned, or transported by winds, rivers and animals into the marine and coastal environment

Marine Strategy Framework Directive 2008/56CE

Macroplastics are synthetic solid items or particles with size ranges larger than 5 mm

ISO/TR 21960

Microplastics are any synthetic solid particle or polymeric matrix with regular or irregular shape, with size ranging between 1 µm and 5 mm, of either primary or secondary origin, which are insoluble in water

Frias and Nash, 2019

Nanoplastics are synthetic solid particles with colloidal properties, that have a size range between 1 nm and 1 µm and that result from the fragmentation of larger plastic items

Gigault et al., 2018

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs

Brundtland Report, 1987

INTRODUCTION

Records of the effects and impacts of anthropogenic pollution have been documented since the beginning of the Industrial Revolution. One of the first examples dates to the 1860s and it refers to the famous case of the peppered moth, *Biston betularia,* in the United Kingdom, and how this insect adapted to air pollution levels by changing its colour to survive. Several decades later in 1962, across the Atlantic Ocean, Rachel Carson would publish the book *Silent Spring*, documenting the adverse environmental effects caused by pesticides, particularly Dichlorodiphenyltrichloroethane, also known as DDT. Her book raised awareness to environmental changes due to human activities and influenced the start of an environmental movement. Seven years after its publication, a group of researchers set out to sample the Hawaiian archipelago would report that albatrosses were swallowing indigestible matter in the form of plastic and not the common pebbles or pumice previously reported for the region (Kenyon and Kridler, 1969).

Although plastic production started around the 1950s, records of marine birds and seals interacting with this material were already reported in the late 1960s and early 1970s. Those early reports addressed mainly entanglement and ingestion by marine animals and were only available to a small audience of researchers. They only started reaching international audiences after Carpenter and Smith published an article in Science magazine in 1972, highlighting that although plastic production had only started after World War II, surface seawater samples retrieved with manta trawls, all contained hard plastic and pellets of small dimensions. The study also hypothesised that plasticizers, a form of additives used during plastic production, could potentially leach into the seawater, and affect the surrounding environment (Carpenter and Smith, 1972).

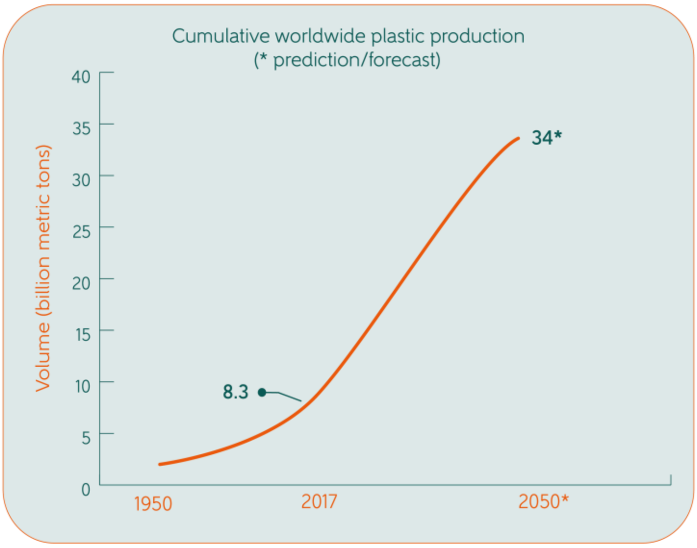


Figure 1 - Cumulative worldwide plastic production and forecast for 2050

More than 70 years have passed, during which global plastic pollution research and plastic production have increased exponentially (PlasticsEurope 2010-2020; Zhang et al., 2020). Production is expected to double over the next two decades (Figure 1). It is undeniable that plastics are cheap versatile materials, whose physical, thermal, and chemical properties allow for a wide range of uses in diverse industries, from packaging to medical applications. Plastics are lightweight, durable, resistant to shock, resistant to corrosion, chemicals and water, which makes them extremely versatile but also extremely persistent in environmental conditions. The characteristics and low cost of plastics have enabled them to surpass all other materials in global value chains, particularly in the packaging sector (Peters et al., 2017; EU Parliament, 2020). Plastic production has been exponentially increasing at a rate of 8% per year since the 1950s (PlasticsEurope 2010-2020) and until 2017, a cumulative 9.2 million metric tons had already been produced (Figure 2; Plastic Atlas, 2019).

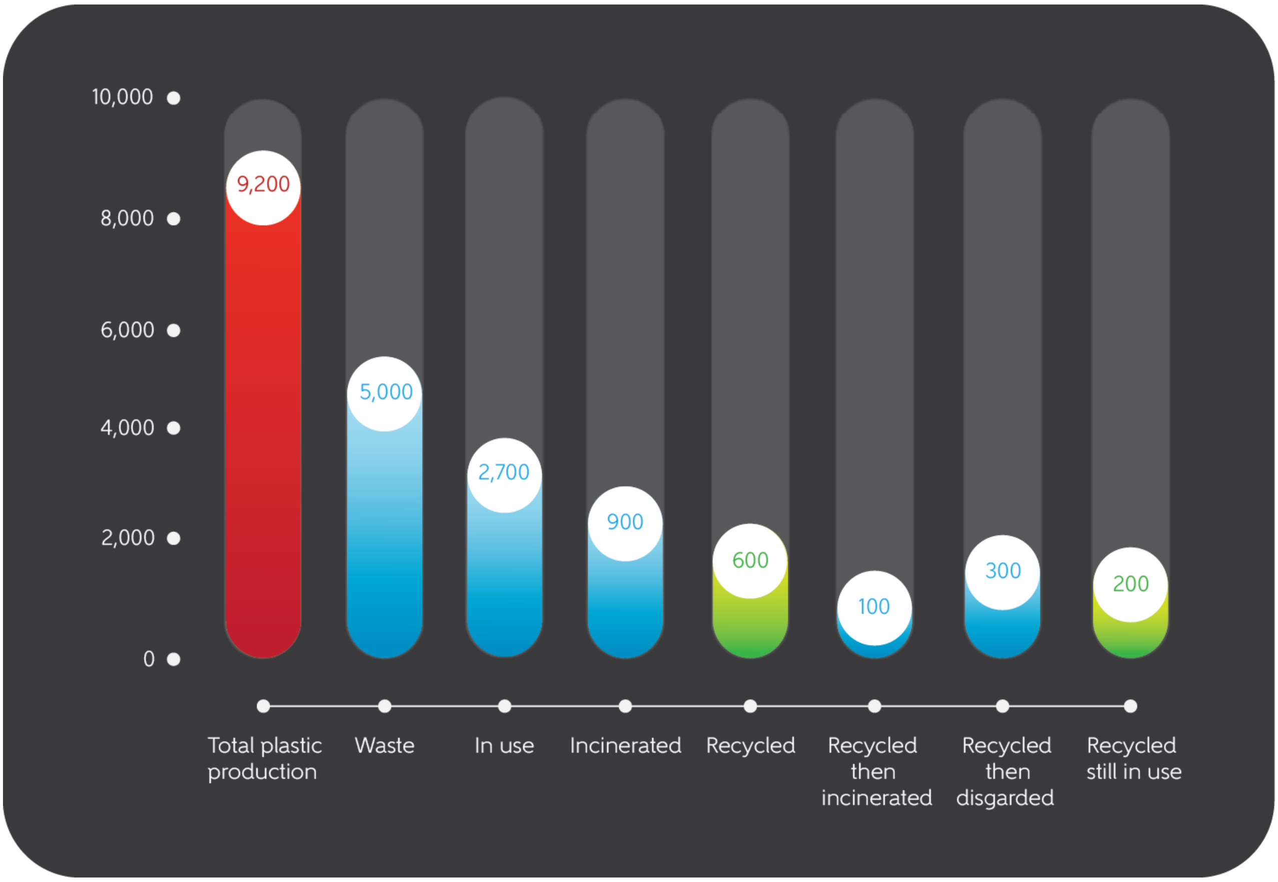


Figure 2 - Flow of plastic materials worldwide between 1950s and 2017 in million metric tons (Source: Plastic Atlas, 2019)

This is the equivalent to 900,000 Eiffel towers, 88 million blue whales or 1.2 billion elephants (Geyer, 2020), and represents **more than 1 ton per person alive today.** From these, about 600 million metric tons were recycled and 200 are recycled materials still in use (figure 2).

It is undeniable the economic success story that the plastic industry is, particularly emphasised by **the 1.56 million jobs created in Europe and the €350 billion revenue generated in 2019** (PlasticsEurope, 2020). However, the **traditional linear economy system** (extraction → production → transport → consumption → disposal), the **lack of or the inefficient global solid waste management**, and the **very low plastic recycling rates** allowed the generation of considerable amounts of waste that are now accumulating in the environment (EU Parliament, 2020). When inadequately discarded or disposed of, plastics tend to accumulate in the environment where exposure to environmental conditions (solar radiation, temperature changes, physical interactions with vessels, rocks, and animals) contributes to the degradation and consequent fragmentation of plastics into smaller pieces known as microplastics. Fragmentation increases the scale of the plastic problem, as well as the technical, technological, and logistic solutions to solve it. Predictions of macro- and microplastics into the ocean based on different scenarios are becoming more frequent (Figure 3; Lebreton et al., 2019), which are valuable contributions to address the flow of materials into the future.

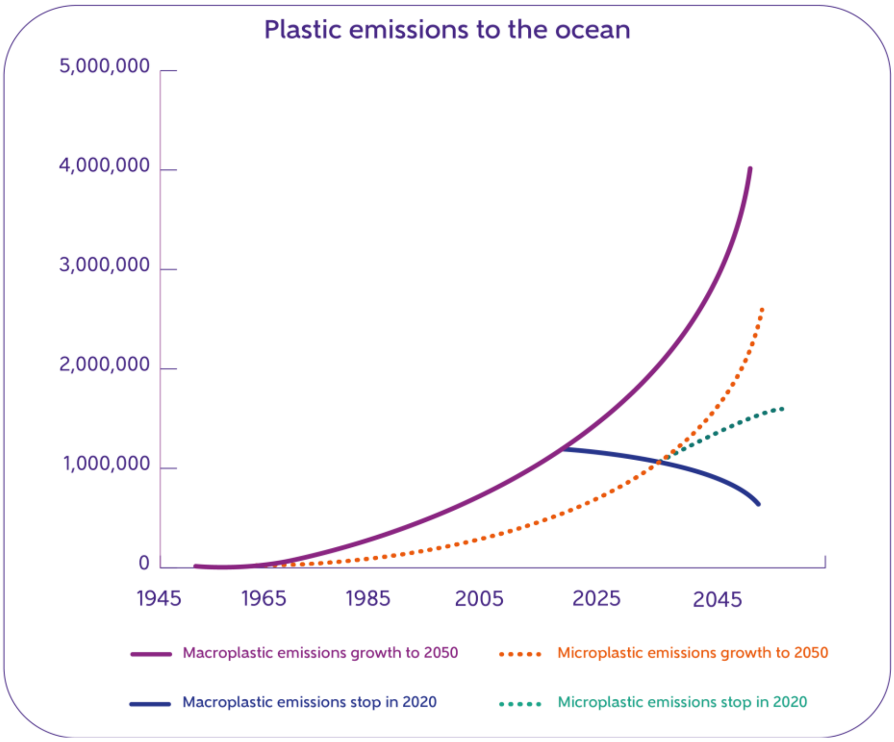
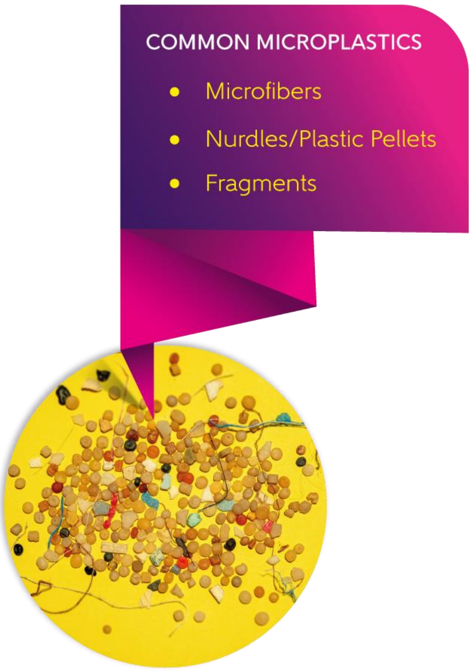


Figure 3 - Emissions of micro and macroplastics to the ocean (Source: Lebreton et al., 2019)

These plastics breakdown to form microplastics; the most common types reported in scientific literature, are **microfibers, plastic pellets, and fragments**. Plastic is now a ubiquitous material in the marine environment, or in other words, **plastic is found everywhere**. Researchers have found evidence of plastics from the top of the Swiss Alps (Bergmann et al., 2019) and the top of Mount Everest (Napper et al., 2020) to the bottom of the Mariana Trench (Chiba et al., 2018). Plastics have also been found floating and accumulating in ocean gyres, particularly in the North Pacific (Lebreton et al., 2018), the South Pacific (Erikson, Maximenko and Thiel, 2012), the North Atlantic (Law et al., 2010; Pham et al., 2020) and in the South Atlantic (Ryan et al., 2019) gyres, except for the Indian Ocean Gyre (Van der Mheen et al., 2020), where currents prevent accumulation.



Plastic accumulates in coastal zones where it is colonized by macro- and microbiotic communities in what has been recently coined as plastisphere (Figure 4; Amaral-Zettler et al., 2020). Several species attach and colonise plastics, most of them harmless, but there are other species (e.g., Vibrio spp.) that are potentially pathogenic. Because of their lightweight, plastics float in the open ocean, and are often referred to as a transport vector for invasive species into remote ecosystems, across continents (Amaral-Zettler et al., 2020).

Figure 4 – Barnacles colonizing plastic cup collected in the West coast of Ireland

(Credits: Sibeal Alliot, 2021).

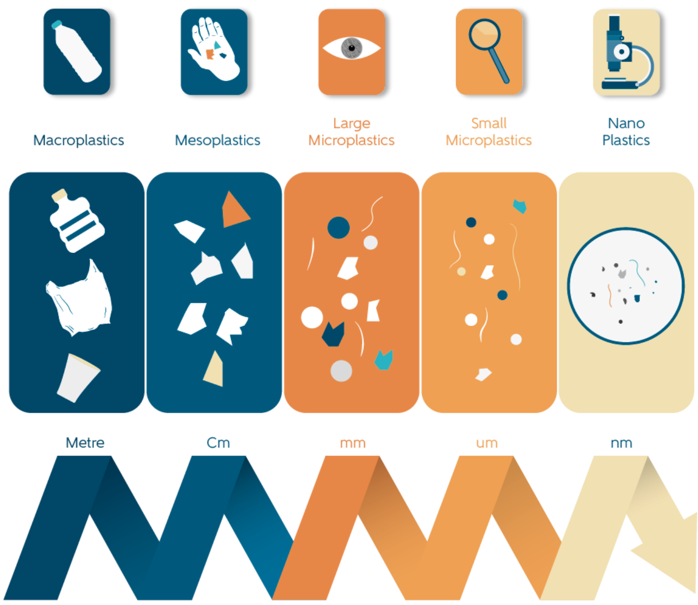
Another threat associated with plastics are the chemical additives introduced during production to ensure physical, thermal, or chemical properties (Al-Malaika et al., 2017; Coleman, 2017; Hermabessiere et al., 2017). Plastics have been shown to leach these additives into seawater (Teuten et al., 2009), raising concern about the consequences of such transfer, as many additives are known to be toxic or to have endocrine disrupting properties (Hahladakis, et al., 2018). It is known that plastics have the ability to adsorb and/or absorb persistent, bioaccumulative and toxic chemicals (PBTC), such as persistent organic pollutants (POP) and trace metals from the surrounding environment (Mizukawa et al., 2013; Holmes et al., 2012). While direct exposure of leached additives from microplastics and impact or risk assessment modelling were considered inconclusive for worms and fish species (Koelmans, Besseling and Foekema, 2014) a recent study by the University of Washington established a direct link between chemicals in tyre wear run offs and the mass mortality of silver or coho salmon (*Oncorhynchus kisutch*) (Tian et al. 2021). Among the scientific community studying microplastics, additives are through to pose a higher risk when compared to sorption of pollutions from the marine environment.

Additionally, to all the information available, there are currently several conventions, legal frameworks, and market-based instruments in place to regulate the use of plastics, as it is the case of the Marine Strategy Framework Directive (MSFD), the Convention for the Prevention of Pollution from Ships (MARPOL) or the plastic bag levy (Brink et al., 2009; Luís and Spínola, 2010; Schuyler et al., 2018).

Market-based instruments such as the plastic bag levy substantially contribute to reductions of plastic consumption as studies suggest (Brink et al., 2009; Luís and Spínola, 2010; Schuyler et al., 2018). Ireland was the first country to impose a levy on plastic bags in 2002, which was followed by a drastic reduction on plastic consumption of up to 90% after the enforcement of the legislation (Luís and Spínola, 2010; OECD, 2021).

These legal instruments address plastic pollution by prevention, removal, mitigation and/or education strategies. Prevention focusses on the 3R's policy rule: **Reduce**, **Reuse**, **Recycle**, meaning reduce at the source, reuse materials, and recycle when possible. Recently, under the scope of circular economy approaches, other R's have been proposed such as **Rethink** lifestyles, **Refuse** non-essential single use items, **Removal** and **Repair** of electric and electronic equipment. Removal addresses clean-up actions on beaches, rivers or terrestrial sites and mitigation, often used in the scope of plastic pollution, refers to development of discharge regulations and litter disposal (Chen, 2015). Another important aspect is education, awareness, and outreach campaigns, who alongside with market-based instruments are useful approaches to reduce plastic pollution (Chen, 2015). Further information on the current legal frameworks and market-based instruments can be found in Appendix 1.

This report addresses the highlighted issues in this introduction in four chapters.



The first chapter explores the sources, pathways, and routes of microplastics in the environment. Sources are divided into land-based and marine and maritime-based sectors generating plastic litter. Pathways focus on natural transport versus transport enhanced by human activities.

The second chapter focuses on the impacts on marine wildlife, marine ecosystems, human health, and climate change. Focus is given to the known effects and impacts, from biological and socio-economic perspectives.

The third chapter focuses on monitoring based on expert opinion from researchers in the field of microplastics.

The fourth and final chapter of this report is focused on policy recommendations targeted at tackling the sources and pathways and minimising and mitigating the impacts of marine microplastic pollution.

CHAPTER 1

SCALE, SOURCES AND PATHWAYS OF MARINE MICROPLASTIC POLLUTION

SOURCES OF PLASTIC POLLUTION

The term pollution refers to the presence or introduction into the environment of any substance that has negative impacts on ecosystems and organisms that live in it (National Geographic, 2020). There are seven main types of environmental pollution with diverse environmental effects and consequences: air, water, soil, thermal, radioactive, light and noise pollution (WHO, 2020). Pollution assessment is conducted by identification of sources. Sources can be divided into point source (traceable and identifiable) or diffuse pollution (no specific point of discharge) (WHO, 2020). Attempts to identify the source of microplastic pollution are common, and according to the most recent data available the main source of microplastics are synthetic fibres released from textiles, followed by car tyre particles and city dust (i.e., dust naturally settling out of the atmosphere) from tyre wear, shoe wear, microfibers etc) (figure 5).

This section will explore the main sources of land-based and marine and maritime-based plastic pollution in diverse environmental matrices, including their transport routes and pathways. Focus will be given to the most common types of microplastics commonly reported in scientific literature, namely microfibers, fragments and plastic pellets which are usually small rounded, spherical, or cylindrical bodies.

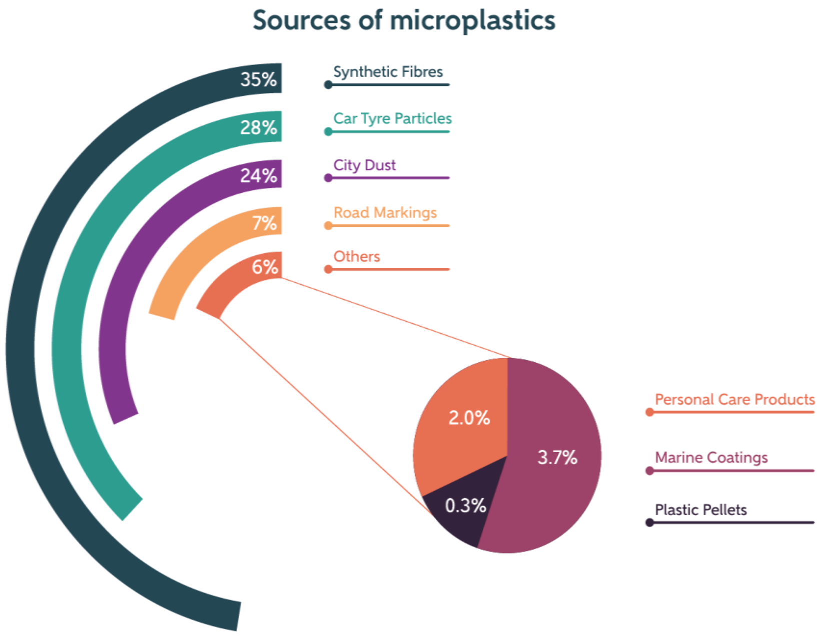
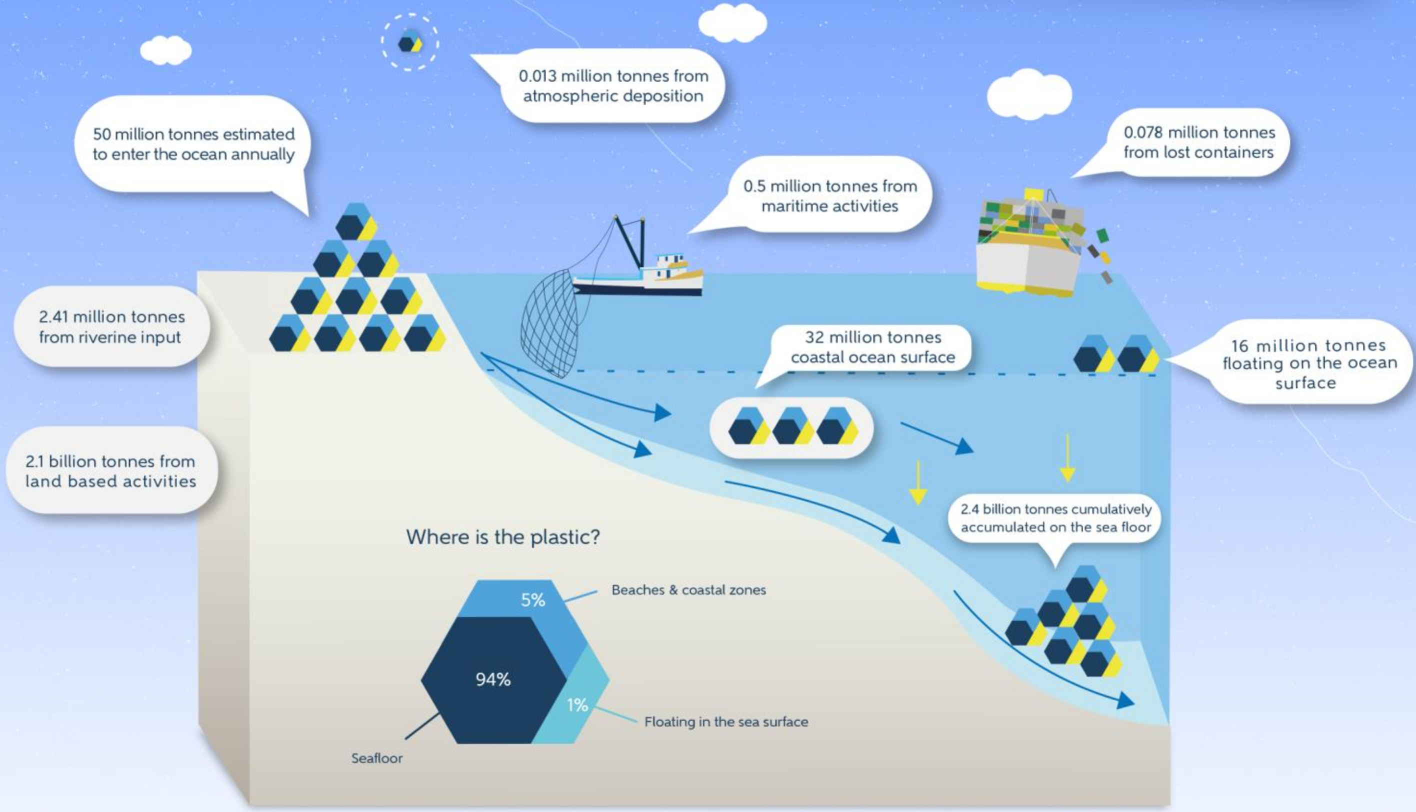


Figure 5 – Sources of microplastics

(Source: Citi GPS, 2018)

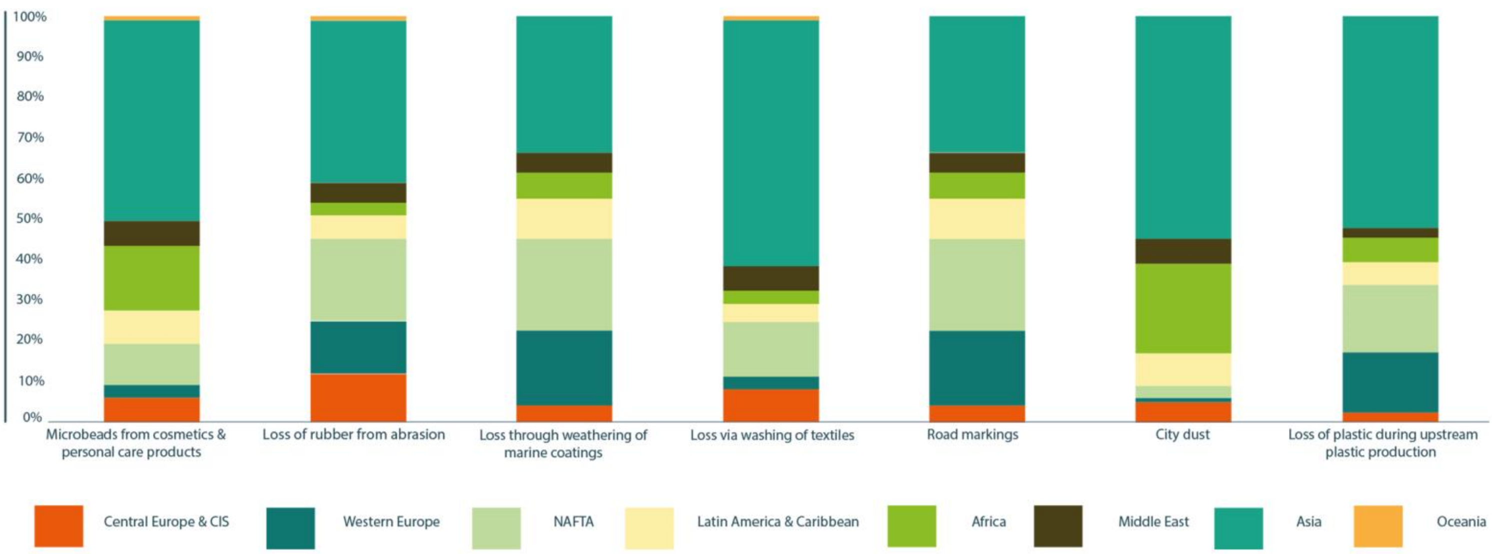
Estimates of plastic entering the ocean

In 2004, Prof. Richard Thompson raised an interesting question in the title of one of the publications of his research team: Where is all the plastic? Several research groups have tried to come up with accurate estimations. The figure below is a compilation of the most recent data on microplastics in the environment:



References Proportions of plastics and microplastics entering the ocean (Sources: van Sebille et al., 2015; IUCN, 2017; Geyer et al., 2017; Borrelle et al., 2020; Evangeliou et al., 2020)

Regional breakdown of microplastic pollution sources



LAND-BASED SECTORS GENERATING PLASTIC LITTER

Approximately 80% of marine litter derives from land-based sources, with plastic encompassing between 70 - 95% (UNEP, 2005; Boucher and Friot, 2017). Several sectors use plastic products in their daily activities (Figure 6), but some of them have been consistently identified as sources of microplastics into the environment.

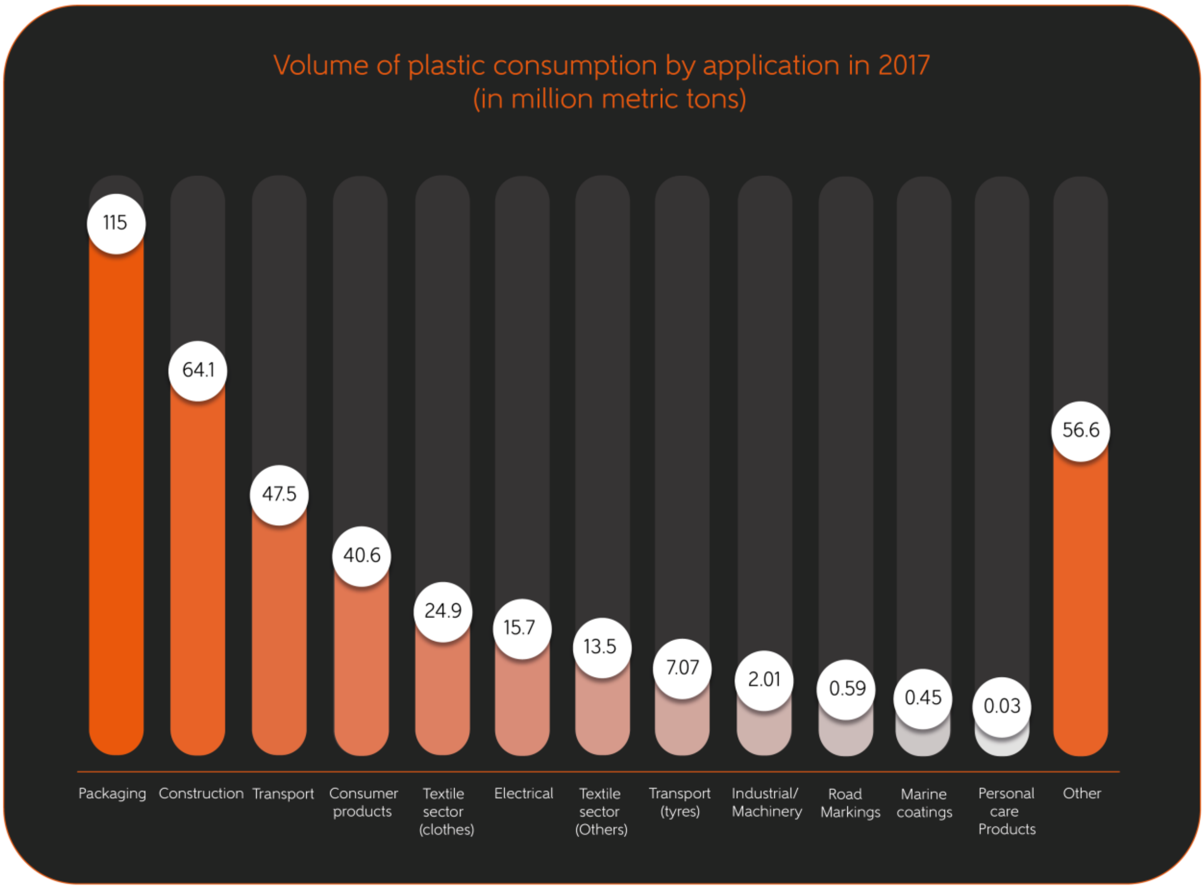


Figure 6 – Volume of plastic consumption by application, in 2017 (Source: UNEP, 2018)

This section explores the release of microplastics from the agriculture, tourism, personal care, textile, transport, and plastic industry sectors.

AGRICULTURE

Agriculture is one of the most important economic sectors globally, as food is vital for human survival. Rapid global population growth and increased food demand, coupled with limited availability of fertile land and productivity rates, pose significant challenges for the agricultural sector. To meet this ever-increasing demand, industrial farmers sometimes resort to unsustainable practices to increase productivity.

Modern farming practices involve the use of plastic materials to grow, transport and store fruits and vegetables, however these have the potential to harm terrestrial ecosystems. Ongoing research aimed at creating suitable plastic alternatives while ensuring productivity are on the rise, however to date, none of these alternatives are economically viable. The use of plastic within the agricultural sector is extensive and applied in a variety of forms from its use in fertilizers to polyethylene (PE) mulch and polyvinyl chloride (PVC) irrigation pipes, making agriculture a significant source of microplastic pollution (Hurley et al., 2020).

Intensive agriculture, where crop rotation is not the norm, results in the depletion of nutrients originally present in the soil within a few years (GESAMP, 2015). To counteract this, farmers use supplementary fertilizers. Advances in farming technology have resulted in the development of a Control Release Fertilizer (CRFs), which minimise the amount of fertilizer required per hectare (GESAMP, 2015). CRFs, often referred to as nutrient pills, are encapsulated in plastic pods containing various nutrient combinations, such as nitrogen, phosphorus, potassium, and other elements (GESAMP, 2015). The nutrient pill is applied to the base of the plant, and the fertilizer gradually diffuses into the soil over a predetermined time. However, once the nutrients are released, the remaining polymer coating, often polysulfone, polyacrylonitrile or cellulose acetate, does not degrade, ultimately contributing to local microplastic pollution (GESAMP, 2015).

In addition, the agricultural industry has discovered a novel and effective way to protect the germinating seeds and seedlings from soil-borne pathogens and insects through applying pesticides directly to the seed, in the form of a thin plastic-like coat (Accinelli et al., 2019). The coating contains a mixture of fungicides and/or insecticides, along with polymers, fillers, and dyes. These coatings break or fragment when the seeds are planted in the soil due to abrasion (Accinelli et al., 2018; Accinelli et al., 2019) and unless retrieved post germination, the fragmented seed coatings are left to further contribute to microplastic pollution.

Polyethylene is the most common polymer used in agricultural plastic mulch, as it is highly flexible, durable, and can be customizable with the help of additives such as plasticisers, stabilizers, or other polymers (Lamont, 2005). Plastic mulching is widely practiced in Europe, due to cost-effectiveness of achieving both a higher yield of quality crops and more efficient water use (Lament, 1993; Steinmetz et al., 2016). Mulching covers a considerable [427,059 hectares (ha)] proportion of agricultural land. The estimated coverage of mulching is much larger than the surface coverage for greenhouses and large low tunnels (Figure 7; Scarascia-Mugnozza et al., 2011).

Figure 7 – Use of plastics in the agriculture sector, in ha
(Source: Scarascia-Mugnozza et al., 2011)

Plastic mulching is largely applied only for a few months in an agricultural setting, and in most cases, it is not possible to retrieve back 100% of the film. Consequently, more plastic waste fragments are regularly left behind after each application. If this plastic waste is exposed to extreme weather events, such as storms, strong winds or intense sunlight, processes such as physical fragmentation and chemical ageing are accelerated

(Scarascia-Mugnozza et al., 2011), leading to the rapid creation of secondary microplastics (Steinmetz et al., 2016) and further plastic pollution.

In addition, there are many other potential sources of plastic and microplastic pollution in this sector that are still **overlooked and not monitored**. Some of these sources include plastic covers used in fodder mulching for haystacks, milking liners, silage coverings, tyre wear from tractors and other small machinery, irrigation pipes, rubber boots and clothing.

TOURISM

Tourism represents a global multi-trillion-dollar industry (Buckley, 2011) and currently ranks as the 4th largest preceded by the fuel, chemical and food industries, respectively. Accounting for 5% of the global Gross Domestic Product (GDP), it provides direct and indirect employment to approximately 6-7% of the global workforce (Hall et al., 2014). Tourism is an internationally traded commodity where in 2011, the United Nations World Tourism Organization (UNWTO), estimated it to be worth US $1.2 trillion or 6% of total exports. Despite occasional drops in revenue, to which 2020 is an exception, tourism is expected to grow at an average rate of 3.3% per year by 2030 (UNWTO, 2012).

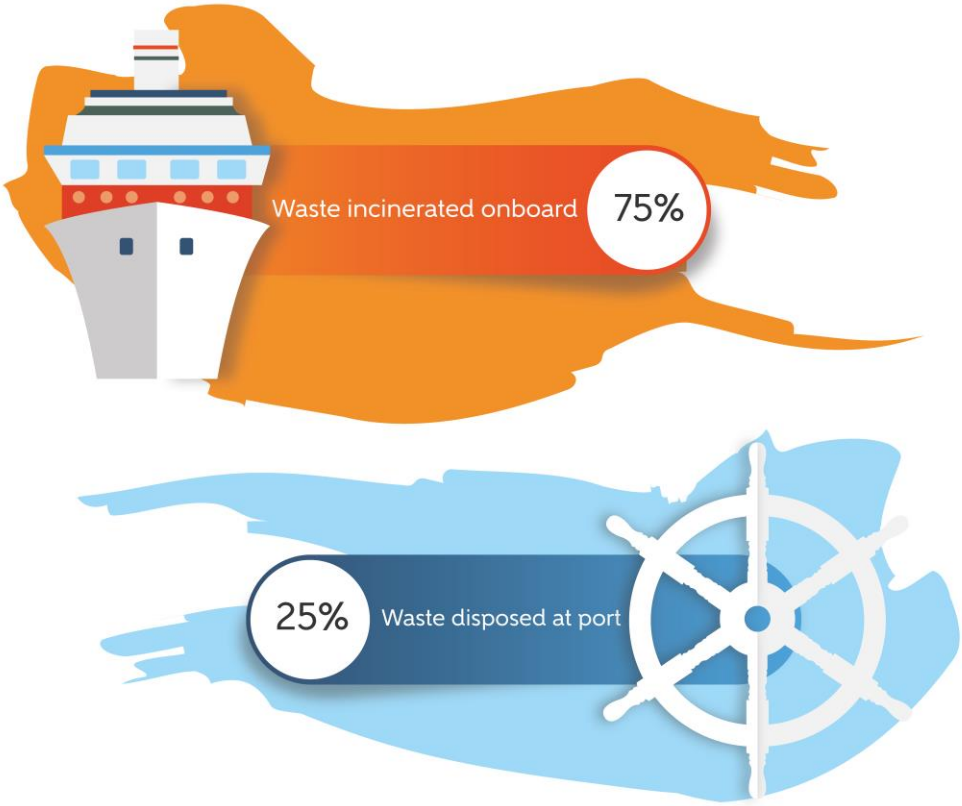
Among the different tourism sectors, marine and coastal tourism is one of the fastest growing areas (Hall, 2001). **In Europe, maritime and coastal tourism generates a total of €183 billion,** accounting for over one third of the maritime economy (EU Commission, 2021). Tourists seeking sunny, sandy beaches, blue waters, water sports and diving experiences travel to coastal areas, where nature itself is often sold as a product (Buckley, 2011). The appeal and charm of these destinations largely depends on aesthetics and overall pristine appearance (Buckley, 2011; Jang et al., 2014) however, the tourist industry is a significant source of plastic pollution (Wilson and Verlis, 2017).

Several economists have tried to quantify the impact of pollution on the tourism industry (Ballance et al., 2000; Brink et al., 2009; McIlgorm et al., 2011; Wilson and Verlis, 2017). A study conducted in Geoje Island, South Korea, estimated an economic loss of US $29-37 million in tourism revenue due to a single heavy rainfall which led to an increase in plastic pollution in the beach (Jang et al., 2014). A different study conducted in the Southern Great Barrier Reef in Australia, found that where human activities were common, there was a significant increase in debris that originated on the island. One of the islands surveyed, Heron island, had a resort, and the presence of tourists there is thought to be one of the contributors to the local marine debris (Wilson and Verlis, 2017).

Tourism within the Mediterranean has generated 30% more waste in coastal municipalities than inland municipalities, which has created pressures on waste management facilities. Such pressures result in waste either being left uncollected or unsafe waste management practices were employed during collection (WWF, 2019). Similarly, GESAMP (2016**) stated that areas with a high tourist activity can be considered as a source and proxy of plastic pollution, due to the higher concentration of people in a given area**. Tourists on holiday may not consider the potential environmental impact of convenient disposable products such as plastic beverage bottles or food containers (GESAMP, 2016), which often leads to a local pressure on waste management.

'24% of all shipping waste is generated by cruise ships'

The global cruise industry has grown from carrying 4 million passengers annually in the early 1990s to an estimated 27 million passengers in early 2020, an equivalent to 7% annual growth (FAO, 2020). Although cruise ships only account for a small proportion of the global shipping industry, they represent an important source of plastic pollution, with an estimated 24% of all shipping waste generated by this sector (Carić and Mackelworth, 2014). **A large cruise ship at sea for one week can generate eight tons of solid waste**. A ship with 3,000 passengers and crew members can generate approximately 56,800 – 113,600 litres per day of sewage and 706,000 litres per day of greywater (i.e., wastewater without faecal matter). **Greywater is a significant source of microfibres into the ocean, particularly considering washing machines on board of ships**. MARPOL Annex V requires vessels to treat sewage before discharge, however, greywater can be released directly into the ocean without any treatment (FAO, 2020). As storage space is often limited on cruise ships, approximately 75% of the waste generated is incinerated onboard (FAO, 2020). The remaining 25% is disposed of at port facilities and this influx of waste can overwhelm ports and harbours that lack adequate resources (FAO, 2020).



PERSONAL CARE PRODUCTS

Personal care and cosmetic products (Figure 8) represent a multi-billion-euro market that is projected to continue to grow in upcoming years (Statista, 2021a). These care products include a wide range of personal hygiene items and cosmetics namely skin moisturizers, exfoliants, shower gels, nail polishes, eye and facial make-up preparations, shampoos, hair dyes, and toothpastes. Care products of the past contained natural added particles from salts, seeds, fruit pits and oils, which contributed towards the exfoliant and abrasive nature of these products. Most products nowadays, such as facial and body scrubs, toothpastes, exfoliating soaps, and gels contain intentionally added plastic microbeads or glitter (Galafassi et al., 2019; UNEP, 2016; Xu et al., 2020). Traditional and natural scrubbers have slowly been replaced by plastic microbeads due to their cheaper production costs, size, and versatility, which has led them to be introduced as a main ingredient in numerous personal care products (Ryberg et al., 2018) without prior public consultation.

Microbeads are primary microplastics predominantly made of polyethylene (Ryberg et al., 2018) and depending on the application they can come in a variety of shapes, from smooth spherical to irregular fragments, with dimensions that are usually under 0.5 mm (Galafassi et al., 2019). The Plastic Soup Foundation, through its 'Beat the Microbead' campaign, has identified more than 500 microplastic ingredients widely used in cosmetics and personal care products, still on the European market today (UNEP, 2015; Ooms et al., 2015; ECHA, 2018). Many personal care products, for example, eyeshadows with glitter and highlighters, nail polish with decorations, hair sprays, etc., can be categorized as "open use", which means that they are intended to be washed off after one use and the product along with the microplastics are released into the drains (Sundt et al., 2014).

Figure 8 – Examples of personal care products containing microplastics

It was estimated that 4,130 tonnes of microbeads were used between 2015 and 2019, to make cosmetic products each year in EU countries (Gouin et al., 2015; Guerranti et al., 2019). Napper et al. (2015) investigated the average habits of women in the U.K. and estimated that between 4,600 and 94,500 microbeads could potentially be released in a single use. Based on the toothpaste usage in Istanbul, it was estimated that an average of **871 million grams of microplastics are released every year** (Ustabasi and Baysal, 2019). **Reports from China further estimated that 209.7 trillion microbeads (i.e., 306.9 tonnes) are released into the environment every year, accounting for 0.03% of the plastic**

waste that ends up in the ocean (Cheung and Fok, 2017). This indicates that microbeads released from personal care products are a major source of primary microplastic pollution.

Several countries in the European continent, for example Ireland, United Kingdom, and France, have introduced legislation to ban the manufacture or placing on the market of certain products containing microbeads, thereby banning the intentional adding of microbeads. In addition, the EU plastic strategy has identified and is to target intentionally added primary microplastics and personal care products with prevention measures and market restrictions under REACH. China has also announced plans to ban the production of cosmetics that contain plastic microbeads by 31 December 2020, with sales of existing stock to be prohibited by 31 December 2022, which would hugely reduce the imported MPs to Europe.

TEXTILES

The textile industry and its related activities are one of the main emitters of microplastic fibers into the environment. It is estimated that between 200,000 and 500,000 tonnes of synthetic fibers from textiles are released into the marine environment each year (EEA, 2021). Textiles represent 20-35% of all microplastics in the marine environment (Rathinamoorthy and Balasaraswathi, 2020). Considering the scale of the textile and fashion industries, they are the most significant source of microplastics contributing to the overall problem (Figure 5).

Microfibers or micro-synthetic fibers are considered a subset of microplastics, referring to the fibers that shed from clothing made from synthetic fabrics (Henry et al., 2019; Kelly et al., 2019). Browne et al. (2011) estimated that microfibers, predominantly polyvinyl chloride, polyester, and synthetic polyamide (nylon), make up 85% of all anthropogenic debris found on the global shorelines.

Microfiber pollution is challenging to address, as more than 60% of global textiles are currently produced from synthetic fibers and both industrial and individual consumers are unconsciously contributing to the release of large amounts of these fibers during the washing process (Galafassi et al., 2019). Microfibers are mainly produced when fabrics or clothing are washed in an industrial or domestic washing machine, **with a single item of**

clothing reported to produce over 1,900 fibers per wash (Browne at al. 2011) and **700,000 microfibers being released from a 6 kg load of acrylic fabric washed** (figure 9; Napper and Thompson 2016). **On average a garment loses 2% of microfibers via washing during its lifetime** (Ryberg et al., 2018), for example**, a pair of jeans releases 56,000 microfibres per wash** (Athey et al., 2020). After successive washes, around four to five washes, the number of released microfibers is reduced (De Falco et al., 2018). The laundry process is found to cause the maximum damage to the clothing and subsequent release of microfibres (Rathinamoorthy and Balasaraswathi, 2020). Consequently, the life of a garment is usually estimated by the textile industry based on its ability to withstand a predetermined number of washes.

Figure 9 – Release of microfibres during washing
(Source: Napper and Thompson, 2016)

Studies conducted in North America (Canada and U.S.A.) revealed that approximately 218 to 300 laundry loads are performed per household every year. Based on this, it is estimated that, in this region alone, the yearly microfiber discharge into the ocean via wastewater treatment plants is about 878 tonnes. This represents 135 grams of microfibers per household per year (Vassilenko et al., 2019). It should be noted however, that the release of microfibers from synthetic clothing is not universal or constant, and there are multiple factors that influence the release of microfibers, such as – the type of material, detergents and conditioners used, washing temperature, water hardness, age of the clothes, type of weaving within the garment, etc. Most studies have found that polyester fleeces shed the greatest amounts of fibers, that is on average 7,360 fibers m^{-2} L^{-1}(Xu et al., 2020) when compared to other synthetic fabrics such as acrylic or polyamide. Higher temperatures and washing time also enhance the release of fibers while fabric softeners can reduce the generation of microfibers by 35% as it minimizes abrasive damage (Xu et al., 2020).

Another potential threat associated with textiles is 3D printing (Chakraborty and Biswas, 2020), as it opens a new way to widespread micro- and nanoplastics in the environment (Zhang et al., 2019; Rodriguez-Hernandez, et al 2020). Research on the effects and impacts of such innovative technology are underway.

PLASTIC PRODUCTION

Plastics have replaced many of the traditional materials, such as glass and metal, because of the lower cost of manufacturing. As a result, plastics are now a diverse set of items that range from cigarette filters, tampons, tablet capsules, dental floss, toothbrush bristles, children's toys, to pipelines transporting oil, water, or underwater cables. While there is a growing environmental awareness concerning plastic pollution nowadays, there is still an impressive number of new products being brought up to the market that are made of plastic or include plastic components. In the current global pandemic related to COVID-19, the increased use of both essential single-use plastics in particular the amplified need for surgical PPE masks and gloves, wet wipes, hand sanitizers and hand washing products, but also non-essential single-use plastics (e.g. cups, straws, plastic cutlery) has contributed to an increase of primary and secondary microplastics into the environment (Fadare and Okoffo, 2020; Zhang et al., 2021).

Plastic products start their life as virgin plastic pellets (figure 10), powders and flakes falling under the category of 'primary microplastics'. Plastic pellets are raw materials that are melted down and moulded into all plastic products (Tunnell et al., 2020). These pellets, powders and flakes are produced in polymeric production industries or at recycling plants, where they are manufactured into different shapes and sizes (OSPAR, 2018; Karlsson et al. 2018). Plastic pellets, also known as beads, mermaid's tears or nurdles, are the most widely used of these raw materials (Hann et al., 2018) having a diameter that ranges between 1 and 5 mm with a regular round shape (Karlsson et al., 2018).

Figure 10 – Example of virgin resin pellets

Plastic pellets have been entering the environment since the 1950s when plastics started being mass produced (Jambeck et al., 2015; Tunnell et al., 2020). The first scientific reports regarding pellets washing up on beaches were published in the 1970s (Gregory, 1977; Shiber, 1979). **In the EU, about 58 to 70.6 million tonnes of plastic pellets are produced every year** (Hann et al., 2018). In 2015, an estimated 16,888 to 167,431 tonnes of pellets are lost to the environment as a result of inadequate handling practices or accidental spillage during production, storage, and transportation, making plastic producers, handlers, and converters one of the largest sources of primary microplastic pollution today (ECOS, 2020). In addition, pellets can be lost by general handling alone or during storage, where the thin film holding the pellets can tear, causing a spillage on site (OSPAR, 2018).

When lost in the environment, virgin resin pellets start aging and undergo discolouration (Endo et al., 2005). Pellets are a significant source of plastic pollution as they are often accidentally lost during production, storage, and transportation (Karlsson et al., 2018).

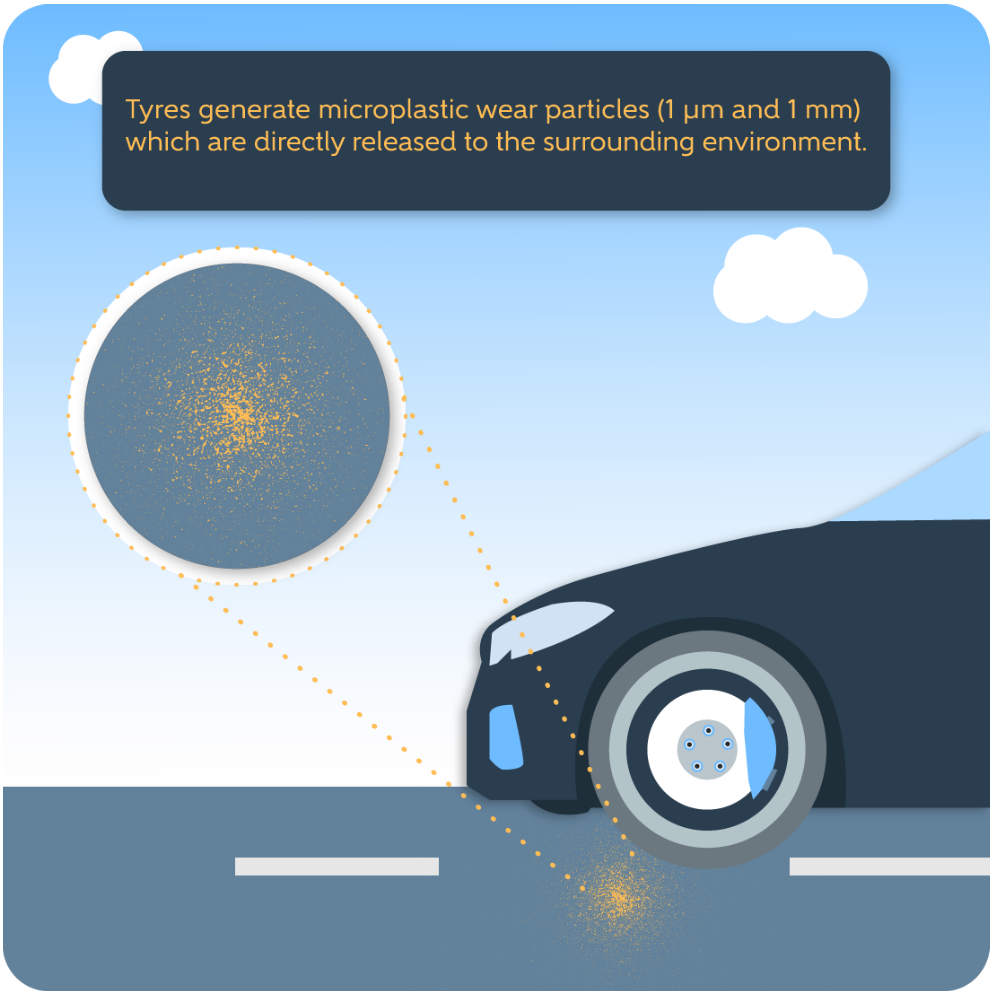
Pellets are regularly lost to the open environment at every stage of the supply chain from manufacturing to transportation (Tunnell et al., 2020). It was estimated that between 3 and 36 million plastic pellets are released annually to the Orust-Tjörn fjord system from the only polyethylene production site in Sweden (Karlsson et al. 2018), corresponding to approximately 5% of the European polyethylene demand (PlasticsEurope, 2014). Occasionally, accidents during transportation, on both roads and at sea, can lead to large scale pollution events (OSPAR, 2018). **The most striking accident involving pellets took place in Asia Hong Kong in 2012 where 6 containers loaded with 150 metric tons polypropylene pellets were lost at sea.** This event released hundreds of millions of pellets that covered the beaches of Hong Kong. A similar accident took place in 2012 in New Zealand with container ship MV Rena sinking with the 1351 containers it had on board (Seas at Risk, 2020). A storm event in 2017 in Durban Harbor, South Africa resulted in the accidental loss of two containers holding 49 tonnes of polyethylene pellets, which spread across a 2,000 km stretch of coastline (Insurance Marine News, 2017). At the time, it was estimated that only 23% of the pellets were recovered (Sky News, 2018). In another accident, more than 10 tonnes of plastic pellets were released into the German Bight when a storm damaged container opened at sea (KIMO, 2020).

Various accidents have taken place in Europe, last of which was the 400 m long container ship MSC Zoe which lost 345 containers in 2019, generating a huge pollution in the North Sea and the Wadden Sea. A massive bio-beads' pollution from the U.K. wastewater treatment plants was monitored since 2006 by local NGOs in the Channel which reached both the Netherlands, Belgium and the North French Coast (from Texel to Cherbourg).

Plastic pellets, as highlighted in figure 5, represents 0.3% of the total sources of microplastics. Nonetheless, there are many technical and technological solutions that can minimise their dispersal in the environment (Fidra, 2020), while ensuring normal production activity for the industry without substantial economic loss.

TRANSPORT

The invention of the wheel dates to 3,500 BC (Bellis, 2020), and although it has many applications, it is primarily used in transportation. While its basic function has remained unchanged over time, the composition of the tyres themselves have changed significantly. Today tyres are a combination of natural (19%) and synthetic rubber (24%) (National Geographic, 2019) with fillers, softeners, vulcanization agents and other additives mixed to improve the quality of the tyre (Baensch-Baltruschat et al., 2020). These additives make tyres more flexible, improving wet grip performance and increasing their longevity (Knight et al., 2020; Kole et al., 2017). While driving, the friction created between the road and the tyres generates microplastic wear particles that usually have a size ranging between 1 µm and 1 mm (Baensch-Baltruschat et al., 2020) and are directly released to the surrounding environment.



In 2018, an estimated 237 million passenger cars were recorded on European roads (Eurostat, 2021), and as a consequence, vehicles tyre wear particles as a result of breaking and accelerating are now considered to be one of the most dominant forms of microplastic pollution (Boucher and Friot, 2017; Knight et al., 2020; Kole et al., 2017; Verschoor et al., 2016).

In Europe, each year about 1.3 million tons of tyre wear are generated (Wagner et al., 2018), while globally it is estimated to be about 6 million tonnes (Knight et al., 2020). In Denmark and Norway, tyre wear particles contribute to 50% of the total microplastic emissions while in Germany, these particles contribute to 30% of the total microplastics recorded (Baensch-Baltruschat et al., 2020). Current models show an annual microplastic emissions per capita ranging from 0.23 to 1.9 kg per country, except for the United States of America where the emissions per capita was much higher at 4.7 kg (Kole et al., 2017). However, an increase in traffic density on the roads does not lead to an increase in microplastic emissions (Knight et al., 2020). Increased braking and acceleration by vehicles were however, found to be a more significant contributor to the high levels of tyre wear microplastics than an increase in traffic flow (Knight et al., 2020).

Emitted tyre particles are dispersed from road surfaces through rainfall and wind (Knight et al., 2020). In the Netherlands, it was estimated that approximately 45% of wear particles remain on the road surface, 40% are transported and deposited in the soil, 10% enter aquatic water bodies while an additional 5% were recorded as airborne (Verschoor et al., 2016). Tyre wear particles make up approximately 5 -10% of all microplastics entering the marine environment (Kole et al. 2017). This suggests that the contribution of tyres to microplastic pollution in the marine environment is not insignificant when compared to the quantities of fibres released from synthetic fabrics during washing highlighting the importance of tyres as a source of microplastics (Kole et al., 2017) or that researchers are not being able to find it in environmental samples.

Recycling of materials is leading to new applications such as using crumb rubber in asphalt (Wang et al., 2020), which has a huge demand for road construction. However**, there are inherent consequences of using tyre wear or shredded plastics to roads, as inevitably these will become sources of microplastic pollution, particularly when it rains.**

MARINE & MARITIME-BASED SECTORS GENERATING PLASTIC LITTER

SHIPPING

The expansion of the global economy is reflected in the international maritime trade which grew at an average pace of 3% annually between the 1970s and 2017 (WSC, 2020). In 2018, the total volume of cargo reached an all-time high of 11 billion tonnes, while in 2019, approximately 226 million containers, a value of $4 trillion, were transported via the international liner shipping industry alone (WSC, 2020). In early 2020, approximately 53,000 merchant ships were registered by the International Maritime Organization (IMO).

Shipping vessels designed for carrying cargo, passengers and/or recreational use all carry supplies for their intended periods at sea and inevitably generate solid waste which can include plastics. In addition, ships will carry items such as large ropes, cables, anchors, oil drums, packaging materials, plastic sheets, boxes etc. The accidental or intentional dumping at sea of waste and plastic materials due to bad handling or unfavourable weather conditions (FAO, 2020) has identified the shipping industry as a significant source of plastic litter in the marine environment.

Extreme weather conditions are just one cause resulting in the loss of cargo or containers to sea. Other causes for cargo loss include infrastructure failure, for example, extremely heavy cargo, improper loading of pallets, poor lashing, improper use of the cargo securing gear and incorrect or unbalanced stowage and inadequate weight distribution (SFE, 2019). In Durban, South Africa, due to a hurricane, containers containing plastic nurdles were damaged and released approximately 2 billion plastic resin pellets, which due to the currents were even carried over to the shore of Western Australia (FAO, 2020). And in 2015, as a consequence of a loss of cargo at sea, thousands of printer ink cartridges washed up along the coasts of the United Kingdom and in the Scottish Hebrides archipelago, Ireland, France, mainland Portugal and the Azores archipelago (BBC News, 2016).

The World Shipping Council (WSC) reported that between 2017 and 2019 that on average 779 containers were lost at sea annually, however this is significantly less than that reported for the previous 3-year average of 1,390 shipping containers (WSC 2020) or the average for the period 2008-2016 of 1,582 containers (KIMO, 2019). Unfortunately, the recovery rate for containers lost at sea is only 2.6% (SFE, 2019) and 2020 saw one of the worst container ship disasters with an estimated 1,816 containers lost or dislodged from its lashings in the Pacific by One Apus. Shipping companies have disclosed survey-based information figures of up to 10,000 containers lost annually at sea (Galafassi et al., 2019). The loss of these large containers at sea represents a large potential source of plastic pollution, but as data on the weight and nature of the lost goods cannot be accessed, it is difficult to quantify (Galafassi et al., 2019).

International treaties and laws, such as MARPOL (in particular, Annex V), work together against plastic pollution through imposing a complete ban on the disposal of all forms of plastics at sea, however enforcement remains difficult.

FISHERIES & AQUACULTURE

In 2017 the EU fleet numbered 83,323 vessels of which 65,567 were active (European Commission, 2020). Therefore, the fishing industry is considered one of the most important industries in Europe, directly employing over 150,000 fishers and generating in 2017 approximately €7.7 billion (European Commission, 2020). However, the expected reduction in wild fish stocks due to overfishing has seen the emergence of aquaculture products in the worldwide market.

In fact,aquaculture is now recognised as a rapidly expanding global industry (Kaiser et al., 2011), where production is expected to grow by >30% worldwide and surpass capture production by 2030 (FAO, 2016) as the need to meet the global consumer demand for animal protein, namely fish and shellfish, grows. The 28 European member states contribute about 3% to the global fish production and each person consumes on average 23 kg per year, making the European continent the third largest consumer of fishing and aquaculture products (European Commission, 2019).

About 600 aquatic species are raised in captivity in 202 countries to meet the increasing global demand (Moore, 2013; FAO, 2020). As of 2016, aquaculture produced a total of 110.2 million tonnes of seafood (i.e. fish, shellfish and aquatic plants) meant for human consumption, having an estimated first sale value of 243.5 billion USD (FAO, 2020). In 2016, the Global fish production (i.e. fish caught in the wild and aquaculture) was estimated at 171 million tonnes and aquaculture represented 47% of the total (Huntington, 2019).

75%

Farœ Islands and the Norwegian continental shelf, ALDFG was found to represent more than 75% of the marine debris

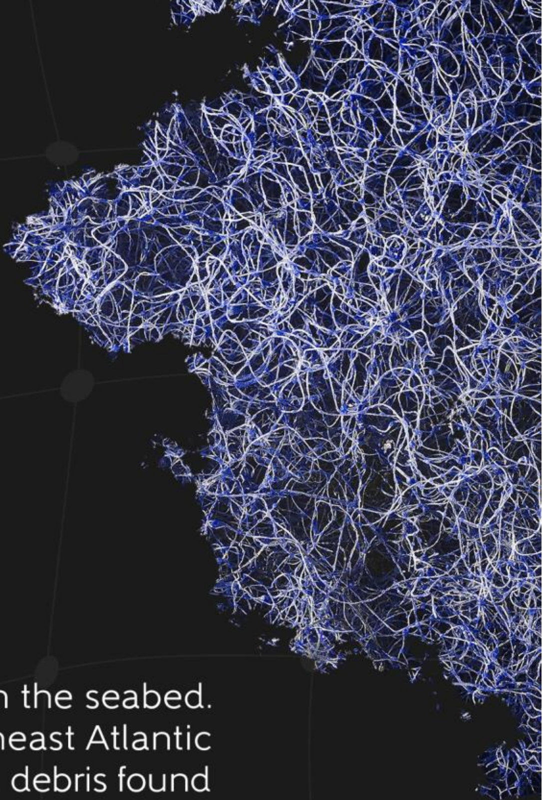
FISHERIES & AQUACULTURE

Traditionally, fishing gear and equipment used for aquaculture consisted of metal and natural materials, such as wool, silk, wood, or plant fibres, which had the ability to degrade over time in the environment. However, metal tended to undergo oxidation, corrosion, or degradation in the marine environment due to salinity (Moore, 2013). The advent of plastics transformed the fishing industry when fishers shifted to synthetic or semi-synthetic materials to make nets and other gear, which offered greater strength and durability than natural rope. Synthetic fibres were also cheaper, lighter, and easier to handle than their natural counterparts (Lusher et al. 2017). As a result, plastic is extensively used in fishing from nets, trawls, floats and lines to boat construction and maintenance and in the aquaculture sector is used for cages, nets, ropes and the harvest bins (FAO, 2017). It is ubiquitous within the industry often utilised to transport catches within styrofoam boxes or hard plastic crates (FAO, 2017).

Mariculture or aquaculture farming in the ocean employ suspended farms or directly place their farms on the seabed in the intertidal or shallow subtidal zones (UNEP 2016). These floating fish farms primarily use plastics (expanded polystyrene (EPS)) for their buoyancy and are held in place with polyamide lines and ropes to ensure stability (Lusher et al. 2017).

Abandoned, Lost or discarded fishing gear (ALDFG) in both the fisheries and aquaculture sectors often comprise nets, ropes, floats, fishing line etc. and other ancillary items such as fish boxes, strapping bands. There are many reasons for fishing gear losses, through accidents as a result of bad weather conditions or deliberately discarded overboard for practical, logistical, economic or illegal reasons (Lusher et al. 2017; FAO, 2016; UNEP 2016). Aquaculture farms may be purposely abandoned if the costs of decommissioning or collection and transport are deemed too high. Similar to the fishing sector extreme weather conditions (e.g. storms, high winds, large waves or freezing temperatures) are often considered to be one of the main reasons contributing to the loss of debris from aquaculture farms (Huntington, 2019) and a source of microplastics to the surrounding environment.

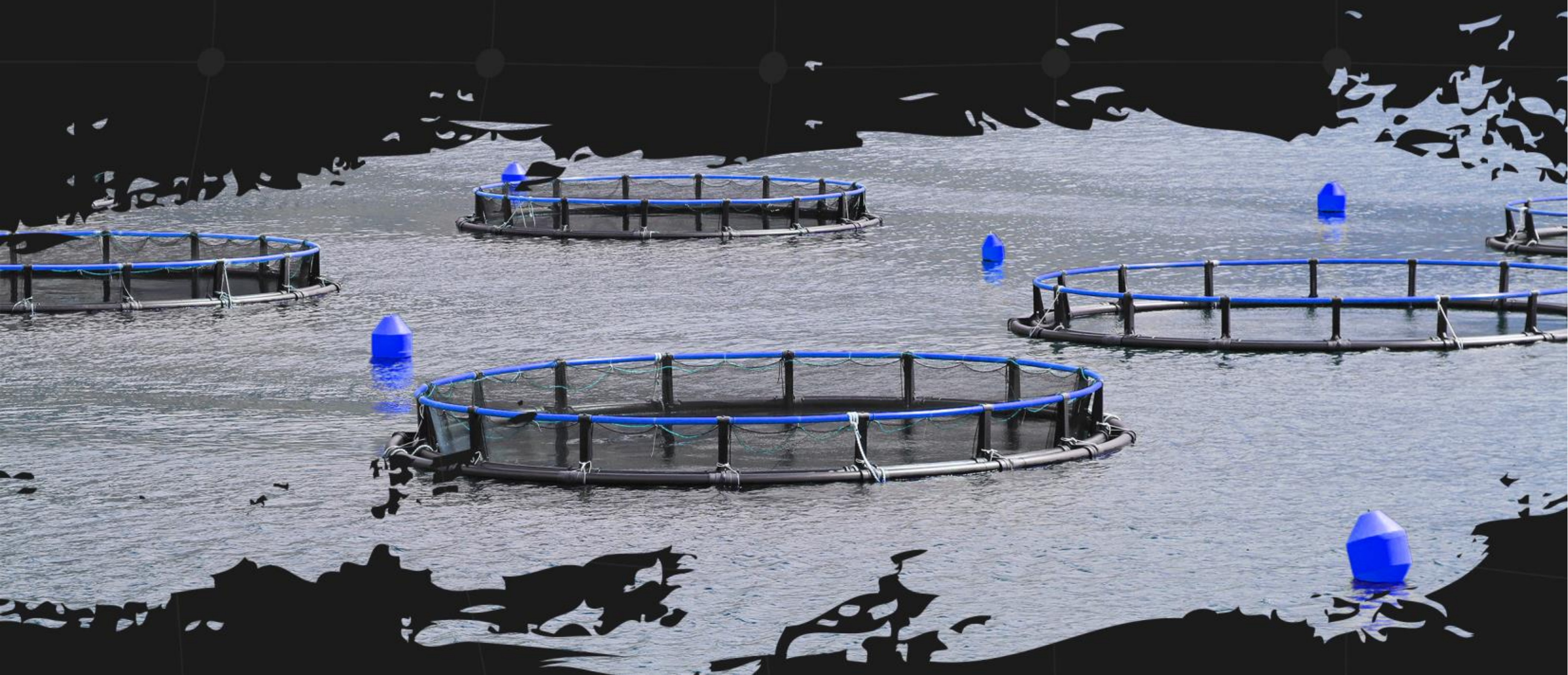
FISHERIES & AQUACULTURE



Fibres and fragments are released into the marine environment due to normal wear and tear of fishing gear and aquaculture equipment (UNEP 2016) and the breakdown of ALDFG represents a large source of microplastic pollution in the aquatic environment. Therefore, due to the extensive use of plastic in both the fishing and aquaculture sectors they have been identified as sources of microplastic pollution.

Derelict fishing gears have been found to accumulate on the seabed. A study conducted in the Mediterranean Sea and Northeast Atlantic estimated that ALDFG accounts for up to 34% of the overall debris found (Pham et al. 2014). In some locations such as the Farœ Islands and the Norwegian continental shelf, ALDFG was found to represent more than 75% of the marine debris (Lusher et al. 2017). It is estimated that 5.7% of all fishing nets, 8.6% of all traps and 29% of all lines are lost around the world every year (Richardson et al. 2019).

While it is difficult to estimate the contribution of aquaculture to plastic pollution, as monitoring programs are often non-existent at either the local or the national level (Huntington, 2019), it is estimated within the European Economic Area that 95,000 - 655,000 tonnes of litter generated from aquaculture facilities are already in the ocean (FAO, 2020). In 2011, a Norwegian aquaculture farm generated 12,300 tonnes of plastic waste of which approximately 21% was recycled, and the rest was discarded as waste (Huntington, 2019) extrapolating from this, for every ton of aquaculture product output, 11 kg of plastic waste is generated in Norway (Sherrington et al., 2016).



PATHWAYS OF POLLUTION

A pathway is a route or a trajectory from a source until a destination. It has become apparent that microplastics are not limited to one ecosystem or habitat. They are ubiquitous in the environment, independently of their original source. Microplastics have been found in some of the most remote places on earth, such as the polar sea ice (Peeken et al., 2018), or the rivers and lakes in the Tibetan plateau (Zhang et al., 2016). These findings raise questions of how microplastics can travel long distances to pristine environments.

ATMOSPHERIC DEPOSITION

> The lightweight nature of microplastics allows them to be transported to remote areas, including the worlds most prestine locations

Microplastics are associated with atmospheric transport and subsequent deposition through wind, rain, ice, and snow (Zhang et al., 2020). Large urban areas are expected to have higher microplastic fallouts (Dris et al., 2016) as many sources of microplastics, from the wear and tear of tyres or resulting from the release of synthetic fibres from clothing are likely to exist in higher concentrations. Other sources include painting and coatings in buildings. However, the lightweight nature of microplastics allows them to be transported through the atmosphere to remote locations, such as the Pyrenees mountains, where microplastics, predominantly in the form of fragments (68%), have been found 95 km from the closest town (Allen et al., 2019). **Microplastics have been recorded falling from the atmosphere at a rate of 325 particles per square meter per day in mountains** (Allen et al., 2019) which is comparable to estimates for urban areas (Hale et al., 2020) ranging from 275 particles in Hamburg, Germany to 718 microplastic particles in London, England (Klein and Fischer, 2019; Wright et al., 2020).

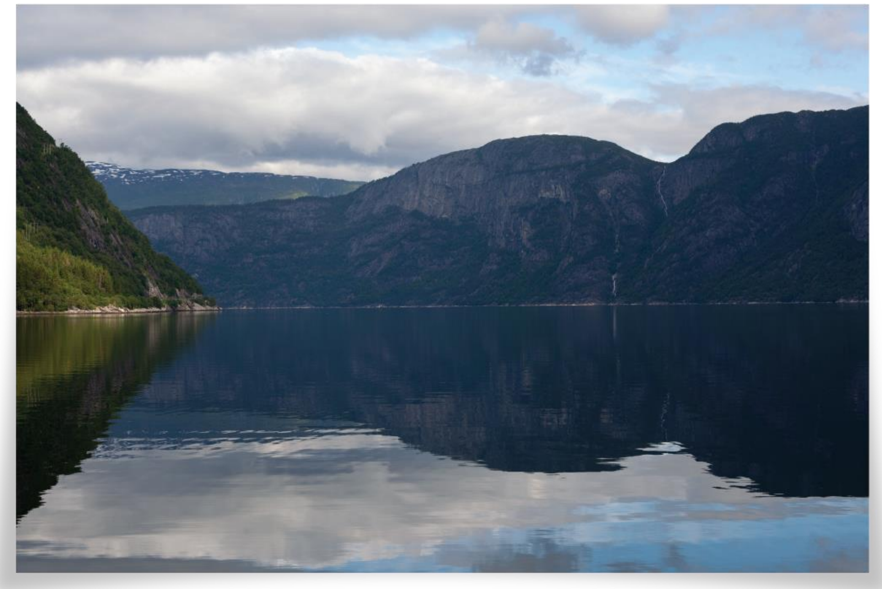
These results highlight the importance of considering the atmosphere as a vector for the long-distance transport of microplastics (Dris et al., 2016). The dispersal and fallout rates are highly dependent on the prevailing weather conditions (Allen et al., 2019; Bianco and Passananti, 2020). Heavy rains, storms, strong winds and snow all increase the rate of deposition of microplastics from the atmosphere to the soil or aquatic environments beneath.

Microplastics were identified in 95% of all snow samples collected from the Swiss Alps, Bremen (Germany), in the Arctic (Bergmann et al., 2019), and more recently in Mount Everest (Napper et al., 2020). The Arctic, once considered a pristine environment, is now facing is now facing diverse environmental threats from climate change (Cassotta et al. 2019) to microplastics (Kanhai et al., 2019; Bergmann et al., 2019; Tekman et al., 2020). Despite this, Arctic snow has recorded concentrations ranging from 0 - 14,400 MPs per litre which is significantly lower than concentrations found in European snows (190 -154,000 MPs per litre) (Bergmann et al., 2019).

Exploration of the transport of terrestrial microplastics to the ocean through the atmosphere in the west Pacific Ocean found **that the abundance of microplastics recorded doubled during the day** (0.45 ± 0.46 MP m^{-3}) **compared with values at night** (0.22 ± 0.19 MP m^{-3}) and that the abundance of **microplastics decreased from coastal zones** (0.13 ± MP m^{-3}) to the **pelagic environment** (0.01 ± 0.01 MP m^{-3}) (Liu et al. 2019). While numbers recorded may appear low, given the vastness of the ocean, is it only natural that the atmospheric transport and deposition represents a significant pathway for microplastics to enter the marine environments (Hale et al., 2020).

RIVERS

Rivers and lakes represent a focal point for the settlement of human civilizations, providing important sources of freshwater, food, and recreational activities to local communities (Anderson et al. 2019). It is estimated that approximately 2.7 billion people live near a river (Best, 2019), with socio-economic benefits arising from both domestic and industrial sectors, namely agriculture, fishing, aquaculture, trade routes, well-being, and hydropower electrical generation (Anderson et al., 2019; Best, 2019, Emmerik and Schwarz, 2020). As human communities thrive and populations grow, pressure on natural systems



intensifies (Best, 2019), due to the increased demand for water supply and energy consumption. Human activities can cause significant changes to the landscape, such as large-scale damming or mining of sediments and minerals, threatening the natural integrity and balance of ecosystems (Best, 2019).

The consequences of human activities, such as soil and water pollution and/or the introduction of non-native species, have the potential to trigger long term irreversible changes to freshwater ecosystems and their resources (Best, 2019). Historically, rivers have always been used for the disposal of solid and liquid waste products, and in addition, since the 1960s, have been recognised as a pathway for land-based plastics to the marine environment (Liro et al., 2020).

Sources of plastic pollution in and around freshwater systems are directly related to a wide range of human activities. Studies have reported high correlations between plastic abundance and population density, urbanization, and solid and liquid waste management infrastructures (Best et al., 2019).

Plastic waste enters rivers through natural processes influenced by wind or rain-induced surface runoff, or via direct dumping or disposal, which can be deliberate or unintentionally through wastewater treatment plants (WWTPs). Plastic transport in an area is influenced by several factors including the topography, geography, frequency and strength of rain and sandstorms and extreme climate events (Emmerik and Schwarz, 2020). **Therefore, temporal changes and extreme climate events may play an important role in the abundance of floating plastics present, for example a 14-fold increase in microplastics concentrations (from 1197 to 22,785 MPs) was reported post-flood in Mersin Bay, in Turkey.** Only regular monitoring will detect these elevated levels of plastic pollution in rivers and their subsequent flow downstream to the marine environment (ter Halle et al., 2016; Gündoğdu et al., 2018; van Calcar and van Emmerik, 2019).

Plastics can enter rivers via illegal dumping, particularly in countries where regulations concerning dumping, disposing, and littering are non-existent, but also in countries where such regulations exist, but are not enforced or monitored (Rech et al., 2015). Rivers and riverbanks are not regularly monitored (Rech et al., 2015; Kiessling, et al., 2019). Along riverbanks in Chile, the frequency of littering for several identified illegal dumping sites (with littered areas ranging from 1 to 10 m^2) were dependent on the surrounding land use and vehicle accessibility to these sites (Rech et al., 2015).

Several rivers examined in Germany (Rhine, Weber, Elbe) found that plastics (mainly cigarettes, food packaging and used personal hygiene items) accounted for **30.5% of all litter deposited in and alongside riverbanks** which were intentionally or accidentally left behind by people visiting rivers for recreation (Kiessling et al., 2019).

Recent models estimate that between 1.15 – 2.41 (Lebreton et al., 2017) **and 0.41 – 4.0** (Schmidt et al., 2017) **million tonnes of plastic reach the ocean from rivers annually**, with the majority of plastic (74%) entering the ocean between May and October. It has also been estimated that a large majority (67%) of the global input of plastics originates from 20 major rivers, most of which are in Asia (Lebreton et al., 2017; Best et al., 2019). European rivers' annual plastic abundance ranges from 0.71 (Rhône river) to 1,533 (Danube river) tonnes per year (Emmerik and Schwarz, 2020). In southeast Asia estimates range from 1,300 tonnes per year, in the Saigon river, Vietnam (Emmerik and Schwarz, 2020) to 333,000 tonnes per year in the Yangtze river in China (Lebreton et al., 2017) with the Yangtze river considered to be one of the most polluted rivers on the planet. These estimates are likely to be conservative as data from the rivers of Central America and Africa is limited and only a few rivers in Southeast Asia have been monitored so far. Additionally, such estimates focus on either floating plastics or plastics on riverbanks, and often neglect concentrations in the water column and riverbeds (Emmerik and Schwarz, 2020).

> Recent models estimate that between 1.15 – 2.41 and 0.41 – 4.0 million tonnes of plastic reach the ocean from rivers annually

While all evidence suggests that rivers are thought to be a major contributor to oceanic plastic, recent estimates from models highlight that a **large fraction of plastics (~99%) will not reach the ocean, as they get entrapped or entangled along the way which would suggest that rivers are also a significant sink for microplastics**. However, it is accepted that models are only as good as the quality of data entered and plastic pollution in rivers is at its infancy in comparison to the marine environment. Additional empirical good (quality) data will help to build better performing models to reflect the current situation more accurately.

GYRES

Gyres are created due to the combination of equatorial currents, western and eastern boundary currents, prevailing westerly winds, and the Coriolis effect. Combined they create a circular flow within a basin that is called a gyre. Gyres are similar to large conveyor belts, playing a crucial role in nutrient transport and temperature and salinity control across the global ocean (National Geographic, 2021). There are 11 large gyres around the world of which 5 are classified as subtropical (Figure 11; Eriksen et al., 2016).

Large quantities of plastic were found to accumulate in these convergence zones (Eriksen et al., 2016; Lebreton et al., 2012; Moore et al., 2001; Cózar et al., 2014, NOAA, 2021). The North Pacific Central Gyre, commonly known as the "Great Pacific Garbage Patch", is where waters within the convergent zone tend to sink a few hundred meters deep, while positively buoyant plastic particles tend to float to the surface, thus creating a hotspot for microplastic pollution (van Sebille, 2015).

Concentrations of plastics are known to increase closer to the convergence zones of gyres (Cózar et al., 2014; Eriksen et al., 2014; Law et al., 2010, Eriksen et al., 2013; Lebreton et al., 2012) and the plastic loads across the Northern and Southern hemisphere gyres are now comparable, unlike the previously available models had indicated. In early stages it was thought that accumulation zones within the Northern hemisphere i.e., the North Atlantic and North Pacific had higher concentrations of plastic (Lebreton et al., 2012).

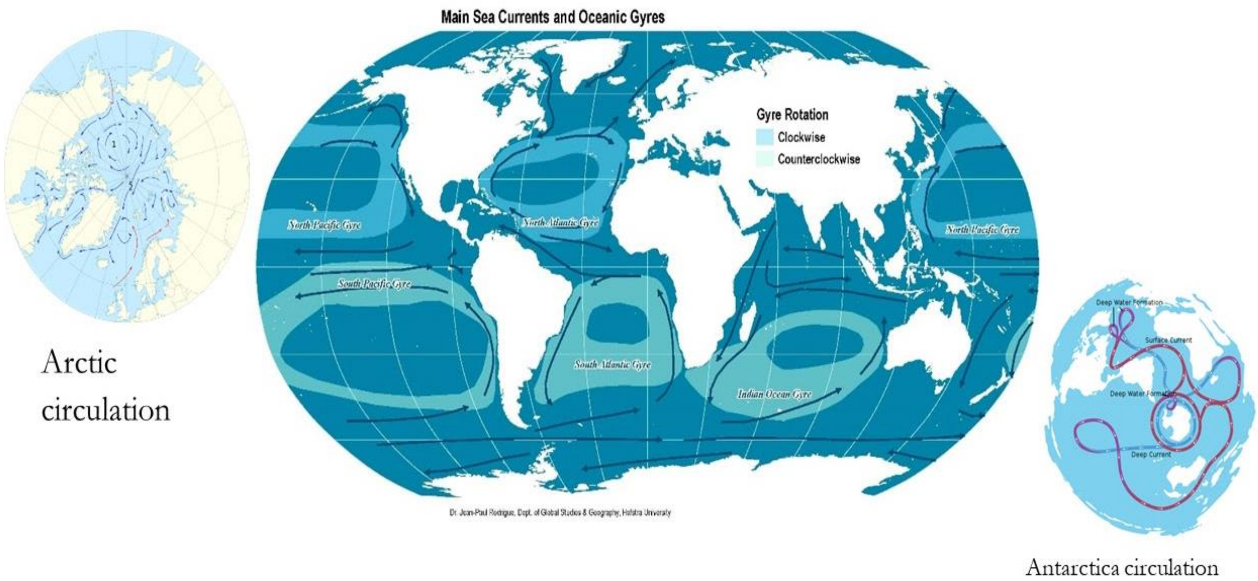


Figure 11 – Main sea currents and oceanic gyres
(Source: Frias and Nash, 2020)

Movement of plastics across the gyres and hemispheres is more easily transported due to their buoyant nature (Eriksen et al., 2014). Globally, the plastic concentration in the North Pacific Gyre accounts for 33-35% of the total oceanic plastic, due to the large population density and its location between East Asia and North America (Cózar et al., 2014). Global estimates revealed that about 5.25 trillion plastic particles were floating across the 5 subtropical gyres, which had a total weight of 268,940 tons (Eriksen et al., 2014). Recent estimates on the North Pacific Gyre are now estimated to range between 1.1 and 3.6 trillion plastic pieces weighing 79,000 tonnes (Lebreton et al., 2018). Planktivorous and mesopelagic fish living or foraging in the vicinity of gyres have higher incidences of plastic ingestion, 35% and 9.2% incidence respectively, due to the high concentrations of floating plastic (Thiel et al., 2018; Boerger et al., 2010; Davison et al., 2011). Results from the mesopelagic fish were scaled to the area of the gyre estimating that between 3.5 to 7.1 million tons of fish contain 12,000 to 24,000 tons of plastic (Davidson et al., 2011). An assessment of plastic ingestion in commercial fish in the South Pacific (Markic et al., 2018) revealed that 33 out of 34 species had ingested plastic. Of these ~ 25% of the individuals had ingested microplastics, however, closer to the centre of the Gyre 50% of the individuals recorded had microplastics present.

In an assessment of the North Atlantic subtropical gyre, collected off the western North Atlantic Ocean and the Caribbean Sea, between 1986 and 2008, reveal that of the 6,100 samples processed, 62% of samples contained microplastic particles (Law et al., 2010).

Plastic litter items in the Azores archipelago shows accumulation in Porto Pim beach in Faial island, with 28,261 litter items collected of which plastic accounted for 93% of the total (Pieper et al, 2015). A full assessment of the Azores archipelago revealed a maximum plastic density of more than 9,300 items m^{-2} (Pham et al., 2020). This assessment identified that for Porto Pim beach, an average plastic loading of 500 items m^{-2} per tidal event is prevalent. In fact, in January 2018, that same beach registered a maximum of 4,782 items m^{-2} (Pham et al., 2020). This is particularly relevant because there is no plastic production in the archipelago.

Tsunamis

Catastrophic natural events such as hurricanes, cyclones and tsunamis cause a multitude of impacts: loss of human and animal lives, damage and destruction of both properties and the natural environment. Extreme events such as earthquakes can trigger subsequent events such as tsunamis. For example an earthquake (Richter scale 9) that affected the northeast coast of Japan and triggered a massive tsunami whose waves reached higher than 40 meters in height

An aspect that is often overlooked by these extreme events is the **generation and transport of large quantities of natural and anthropogenic debris including plastics**. In addition, when an extreme event strikes close to the coastline, the debris generated enters the marine environment. The amount of plastic that enters the ocean in a single extreme event is **comparable to the amount of plastic litter that enters the marine environment globally every year.**

The tsunami that hit the densely populated area of Tōhoku generated **5 to 24.9 million tons of debris that washed ashore** and included massive amounts of plastic, metal and wood litter, while also washing away vehicles, boats and shipping containers (BAGULAYAN et al., 2012; Carlton et al., 2017; Therriault et al., 2018). Although the majority of the **debris settled close to the Japanese coast**, there are records of items that were carried away by currents and washed up along **the American coast, from North to South America.**

References: Bagulayan et al., 2012; NOAA, 2013; Lebreton and Borrero, 2013; Jambeck et al., 2015; Therriault et al., 2018; Murray et al., 2018

Invasive species

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Outside of global trade and transportation, both considered to be pathways for invasive species into new habitats, floating plastic debris represent and important vector of transfer across continents. Alongside with wood, floating plastic debris have the ability to disperse marine organisms throughout the sea, aided by winds and oceanic currents. These large pieces of plastic act as efficient life rafts, and living habitats to fouled organisms who attach to plastic and are transported from their native home to new environments. There,they will compete for the same resources with native species, posing a potential ecological risk. Species that outcompete and adversely affect a local area are termed 'invasive species'

Debris washed ashore on the coasts of Hawaii and North America from the 2011 tsunami, originating from Japan, have recovered **289 living Japanese species both vertebrates and invertebrates belonging to 16 phyla** (Carlton et al., 2017). The arrival of such large numbers of foreign species is of great concern both ecologically and economically. Biological invasions are considered to be the **second biggest threat to biodiversity after habitat loss and every year countries spend billions of dollars to tackle the problem of invasive species** (Therriault et al., 2018). In addition, **invasive hitchhikers such as Vibrio spp.** are **potential pathogens for infectious diseases**.

References: Murray et al., 2015; Kristein et al., 2016; Carlton et al., 2017; Geburzi and McCarthy, 2018; Therriault et al., 2018

WASTEWATER TREATMENT PLANTS

As the world's human population continues to grow and concentrates in urban centres, the global demand for water is predicted to increase significantly over the coming decades. **Of the 3,928 km of freshwater that is sequestered annually worldwide, 44% is used directly by the agricultural sector**. Freshwater can also be used for industrial and municipal applications. After fulfilling its use, all these waters can enter the environment as wastewater effluent (WWAP, 2017).

The fate of wastewater varies greatly depending on the local context and the presence or absence of technology to treat the wastewater. **In high income countries, about 70% of the wastewater is treated sufficiently enough to be recycled back into the receiving environment.** This estimate, however, significantly drops in middle- and low-income countries, where only a small percentage of wastewater undergoes treatment before release, i.e., **28% and 8% respectively** (WWAP, 2017).

In most countries, wastewater is collected from different anthropogenic sources such as domestic, industrial, commercial, and sometimes storm water runoff. This water is then routed to centralized treatment facilities, also known as Wastewater Treatment Plants

(WWTPs) to be purified before it is released into the environment or redirected to agricultural fields for irrigation (Hale et al., 2020). The treatment of wastewater involves the use of both filters and chemical treatments to remove biological and chemical waste from the water. WWTPs were never originally designed to remove microplastics, therefore the wastewater effluent usually contains reduced levels of microplastics (Sun et al., 2019). As the global demand for water is predicted to increase significantly over the coming decades, it is also expected that the concentrations of microplastics released to the receiving environment will also increase (Talvitie et al., 2017).

While WWTPs were not originally designed to handle microplastics as a contaminant (Iyare et al., 2020), they are **surprisingly effective in removing significant proportions of microplastics, i.e., about 84 to 99%, particularly when plants have secondary or tertiary treatment** (Lusher et al., 2019; Rolsky et al., 2020). The efficiency of microplastic retention within the treatment plant depends on the treatment units that are employed, the way the processes are executed and most importantly, the size and density of the microplastics in the influent (Lusher et al., 2019; Sun et al., 2019). Most treatment schemes start off by removing large debris items from the influent using a mesh having a size of 6 mm or larger. This step is effective in removing 65% of microplastics (Habib et al., 2020). The next treatment removes suspended and dissolved organic material, with the help of microorganisms within large aeration tanks. This process enables the solids and microplastics with heavier densities to settle in the form of sewage sludge, and the fats that float to be collected in grease tanks. Both the fat and the sludge are then separated from the post-processing effluent, and follow different routes (Habib et al., 2020). Subsequently, the effluent wastewater goes through the advanced tertiary treatment, where processes such as filtration through sand and/or activated carbon are applied to disinfect the water before it is discharged into the nearest waterbody (Habib et al., 2020). However, it is important to note that not all WWTPs include this tertiary treatment. Altogether, these treatments have the potential to remove almost up to 97% of microplastics from the wastewater.

WWTPs are estimated to release 65 million microplastics into the environment daily despite the high removal rates of MPs (Murphy et al., 2016). This coupled with the fact that a significant number of MPs are smaller and/or lighter than the grading or percolating systems (Horton et al. 2017) which makes WWTPs a significant pathway for microplastics to be released into the aquatic environment. In fact, Gouveia et al., 2020, noted an excessive release of fragments to the environment, when compared to the levels of microplastics usually found in the affluent of WWTPs in Portugal.

In most developed regions, such as in Europe and North America, about 40% of sewage sludge collected within the wastewater treatment facilities, are processed, and used as fertilizer for agricultural fields (Nizzetto et al., 2016; Mahon et al., 2016; Lusher et al., 2019). Establishment of EU legislation such as the Landfill Directive (1999/31/EEC) and in the Renewable Energy Directive (2009/28/EC) have advocated for the reuse of sewage sludge either for energy production or as manure for agriculture fields (Mahon et al., 2016). This is considered to be an economically advantageous technique, as the sludge is rich in nutrients that benefit agriculture fields. Nonetheless, the sewage sludge can be loaded with high concentrations of microplastics ranging between 63,000 - 430,000 tons in Europe and 44,000 – 300,000 tons in North America that are then added to farmlands every year (Nizzetto et al., 2016). This high input of microplastics to a terrestrial ecosystem can potentially have future adverse effects to agriculture production, as it is estimated that microplastics can remain in agricultural fields for up to 15 years after the sludge application (Zubris et al., 2005). Additionally, once the sludge is applied to agricultural fields, environmental processes such as rain have the potential to transport surface microplastics to a wider area, hence potentially contaminating new habitats (Lusher et al., 2019), as it is the case of groundwater (GSA, 2020).

Sewage sludge is loaded with high concentrations of microplastics estimated between 63,000 - 430,000 tons every year

SOLID WASTE MANAGEMENT

Municipal or solid waste covers household waste and all waste similar in nature and composition to household waste. Plastic packaging and single-use plastics are often labelled as "waste" immediately after use. The main difference between litter and waste, is that waste generates value. Every person on the planet generates on average 0.74 kg of solid waste per day resulting in approximately 2 - 6.3 billion metric tonnes of plastic waste generated worldwide (Geyer et al., 2017; Brooks et al., 2018). Waste generation of **plastic packaging** in EU28 is on average 30 kg per capita (Figure 12), with Ireland and Estonia the two countries generating more waste per capita (Figure 13).

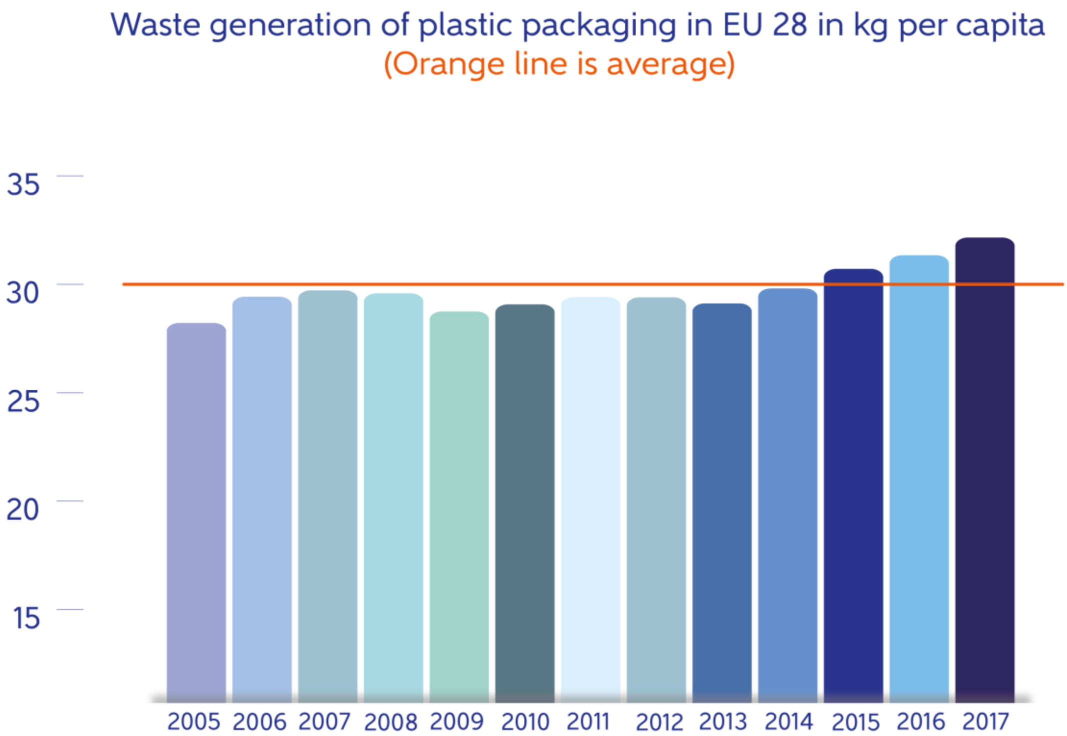

Figure 12 – Generation of plastic packaging waste per capita in the EU (Source: Eurostat 2005 - 2017)

As a result, even today, waste management systems struggle to deal with the tremendous influx of variable plastic materials and therefore of this, approximately 33% is not managed in an environmentally safe manner (Kaza et al., 2018).

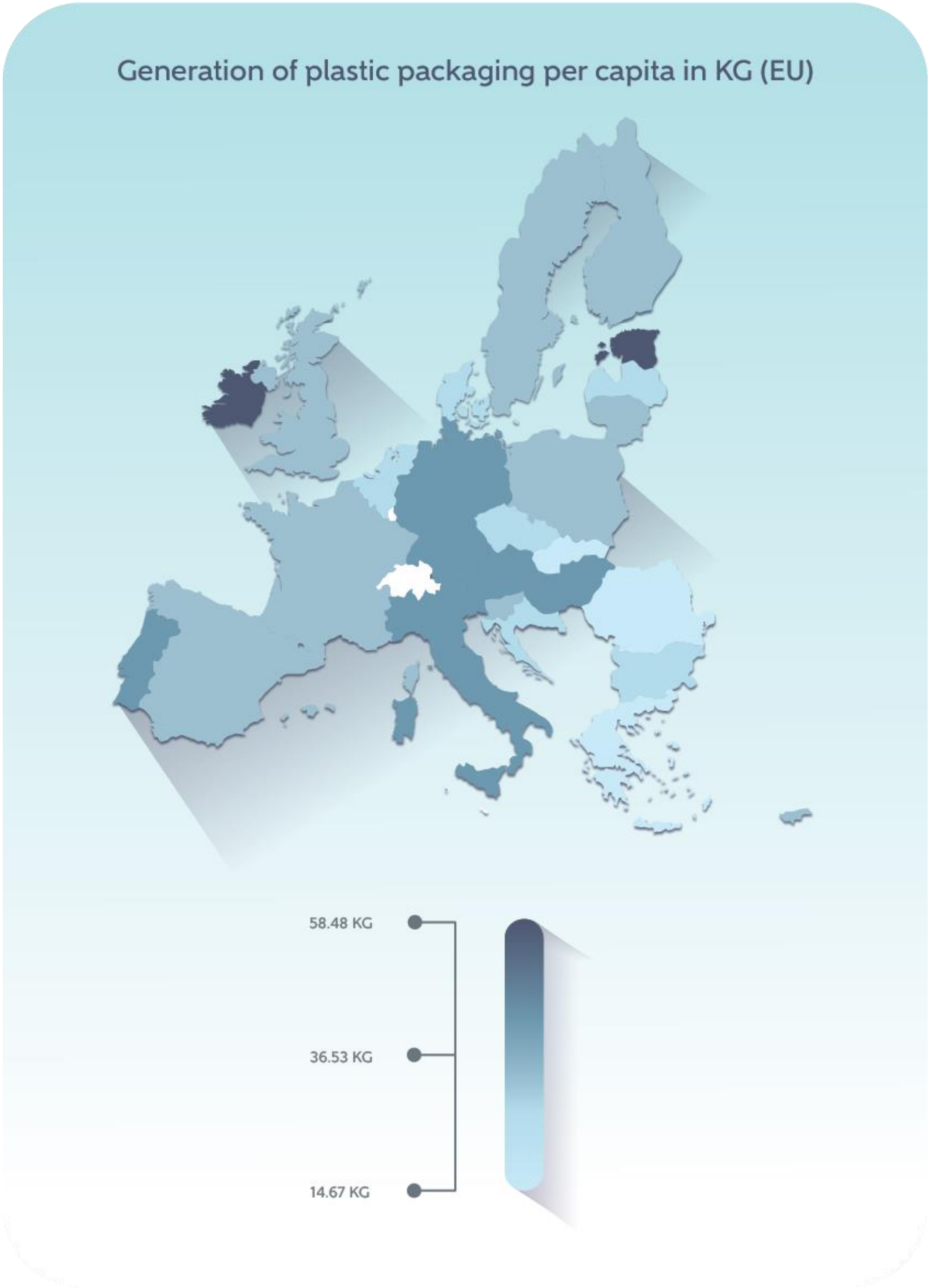

Figure 13 – Generation of plastic packaging waste per capita in the EU in 2017 (Source: Eurostat 2017).

While the term solid waste is used to describe a multitude of items from a wide range of materials what is noticeable is the rapid change in the composition of waste from natural materials to more complex synthetic ones. While the production and use of plastic has expanded quickly, little thought was given to the impact this would have on the solid waste management systems. Plastics now make up a significant proportion of municipal solid waste, with 242 million tonnes of plastic waste generated in 2016, making up 12% of all municipal solid waste. More disposable income means more purchasing power, which roughly translates into more packaging, imports, electric and electronic waste, toys, and appliances (Hoornweg et al., 2013). With income levels often positively correlated to waste generation which is projected to grow to 3.40 billion tonnes by 2050 (Kaza et al., 2018) as societies become wealthier.

> Global waste is expected to grow to 3.4 billion tonnes by 2050. It is estimated that 1.5 to 4% of global plastic ends up in the ocean

Waste management is expensive, and when inadequately managed, it can have a significant negative impact on the environment and human health (Hoornweg et al., 2013). Waste management is the single greatest cost for most local governments, accounting for 4%, 10% and 20% of the municipal budgets in high-, middle- and low-income countries respectively (Bishop et al., 2020; Kaza et al., 2018). Managed plastic waste is usually disposed of by recycling, by energy recovery (incineration) or managed in controlled landfills, whereas mismanaged waste is discarded directly into the environment by littering or mishandled open dumps (Bishop et al., 2020).

Globally, most waste is disposed of in open or sanitary landfills, with varying proportions based on the income level of the country. For instance, in low-income countries 93% of waste dumped in open landfills, while it is estimated that this is only 2% in high income countries (Kaza et al., 2018). Waste dumped in open and uncontrolled landfills represent a significant source of mismanaged waste which can find their way into aquatic and marine environments via runoff or wind (Lebreton and Andrady, 2019). It is estimated globally that 11 million tonnes of the global plastic produced ends up in the ocean (Jambeck et al., 2015; Reddy and Lau, 2020) with 150,000 to 500,000 tonnes of plastic waste entering the oceans annually in Europe. This is equivalent to the waste carried by 66,000 waste collection trucks dumped directly into the oceans, more than 180 per day (Sherrington et al., 2016).

150,000 to 500,000 tonnes of plastic waste entering the oceans annually in europe equal to waste carried by 66,000 waste collection trucks

While some countries produce more plastic waste than others, the amount of plastic waste reaching the marine environment largely depends on the amount of mismanaged waste generated by the country. **The United States produces the highest amount of plastic waste per capita 130.09 kg/year**. Recently, concern has been raised over the plastic waste generated in Asian countries like China and India (Law et al., 2020). Even though these countries have a relatively low per capita plastic use of between 19.88 and 15.67 kg/year, their high population densities can yield large amounts of plastic waste (Law et al., 2020; Lebreton and Andrady, 2019). Compared to high income countries, these developing countries lack the infrastructure, technical capacity, and finance to sustainably manage the large amounts of solid waste that are being generated.

The circular economy model sees recycling as integral to the execution of this model and that includes plastic products. However, plastics are often quite complex to be recycled, as they contain different kinds of additives or fillers blended with the polymer, depending on the use and need of the product while on the market. This means that several recycling techniques are required to recycle the different plastic products available in the market. Additionally, most plastics have a limit on the number of times they can be recycled, as they end up losing their material properties (Brooks et al., 2018; Geyer et al., 2017; Jambeck et al., 2015). **Consequently, most of the plastic waste ends up in landfills (80%) or escapes into the environment and only around 9% is recycled** (Brooks et al., 2018).

In order to adapt progressive environment policies such as a circular economy approaches and manage the increasing amount of plastic waste that is constantly being generated, developed nations worldwide such as in Europe and North America diverted their plastic waste, valued at $71 billion USD, to developing countries most notably located in South-East Asia to be recycled as it is economically advantageous (Bishop et al., 2020; Brooks et al., 2018). Same is also true for Europe (Figure 14). Within Europe, Germany is the biggest exporter of waste to other EU member states (figure 15). Ever since the 1990s up until recently i.e., 2018, China spearheaded most of this operation. Collectively, China and Hong Kong have imported 72.4% or 7.35 million metric Tonnes of all exported plastic waste globally (Brooks et al., 2018). Studies have found that when plastics are exported to be recycled, there is a real possibility for leakage into the environment and represent a potential pathway for ocean debris that has so far been overlooked (Bishop et al., 2020). Of all the polyethylene exported by Europe for recycling, it is estimated that a large portion (31%), is not actually recycled. In fact, 24% of this waste is rejected and has the potential to be an additional source of plastic entering the ocean, accounting for 0.3-3.8% of the total plastic debris entering the ocean. Therefore, it is important to have a critical thinking of reports that mention that 90% of plastics polluting our oceans come from just 10 rivers, and that 80% of those are located in Asia (Schmidt et al., 2017), when the exporting of waste is considered.

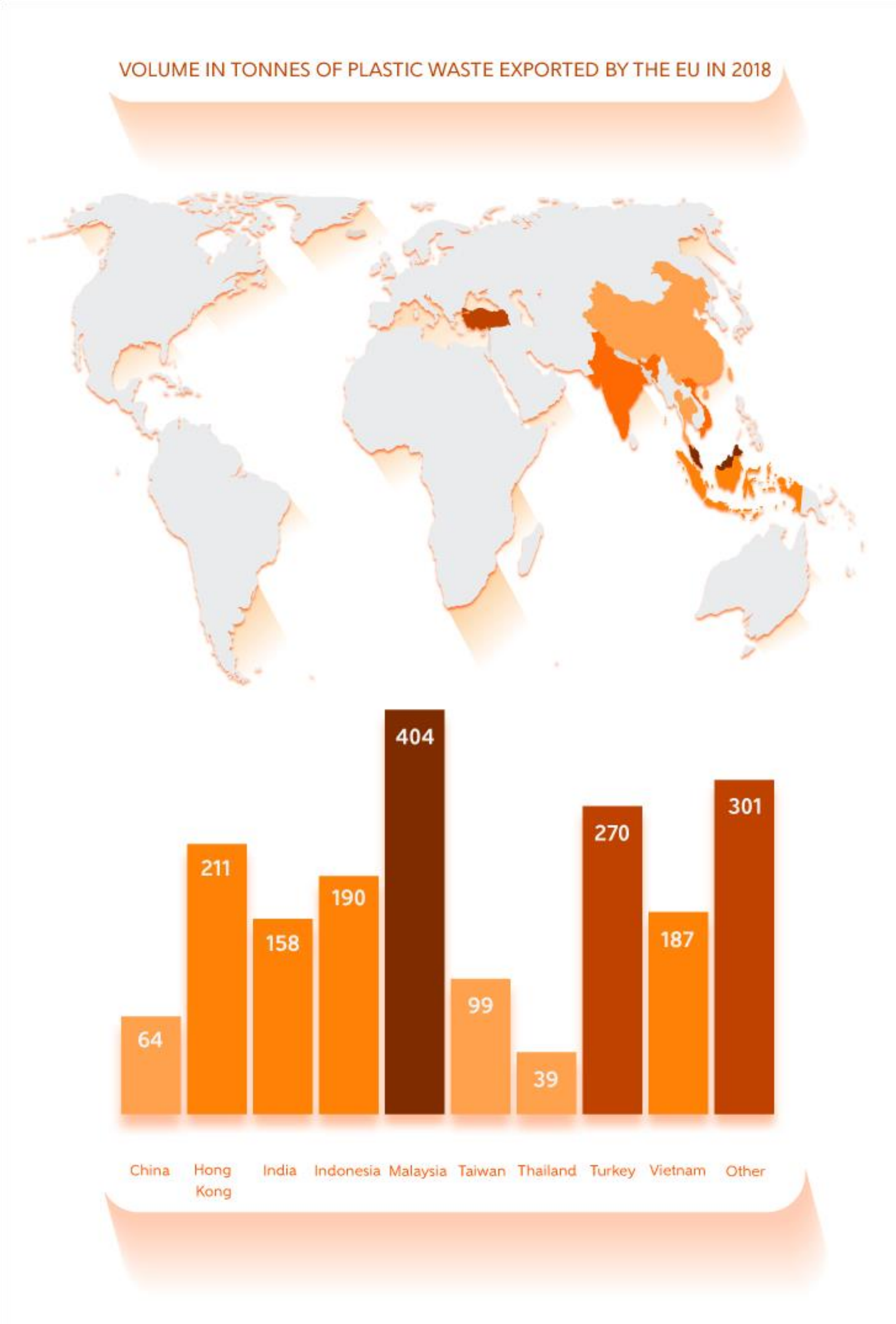

Figure 14 – Export of waste from the EU in 2018, after the Chinese ban (Source: Eurostat, 2018)

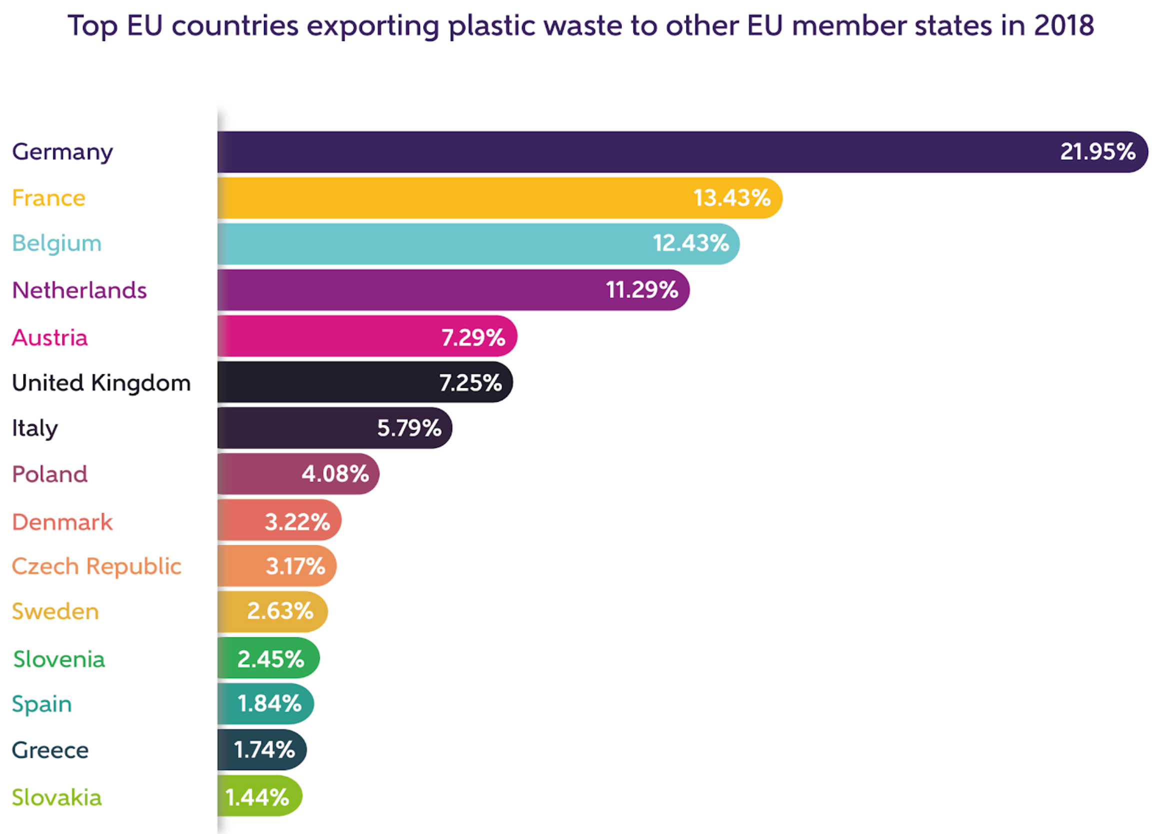

Figure 15 – Top EU countries exporting plastic waste to other EU member states (Source: Eurostat 2019)

China, one of the biggest importers of plastic waste until 2018, has implemented a series of stringent plastic waste import policies, over the last 10 years from requiring that the plastic imports be significantly less contaminated to permanently banning the import of non-industrial plastic waste (Brooks et al., 2018). By the year 2030, a cumulative total of 111 million metric tonnes of plastic waste is projected to be displaced as a consequence of the import ban. Countries that previously exported their waste to China now need to redirect to other low-income countries. However, unlike China, many of these countries lack the necessary capacity and infrastructure to handle their own waste, let alone to receive more plastic waste as imports (Brooks et al., 2018). Consequently, the potential for plastic exports to become mismanaged waste is very high resulting in another potential source of plastic to the oceans (Bishop et al., 2020). After the Chinese ban other countries such as Turkey, India, Hong Kong, Indonesia, Malaysia, Taiwan, Vietnam, and Thailand continued to import European waste (figure 14).

CHAPTER 2

IMPACTS OF PLASTIC POLLUTION

Plastics were initially thought to be inert, however recent evidence suggests that they are leaching additives and toxic chemicals into the environment. To understand the magnitude and scale of plastic pollution, efforts to provide reliable assessments of sources, pathways, spatial-temporal distribution, accumulation trends and impacts have been made over the last decade.

The main sources and pathways of microplastics have been identified in the previous chapter and it is understood that plastics are ubiquitous in the marine environment. Their size and nature within the marine environment mean that they have the potential to regularly interact with a wide diversity of marine species and habitats.

- What are the implications of such evidence? And what are the repercussions on these marine species and ecosystems?
- Are potential toxic effects of additives taken into consideration while designing plastics?
- Are the potential toxic effects assessed before introducing new products into the market?
- Are the additives incorporated to plastic subject to impact assessment prior to production?
- What are the known impacts of plastics and microplastics on marine ecosystems, on the climate and on living organisms?
- What are the potential impacts to human health? And ultimately, do these impacts have potential long-term effects on marine ecosystems? Or do they hinder the capacity of the ocean to regulate climate at large?

This chapter will explore these complex questions based on the current knowledge available while highlighting the impacts of plastics and microplastics on marine organisms, vulnerable marine ecosystems, and on climate at large. Taking into consideration that ecosystems provide valuable services that also contribute to produce human well-being, impacts on human health will also be briefly included here.

IMPACTS ON ECOSYSTEMS

CORAL REEFS

In terms of diversity, productivity and economic importance, coral reef ecosystems are comparable to tropical rainforests. Despite occupying less than 10% of the ocean, coral reefs provide a habitat for 25% of all marine species (Burke et al., 2011). Warm water coral reefs can only survive in sunlit water and are restricted to a narrow band within the tropics, where climatic and environmental conditions are perfect for the survival and growth of reef-building corals (Burke et al., 2011). Most coral species cannot tolerate cold water temperatures, but those that can handle the cold, are found in cold deep-sea waters, and have a slow growth rate. **Both coral reefs ecosystems are equally important and provide similar ecosystem services and are estimated to be worth over USD $1 Trillion globally** (Heron et al. 2017; Auster, 2005; Roberts, 2006).

Tropical and cold-water reefs face a wide range of intensifying direct and indirect anthropogenic threats which are caused by global climate changes (Burke et al., 2011). It is estimated that more than 60% of the world's reefs are directly impacted by human activities, such as bottom trawling, coastal development, and pollution (Burke et al., 2011). **In combination with global warming, approximately 75% of the world's coral reefs are endangered** (Burke et al., 2011). With large amounts of plastic litter entering the oceans every year (Borelle et al., 2020), plastic pollution is considered as an additional threat to such ecosystems (Huang et al., 2020). Due to their complex physical structure, coral reefs act as a sink for macro- and microplastics (Lamb et al., 2018; Martin et al., 2019; Soares et al., 2020) and it is estimated that approximately **11.1 billion large plastic items are trapped or entangled on coral reefs across the Asia-Pacific region** (Lamb et al., 2018).

> It is estimated that more than 60% of the world's reefs are directly impacted by human activities, such as bottom trawling, coastal development, and pollution. In combination with global warming, approximately 75% of the world's coral reefs are endangered

Mediterranean reef systems in Italy, Spain, France, Croatia, Greece, Malta, Cyprus, Montenegro, and Morocco identified tens of species impacted by marine litter, with corals being the most often documented (Angiolillo and Fortibuoni, 2020). The presence of plastic has a real potential to induce a smothering effect for coral polyps, create low-light micro-environments that lead to anoxic conditions (water depleted of dissolved oxygen), cause physical abrasion and injuries to the coral tissue, and may enable invasive species to attach or are colonized by pathogens (Lamb et al., 2018; Reichert et al., 2018). Exposure to plastic has seen the rates of coral disease exponentially increase from a low infection of 4% to very high infection rates (89%) as a result of the introduction of new microbial communities (Huang et al., 2020; Lamb et al., 2018).

Corals are non-selective feeders and have been observed to ingest a wide range of organisms from bacteria to zooplankton, within the microplastic size range (0.2 – 1,000 μm) (Mendrik et al., 2020; Soares et al., 2020). Coral polyps have been recorded to ingest microplastics and it is expected that microplastic ingestion is a common phenomenon (Hall et al., 2015; Mendrik et al., 2020; Soares et al., 2020).

Although corals have been observed to expel microplastics within 48 hours after ingestion (Axworthy and Padilla-Gamiño, 2019), it is energetically expensive for individuals to ingest non-nutritious microplastic particles (Axworthy and Padilla-Gamiño, 2019; Reichert et al., 2018; Rotjan et al., 2019). It has been reported that microplastic ingestion can lead to detrimental health effects. Indications of stress, such as tissue necrosis, bleaching, negative growth effects, and changes in photosynthetic performance (e.g., 41% decrease in photochemical efficiency) were recorded in some species (Reichert et al., 2018), with microplastic spheres causing less damage than fibres or fragments which are more prevalent in the marine environment.

ESTUARIES

Estuaries represent the transition between freshwater and marine ecosystems and are influenced by both. Estuaries are dynamic ecosystems dominated by tides and rivers, which have variable salinity and high sedimentation rates (McLusky and Elliott, 2004). As such, they are one of the most productive ecosystems on Earth, being often described as biodiversity hotspots and nursery grounds for both aquatic and terrestrial species (McLusky and Elliott, 2004). Estuaries are both hotspots and pathways for plastic pollution, capturing and transferring plastics and microplastics from rivers and anthropogenic sources to marine ecosystems (Bessa et al., 2018; Naidoo et al., 2015).

In addition, estuaries provide key ecosystems services, such as coastal protection, control of erosion, and habitat-fishery linkages (Barbier et al. 2011). They are also vulnerable to a multitude of anthropogenic stressors such as waste disposal, land reclamation, aquaculture, fishing activities and pollution (McLusky, and Elliott, 2004; Bakir et al., 2014; Naidoo et al., 2015; Nel et al., 2020; EEA, 2021). Their semi-enclosed nature is responsible for retaining plastic and microplastic litter within a water body (Bessa et al., 2018). Microplastic concentrations from Galway Bay i.e., a semi enclosed bay was reported to be 0.56 ± 0.33 items per m^3 (Frias et al., 2020) from surface waters and 73 MPs/kg d.w. from benthic sediments (Pagter et al., 2020a) and 0.58 MPs individual^{-1} (Pagter et al., 2020b). These concentrations are of similar ranges reported from the surface waters from the Bay of Brest (0.24 ± 0.35 MP per m^3) (Frere et al., 2017) and the Western English Channel (0.27 microplastics per m^3) (Cole et al., 2014).

The Pearl Estuary, in Hong Kong, has recorded microplastic abundances of 5,595 items per m^2, which is 50% higher than the estimates from South Korea and generally higher than all other international averages for estuaries (Fok and Cheung, 2015). Interestingly the most common microplastic type were fibres (92%) of expanded polystyrene (EPS) which is attributed to the insulated boxes usually used by the fishing industry. In Europe, there are ongoing efforts to quantify microplastic pollution on estuaries, often by analysing surface water samples (TARA, 2019). One of the first assessments of estuaries in Europe was conducted in Douro Estuary, Portugal, where the ratio of fish larvae to microplastics showed a higher abundance of microplastics present in the radio of 1:1.5 (Rodrigues et al., 2018). The study results highlight a total of 2,152 microplastics which refers to an average concentration of 17.06 MPs per 100 m^3.

Microplastic ingestion is prevalent within fish species in European estuaries such as sea bass (*Dicentrarchus labrax*), and flounder (*Platichthys flesus*), which showed an incidence rate of 38% for ingested microplastics while 73% of sea bream (*Diplodus vulgaris*) individuals recorded plastics (Bessa et al., 2018). For plankton, a 100% incidence was recorded; while 81% fish larvae recorded microplastics with the highest microplastic concentrations coinciding with higher river flows (Rodrigues et al., 2019).

Widespread ingestion in fish school assemblages has been attributed to insufficient or inappropriate waste management in the neighbouring areas of estuaries in Brazil (Vendel et al., 2017). Furthermore, microplastic ingestion in adult snook fish (*Centropomus undecimalis*) displayed higher concentrations when compared to the juveniles attributed to ingesting a higher biomass and trophic transfer through contaminated prey (Lima et al., 2014; Ferreira et al., 2019; Rodrigues et al., 2018).

MANGROVES

Located on the boundary of land and sea, mangrove forests are unique intertidal wetland ecosystems found along the coastlines of the tropics and subtropics, including European overseas territories such as Bonaire, French Guiana, and French Polynesia (Marchand, et al., 2003; Bryan-Brown et al., 2020; Feller et al., 2017; FAO, 2021). In fact, mangrove forests that grow in France's overseas territories make up 0.7% of the global mangrove presence

(RCW, 2021). These forests are among the most productive marine ecosystems with rates of primary production equal to those of tropical humid evergreen forests (Carugati et al., 2018) and a capacity to capture and store atmospheric carbon from the atmosphere (CO_2) into the soil, many times greater than a similarly sized rainforest (Alongi, 2012; Bryan-Brown et al., 2020; Donato et al., 2011).

Mangrove ecosystems have great ecological and economic importance, as they provide a wide range of ecosystem services (Carugati et al., 2018) including the ability to filter pollutants from freshwater, dissipate wave energy, reduce soil erosion, and trap sediments (Danielsen, 2005; Carugati et al., 2018; Govender et al., 2020). Mangrove trees and roots are both home, refuges and food sources to a wide range of ecologically and commercially relevant species (Nagelkerken et al., 2008). It is estimated that about 30% of all commercial species are mangrove-dependent, producing an annual catch of almost 30 million tonnes in 2002 (Nagelkerken et al., 2008). For reference, the estimated

ecosystem services and their associated socio-economic benefits provided by Thailand's mangroves ranged from USD$10,158 to $12,392 per hectare (Barbier, 2007).

Mangrove sediments have been identified as a major sink and a hotspot for plastic pollution, sustaining almost 8.5 times higher concentrations of plastic than adjacent bare shores (Govender et al., 2020; Martin et al., 2017; Zhou et al., 2020), trapping plastic particles similar to how the aerial roots of the mangrove trees trap sediment and organic matter (Martin et al., 2020). Along the Saudi Arabian coastline, it is estimated that since the 1930s, about 50 to 110 metric tonnes of plastic have been trapped within the mangrove sediments across the Red Sea and Arabian Gulf (Marti et al., 2017). Tagged plastics released in the Brazilian mangroves, which have the same characteristics as European mangroves of the Amazonian region, found that more than half of the tagged plastics remained within the forest, demonstrating the ability of mangroves to retain plastic over long periods of time (Ivar do Sul et al., 2014). Preliminary macro litter pollution (≥ 5cm) in Bonaire, a Dutch Caribbean island, reported shore litter concentrations ranging from 44 to 116 MPs m^{-1}, corresponding to 3.7 to 5.0 kg m^{-1}, in 2011 (Debrot et al., 2013). Plastic marine litter in this survey corresponded to **72% of the reported litter** (Debrot et al., 2013).

Mangrove sediments have been identified as a major sink and a hotspot for plastic pollution, sustaining almost 8.5 times higher concentrations of plastic than adjacent bare shores

The concentrations and distribution of microplastics within mangrove sediments depends on natural factors such as rainfall, sediment size, root density and anthropogenic factors such as urban land use, fishing and aquaculture activity, tourism, population density, waste management and local dumping (Govender et al., 2020; Li et al., 2020; Zhou et al., 2020). Microplastic type and colours recorded often reflect the activity in the region (Govender et al., 2020), for example styrofoam particles from offshore oyster farms were identified as the dominant pollution source in the marine sediments from Qinzhou Bay in China (Zhou et al., 2020).

High concentrations of plastics are challenging for marine organisms that depend on mangroves as important nursery grounds providing a habitat for food, reproduction and/or protection (Booth and Sørensen, 2020) with a high likelihood of exposure and interaction particularly during vulnerable life stages (Horton and Barnes, 2020). About 52% of juvenile fish (Mozambique tilapia (*Oreochromis mossambicus),* Jarbua terapon *(Terapon jarbua),* Malabar glassy perchlet *(Ambassis dussumieri)* and Flathead grey mullet (*Mugil sp.*)) from 4 mangrove forests in KwaZulu-Natal, South Africa, were reported to contain microplastics within their bodies (Naidoo et al., 2020). The average number of plastics per fish (0.79 ± 1.00 MPs) was higher than juvenile fish of other species sampled in oceanic habitats, suggesting that juvenile fish inhabiting mangroves consume significant higher quantities of microplastics (Naidoo et al., 2020), which could compromise the health and survivorship of future cohorts of adult fish that supply protein and nutrients to humans globally.

SALT MARSHES

Salt marshes are intertidal grassland habitats that are found along the shorelines of temperate zones which are subject to international legislation and designations and require systematic monitoring and assessment for example the European Water Framework Directive. Functionally they are similar to mangrove ecosystems as they are highly productive estuarine ecosystems that protect coastal areas from extreme weather events (Silliman, 2014). They act as large reservoirs of carbon and improve the water quality of the nearby estuaries (Silliman, 2014). The local biodiversity found in salt marshes is low comparatively to mangroves, however, they are rich in biomass and provide important nursery habitats for commercial fisheries (Silliman, 2014; Stead et al., 2020).

The estimated economic value of individual services associated with salt marshes for example, livestock grazing on salt marshes in the UK was estimated to generate €17.50 ha^{-1} $year^{-1}$ (King and Lester 1995).

In southern Louisiana, USA, salt marshes were used to purify wastewater, which saved USD$785 to $15000 per acre (1 acre = 0.4 ha) (Breaux et al., 1995), adding between USD$0.19 to $1.89 to the financial value of Gulf Coast blue crab fishery (Barbier et al., 2011; Freeman, 1991). **Salt marshes ability to sequester carbon was also valued at USD$30.50 ha^{-1} $year^{-1}$** (Barbier et al., 2011; Chumura et al., 2003).

Salt marshes are thought to be efficient sinks for plastic pollution (Hidalgo-Ruz et al., 2012; Martin et al., 2019; Stead et al., 2020; Yao et al., 2019) trapping large plastic debris often scattered in complex accumulation patterns and thought to reside there for long periods of time, fragmenting into smaller microplastics (Weinstein et al., 2016; Yao et al., 2019). Water samples collected in the surface microlayer of a marsh system in Southampton, United Kingdom revealed a significant decrease in microfibre abundance from the flood tide to the ebb tide, on a spring and a neap tidal cycle (Stead et al., 2020). Potential within-marsh sequestration has implications for the land to sea fluxes of microplastics, which are dependent on exposure from intertidal wetlands (Stead et al., 2020).

In fact, concentrations of macroplastics in salt marshes are relatively high (17.3 ± 13.3 items 100 m^{-2}) when compared to intertidal zones (1.3 ± 2.1 items 100 m^{-2}) in the Ria Formosa Lagoon, Portugal (Cozzolino et al., 2020). When it comes to microplastics, abundances ranging between 14.9 and 30.4 MPs kg^{-1} d.w. were observed in the same lagoon.

The highest abundance of macro and microplastics were found at the edges of a marsh in southeast China, with the larger plastic items retained within the interior marsh (Yao et al., 2019).

Microplastics from 6 benthic invertebrate species (*Cerastoderma glaucum* (lagoon cockle), *Limecola balthica* (Baltic clam), *Mytilus galloprovincialis* (Mediterranean mussel), *Scrobicularia plana* (peppery furrow shell), *Hediste diversicolor* (common ragworm) and *Carcinus aestuarii* (Mediterranean green crab)) along the North Adriatic lagoon, in Italy and in the Schelde estuary, in the Netherlands, **revealed that 96% of the analysed specimens** (N=316) **did not contained any microplastics** (Piarulli et al., 2020) inferring that **the microplastic concentration in these systems was very low** (Piarulli et al., 2020). Given the ubiquitous nature of microplastics in all marine habitats it is likely that further studies will follow, allowing a more accurate estimation of spatio-temporal trends and assessment of impacts, within these ecosystems.

SEAGRASS MEADOWS

Seagrasses are the sole flowering plants growing in marine environments having successfully colonised shallow continental shelves often in the form of dense meadows or beds. Seagrass generally grows in soft sediments and thrives in sheltered environments where there is sufficient light for photosynthesis, low salinity and limited wave action and turbidity (Unsworth and Cullen-Unsworth, 2017).

It is estimated that their global distribution covers 125,000 km^2, i.e., 0.2% of the area of the world's oceans (Fourqurean et al., 2012; Unsworth and Cullen-Unsworth, 2017). Although the ecological value of seagrass meadows is extremely high **(€1.5 trillion per year**), they are endangered ecosystems, which have disappeared at a rate of 110 km^2 per year, between the 1980 and 2006 (Waycott et al., 2009).

Seagrasses are primary producers and constitute the basis of herbivore and detrital marine food webs (Short et al., 2011). Vulnerable and critically endangered species like dugongs, manatees and sea turtles depend on seagrass as a direct source of food (Short et al., 2011; IUCN, 2021a; IUCN, 2021b). Additionally, important commercial species such as the Atlantic Cod (*Gadus morhua*) prefer seagrass meadows for nursery grounds (Unsworth and Cullen-Unsworth, 2017).

Seagrass meadows positively modify and enhance their surrounding environmental conditions to promote growth of biomass and biodiversity (Deudero et al., 2011; Unsworth and Cullen-Unsworth, 2017). While, at a small scale they contribute to reducing the impact of ocean acidification as they can alter seawater chemistry (Bergstrom et al., 2019) and have the ability to sequester carbon 40 times faster than tropical forests (Fourqurean et al., 2012; Unsworth and Cullen-Unsworth, 2017). As seagrass meadows occur in coastal waters, they are near to multiple anthropogenic stressors (poor water quality, eutrophication, water pollution) which threaten this ecosystem (Unsworth and Cullen-Unsworth, 2017).

Seagrass meadows play a crucial role in coastal protection, climate change mitigation and biodiversity maintenance, however they are experiencing negative effects from plastic pollution, as they are prone to accumulation of this synthetic material. Plastics (High density polyethylene (HDPE) and biodegradable plastic bags made of starch and vinyl-alcohol co-polymers) present in the sediments of seagrass meadows result in changes to seagrass architecture (reducing rhizome biomass under sedimentation) and growth patterns (Menicagli et al., 2020) reducing their competitive edge against macroalgae in the competition for space (Deudero et al., 2011; Ceccherelli et al., 2014; Green et al., 2015; Menicagli et al., 2020). It is important to note that compostable bags, compliant with composability European standard EN13432 (EC, 2021), are said to completely disappear within 3 months in the environment. Contrary it has been shown that these compostable bags are similar to other materials such as, oxo-biodegradable, biodegradable and conventional bags made of HDPE being present in marine sediments, after 27 months (Napper and Thompson, 2019). This raises the issue of how plastic materials are labelled and what are the technical conditions required for them to degrade within 3 months, as studies in this field test.

Seagrass meadows play a crucial role in coastal protection, climate change mitigation and biodiversity maintenance, however they are experiencing negative effects from plastic pollution

Both eelgrass (*Zostera marina)* and turtle grass (*Thalassia testudinum*) meadows accumulate microplastics (Goss et al., 2018; Jones et al., 2020) likely through their capture or entrapment via epibiont organisms or biofilm communities living on the surface of the seagrasses (Goss et al., 2018; Rummel et al., 2017). The presence of microplastics on seagrass blades would infer that herbivorous species are susceptible to unintentional microplastic ingestion (Bonanno and Orlando-Bonaca, 2020; Goss et al., 2018; Jones et al., 2020). Moreover, the presence of microplastics on seagrass blades encrusted with epibionts, can potentially change trophic interactions and the general health of the ecosystem (Goss et al., 2018; Bergstrom et al., 2019; Tahir et al., 2019), as studies in Scotland on *Zostera marina* (Jones et al., 2020) and in Portugal on *Zostera noltei* (Cozzolino et al., 2020) have demonstrated. There is enough evidence to state that seagrass beds are hotspots for microplastic pollution (Huang et al., 2020; Jones et al., 2020) and that food webs associated with seagrass ecosystems are exposed to microplastics, in potential higher concentrations than the surrounding environment (Bonanno and Orlando-Bonaca, 2020; Huang et al., 2020).

DEEP SEA

The deep sea consists of a vast array of ecosystems (hydrothermal vents, whale falls, coral reefs, etc.) in addition to the vast Abyssal plains usually found at depths between 3,000 metres and 6,000 metres. The deep sea is often described as the overlying water below the photic zone, or in other words, below the surface layer of the ocean that receives sunlight (Gjerde, 2006; Thurber et al., 2014; Van den Hove, 2008).

The deep sea plays a key role in climate regulation, carbon sequestration, regulation of water temperature and nutrients (Thurber et al., 2014), while providing a multitude of resources for human benefit, such as commercial fish stocks, raw materials for pharmaceuticals and a reservoir of oil, gas, metals, and minerals (Ottaviani, 2020). The **annual economic value of the deep sea is estimated to be USD $423 billion** (Ottaviani, 2020), with 58% attributed to oil and minerals, 38% to carbon sequestration, 5% to natural resources such as fish and pharmaceuticals and 2% to scientific research and tourism (Ottaviani, 2020).

Of all plastic litter entering the sea it is estimated that an astonishing 94% is found within the deep sea. While it is estimated that between 19 and 23 million tons of plastic waste entered aquatic ecosystems in 2016 (Borelle et al., 2020), approximately 9-10 million tons were cited as entering the ocean annually (Geyer et al., 2017; Jambeck et al., 2015; Kane et al., 2020; Koelmans et al., 2017). The ubiquitous distribution of macro and microplastic pollution in the deep sea (Cunningham et al., 2020; Kanhai et al., 2019; Zhang et al., 2020) is evident from historic video and photographic evidence collected over 30 years (Chiba et al., 2018). The relative abundance of plastic debris recorded was larger at depths greater than 6000 meters and more than 89% of the plastics identified were single-use products (Chiba et al., 2018).

Of all plastic litter entering the sea it is estimated that an astonishing 94% is found within the deep sea. While it is estimated that between 19 and 23 million tons of plastic waste entered aquatic ecosystems in 2016

The concentrations of microplastics, primarily fibers, recorded within deep sea sediments, was found to be four times more abundant per unit volume than in contaminated sea-surface waters (Woodall et al., 2014) with some estimates of 1.9 million particles per m^2 being recorded (Kane et al., 2020). The distribution of these microplastics within the deep sea was influenced by thermohaline driven currents, or bottom currents, indicating that the known biodiversity hotspots are likely to closely align with microplastic hotspots (Kane et al., 2020). Increased microplastic concentrations within biodiversity hotspots, would inevitably lead to greater exposure and ingestion by the benthic organisms (Horton and Barnes, 2020).

Microplastic ingestion has been recorded in several deep-sea species from fish (Zhu et al., 2019) to invertebrates (Courtene-Jones et al., 2017; Jamieson et al., 2019), each having a range of feeding strategies and found at different trophic levels (Horton and Barnes, 2020; Taylor et al., 2016). This suggests that microplastic ingestion by deep sea fauna can occur through trophic transfer (Horton and Barnes, 2020). The abundance of microplastics recorded within deep-sea fauna is of the same order reported in coastal species (Courtene-Jones et al., 2017).

Deep sea organisms are adapted to some of the most extreme environmental conditions found on earth, making it exceptionally challenging and costly to collect these species and maintain them within a lab (Danovaro et al., 2017). For these reasons, there are very few experimental studies that have been carried out on deep sea organisms. Therefore, to identify the impact of microplastics on deep sea organisms, Horton, and Barnes, 2020 recommended using **long-term monitoring as a policy decision making tool**.

Species found in the deep sea generally have longer life spans, grow slowly, and mature later. Given the limited and periodic availability of food these organisms give birth to fewer offspring and have a lower metabolism to conserve energy (Danovaro et al., 2017; Victorero et al., 2018). These characteristics reduce the resilience and adaptive capabilities of deep-sea biota to human pressures such as fisheries, anthropogenic contaminants such as microplastics and climate change (Danovaro et al., 2017; Horton and Barnes, 2020).

Submarine canyons in European Seas accumulate a higher density of anthropogenic litter when compared to continental shelves, and slopes of ocean ridges (Pham et al., 2014). Of the litter mapped, plastic represented 41% of all items, with derelict fishing gear constituting 34% of the total. Similarly, derelict fishing gear (59.8%) was recorded as a main component of litter recorded (0.26 items 100 m^{-1}) in between two islands of the central group of the Azores archipelago, Portugal (Rodriguez and Pham, 2017). Submarine video footage of the Atlantic and the Indian Ocean, revealed a 48% incidence (56 items in 11.6 ha) of plastic in the Atlantic versus a 60% incidence (31 items in 5.6 ha) in the Indian ocean (Woodall et al., 2015).

The deep sea is the ultimate sink for plastics, and its presence has ecologic and economic implications. Over the next decade, it is expected that increased efforts to map underwater accumulation hotspots for macro and microplastics will be relatively common. Deep sea cleanup efforts are constrained by their economic feasibility associated with depth. Long-term consequences of the presence of plastics in this ecosystem are not fully understood and require more investigation.

POLAR REGIONS

The Arctic, in Earth's Northern Hemisphere, is a frozen ocean surrounded by continental landmasses, while the Antarctic, in the Southern hemisphere, is a frozen continent entirely surrounded by the ocean (Tirelli et al., 2020). Supporting unique ecosystems, originally thought to be pristine, the organisms here have adapted to an environment, with minimal anthropogenic impact (Horton and Barnes, 2020) and the **resources provided by the Arctic ecosystem are valued at USD $290 billion per year** (WWF, 2015; O'Garra, 2017).

The value of Antarctic blue carbon is estimated to be between **€0.75 and 2.02 billion (~$2.27 billion USD),** for sequestered carbon in the benthos around the continental shelf (Neumann et al., 2019; Bax et al., 2020). Any alteration to the physical systems of these areas has the potential to endanger the stability of the biological system as well (Horton and Barnes, 2020).

The Arctic hosts about 4 million people permanently (Larsen and Fondahl, 2015), while Antarctica has a transient population comprised of scientific research staff, tourists and members of fishing vessels and research vessels that fluctuates between 4,400 in Summer and 1,000 people in Winter (Tirelli et al., 2020).

The Arctic is relatively more susceptible to anthropogenic pollutants such as plastics and microplastics than the Antarctic as a result of the Antarctic Circumpolar current which acts as a barrier and prevents the physical exchange of oceanic water (Tirelli et al., 2020). However, plastics and microplastics have been detected in different compartments across the Antarctic ecosystem linked to local sources as opposed to transportation by oceanic currents. For instance, the highest concentrations of microplastics were recorded from sediments collected near areas of human activity such as a sewage treatment plant outfall or the scientific research station as opposed to sites further from anthropogenic activity (Reed et al., 2018 and Munari et al., 2017).

Microplastics have been identified in most of the environmental compartments within the Arctic (Amélineau et al., 2016; Bergmann et al., 2017a, 2017b; Woodall et al., 2014) with concentrations within the sea ice (38 to 234 MPs m^{-3}) reported to be higher than concentrations in surface oceanic waters (Kanhai et al., 2020; Obbard et al., 2014) indicating that when the sea freezes to form ice, it collects and concentrates particles from the surrounding oceanic water. As a result, the microplastics remain trapped until the ice melts. As sea ice melts due to climate change, decades of trapped plastic particles could be released in the ocean, with unforeseen consequences (Obbard et al., 2014; Peeken et al., 2018). An island in the Bering Sea reported concentrations of plastic marine litter per linear kilometre had increased 2.4 times between 1972 and 1974, from 2,221 to 5,367 items km^{-1} (Merrell, 1980).

Suaria et al., 2020 measured the abundance of floating plastics across the Southern Ocean, were they detected low concentrations of macro- and microplastics south of the Subtropical front. They hypothesise that the front acts as barrier, preventing floating plastic litter from entering the Southern Ocean. It is also thought that microplastics in the Antarctic are linked to local sources (Reed et al., 2018 and Munari et al., 2017).

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In the Arctic, plastic ingestion was first recorded in the 1960s, when plastic fragments were found in Canadian seabirds (Threfakk, 1968, Harper and Fowler, 1987; Tirelli et al., 2020). Since then, microplastic ingestion has been recorded regularly in a wide range of seabird species in the Arctic and Antarctic including the northern fulmar (*Fulmarus glacialis*), mew gull (*Larus canus*), thick-billed murre (*Uria lomvia*), great skua (*Stercorarius skua*), little auks (*Alle alle*), Antarctic petrels (*Thalassoica antarctica*), Gentoo penguin (*Pygoscelis papua*), King penguin (*Aptenodytes patagonicus*) and snow petrels (*Pagodroma nivea*) (Amélineau et al., 2016; Fang et al., 2018; Iannilli et al., 2019; Morgana et al., 2018; Bourdages et al., 2021; Ryan, 1987; Bessa et al., 2019; Le Guen et al., 2020; van Franeker and Bell, 1988). Within the Arctic and globally, seabirds are used as bio-indicators for plastic abundance in surface waters (Trevail et al., 2015). The northern fulmar has been identified as an effective bio-indicator for plastic pollution in the Arctic (Avery-Gomm et al., 2018, 2012; Kühn and van Franeker, 2012; Trevail et al., 2015).

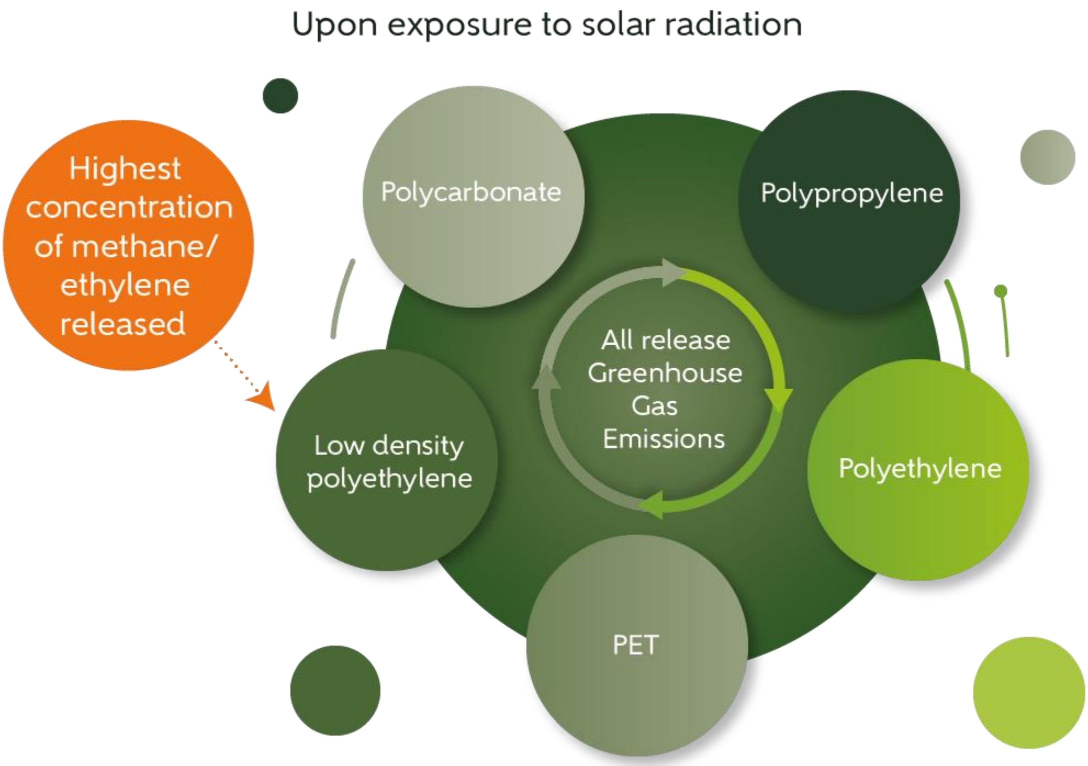
Arctic and Antarctic fish and benthic invertebrates have also been recorded to ingest microplastics, namely sculpin (*Triglops nybelini*), polar cod (*Boreogadus saida*), and crab (*Chionoecetes opilio*) respectively (Kühn et al., 2018; Morgana et al., 2018, Fang et al., 2018). Among invertebrate species which recorded microplastics, *Asterias rubens (starfish),* a benthic predator, and bivalves were observed to have the highest quantities of microplastics, suggesting trophic transfer (Fang et al., 2018; Sfriso et al., 2020). The sea anemone (*Actiniidae und.*) was identified as a potential bioindicator for the Arctic benthos as microplastic abundances within this species positively correlated with the seasonal changes of sea ice (Fang et al., 2020). To conclude, polar regions are no longer pristine when it comes to plastic and microplastic pollution.

IMPACT OF PLASTICS ON THE CLIMATE

Traditionally, products were manufactured following a linear economy system starting with resource extraction followed by production, distribution, consumption, and ending at disposal of the items. A recent paradigm is emerging, fostered by decades of research and the implementation of the New European Green Deal, where a transition into a circular economy model in Europe is underway. Nonetheless, the impacts of plastic production and of inappropriately discarded plastic products do not cease, particularly when considered the release of greenhouse effect gases to the atmosphere. Disposal is the shortest phase in the plastic lifecycle (CIEL, 2019) and the one consumers relate to the most. Understanding the fate of plastics in the environment has been the focus of research in recent decades, and general facts about plastics along with its capacity to fragment into microplastics (Thompson et al., 2004) and nanoplastics (Gigault et al., 2018) raise several concerns. Once in the environment, plastics can leach additives and adsorb toxic chemicals from and to the surrounding environments (Frias, 2020; Yeo et al., 2020). Plastics are also known to harm marine animals by entanglement (Jepsen and de Bruyn, 2019), by ingestion leading to starvation or by a wide range of health impacts on a several organisms (Cole et al., 2013; Courtene-Jones et al., 2017). However, links on how such findings relate to a larger climatic scale are often not part of the scope, are not included nor comprehended. The following sections will address the potential impact plastics and microplastic pollution can have on the climate.

PHOTODEGRADATION AND RELEASE OF GREENHOUSE GASES

Once exposed to solar radiation, plastic undergoes chemical changes which contribute to a gradual degradation and fragmentation of the polymers (Royer et al., 2018). In addition, multiple plastic polymers (e.g., polycarbonate, polypropylene, polyethylene, polystyrene and PET) contribute to greenhouse gas (GHG) emissions to produce measurable quantities of methane and ethylene when exposed to solar radiation (Royer et al., 2018). The quantities of methane and ethylene differed by more than two orders of magnitude between plastic polymers. Of the two, methane has a greater potential to significantly contribute to greenhouse gas effects (28 times greater than CO_2) contributing to 23% of overall global warming (Saunois et al., 2020; IPCC, 2013).



Among the tested polymer types, Low Density Polythene (LDPE) released the highest concentrations of methane and ethylene when exposed to solar radiation and produced approximately twice as much methane gas and 76 times more ethylene than LDPE fragments submerged in water (Royer et al., 2018). LDPE is a common polymer type that is most widely employed in single-use products (PlasticsEurope 2019). The same weight and density of LDPE in powder form produced 488 times more methane and 135 times more ethylene when compared to LDPE in pellet shape; while both virgin and aged LDPE pellets exponentially released more gas over time (Royer et al., 2018) showing that greenhouse gases (GHG) might be produced throughout the entire lifetime of plastic products (CIEL, 2019).

Low Density Polyethylene (LDPE) released the highest concentrations of methane and ethylene when exposed to ambient solar radiation. It produces twice as much methane gas and 76 times more ethylene than LDPE fragments submerged in water. LDPE is most widely employed in single-use products.

Additionally, as virgin pellets degrade due to ultraviolet radiation, salinity, temperature, etc., its surface starts to have micro fissures and fractures, increasing the surface area and leading to accelerated production of GHG (Royer et al., 2018). Therefore, plastics exposed to atmospheric conditions in warmer climates are likely to release higher amounts of greenhouse gases than plastics in colder climates. As such, it is imperative to understand the meaning of such results to the overall emissions of GHG and whether those emissions have significant impacts in the global carbon budgets.

Multiple methane emissions models estimated annual emissions **of 76 Mtonnes year^{-1} worldwide from plastic degradation** (van Sebille et al., 2015; CIEL, 2019). With an expected increase of 33-36% in plastic production by 2025 (figure 1), emissions of methane are predicted to rise to 101-103 Mtonnes year^{-1}, if no mitigation efforts are implemented (CIEL, 2019). Empirical data for microplastics' GHG emissions with relevant environmental parameters are necessary for more accurate modelling of future global carbon budgets.

IMPACTS ON CARBON SEQUESTRATION

The impacts of microplastic pollution affect not only marine food webs but also atmospheric carbon sequestration (Coppock et al., 2019). The ocean is the largest natural carbon sink, estimated to store 50 times more carbon than the atmosphere and 20 times more carbon than soil (Santhanam et al., 2019). The ocean absorb approximately 26% of the CO_2 emitted from anthropogenic sources (Le Quéré et al., 2015) in a process known as carbon sequestration (Santhanam et al., 2019).

Ocean circulation and the biological pump are the two main processes that capture atmospheric carbon through primary producers, such as phytoplankton (Passow and Carlson, 2012; Bopp et al., 2015; Wieczorek et al., 2019; Chow, 2014). Inorganic carbon (e.g., carbon dioxide) is fixed into organic matter via photosynthesis and then sequestered away from the atmosphere generally by transport into the deep ocean via the sinking of particulate organic matter (POM), faecal pellets, or marine snow when plankton dies (Wieczorek et al., 2019).

Microplastic pollution threatens the oceanic ecosystem health through interfering with the efficiency of the biological pump (CIEL, 2019) as small herbivores and zooplankton ingest microplastics, the particles ingested will affect the sinking rate velocity of the faeces and subsequent carbon sequestration (Cole et al., 2016).

Plankton

The term plankton is a collective name for all organisms that are nonmotile or too small or weak to swim against the current. Plankton is distinguished from nekton, which is composed of strong-swimming animals, and from the benthos, which include sessile and burrowing organisms on the seafloor. Pleuston are other forms of life that live in the interface between air and water.

Zooplankton refers to a wide community of microorganisms, both with vertebrate and invertebrate species of different size ranges. The zooplankton community can be categorized into two main groups; Holoplankton, organisms that are planktonic for their entire life cycle and Meroplankton, organisms that only spend part of their life cycle as plankton (Lalli and Parsons, 1997). Below we will explore how both phyto- and zooplankton affected by microplastics can interfere with carbon sequestration processes.

Phytoplankton

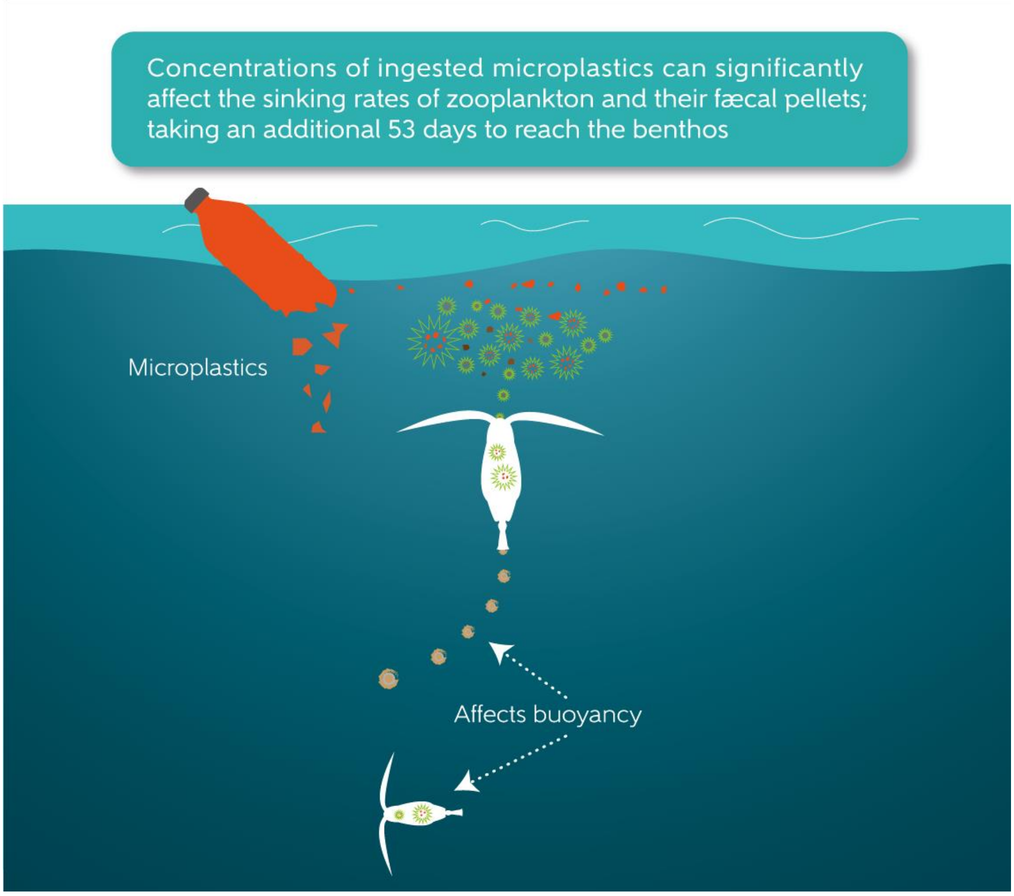
Phytoplankton communities are the main oceanic primary producers and capture nearly half of the CO_2 that is released into the earth's atmosphere (CIEL, 2019). Microplastic pollution can disrupt the functioning and affect the behaviour of phytoplankton and their photosynthetic ability affecting the rate of CO_2 uptake (Mao et al., 2018).

Phytoplankton have been shown to accumulate microplastic particles (Chen et al., 2011; Prata et al., 2019). If the build-up of microplastics within the plankton increased significantly, then light availability to plankton could be reduced, impacting the photosynthetic rates and subsequent carbon sequestration (Chen et al., 2011; Mao et al., 2018; Zhang et al., 2020; Long et al., 2015). However, this potential scenario is far from reality still, based on currently available scientific literature.

Zooplankton

Zooplankton communities play a pivotal role in marine food webs, as they are an important food source for higher trophic levels; they assist in nutrient cycling and play a crucial role transporting carbon to the seafloor (Coppock et al., 2019).

Zooplankton that feeds on primary producers play a fundamental role in carbon transport and storage by enabling the transfer of carbon to deeper depths through the excretion of sinking faecal pellets as part of the marine snow. These carbon-storing pellets provide food for biota and are recycled by bacteria (Cole et al., 2016; Wieczorek et al., 2019). **Concentrations of ingested microplastics can significantly affect the sinking rates of zooplankton and their faecal pellets; taking an additional 53 days to reach the seafloor** (Cole et al., 2016; Coppock et al., 2019). This will allow for increased consumption, fragmentation, and microbial degradation during descent, reducing carbon sequestration rates which has repercussions on the diel-vertical movement of zooplankton (Botterell et al., 2019; Jónasdóttir et al., 2015) by releasing carbon in the upper regions of the water column and decreasing carbon storage rates on the seafloor (Cole et al., 2016).



The presence of microplastics in the gut of zooplankton, in addition to the decreased reproduction rates, induces a feeling of satiety therefore reducing the feeding capacity and the uptake of carbon, for example, Copepoda captures 40% less carbon biomass when in the presence of microplastics (Cole et al., 2015). This reduction in consumption of phytoplankton could enable these communities to bloom in optimal conditions resulting in the potential for more frequent harmful algal blooms (Zhang et al., 2020), as well as a significant impact on the efficiency of the biological pump (Galloway et al., 2017).

Seagrass meadows

Seagrass beds are among the most significant natural carbon sinks worldwide (Ricart et al., 2020). Climate change, ocean warming, acidification, and more recently plastic pollution are factors that, when combined, have a detrimental effect on detrital decomposition (Litchfield et al., 2020). Plastic has been shown to **significantly slow the rate of eelgrass (*Zostera muelleri*) decomposition** (Litchfield et al., 2020), which is thought to have a ripple

effect for carbon and nutrient cycling, as well as secondary production. The joint effect of temperature, acidification and plastic pollution contribute to the liberation of elements, reduction of carbon to nitrogen ratios, and breakdown processes of the kelp and eelgrass detritus. This means that the presence of plastics slows the production of detritus and increases the release of carbon. Ensuring that seagrass meadows grow in plastic free environments is essential to increase their underwater areas and reduce the effects of climate change.

IMPACT ON MARINE LIFE

Plastic initially was thought to be chemically inert, however research has identified lethal and sub-lethal impacts associated with these synthetic particles (Trestrail et al., 2019). The toxicity associated with microplastics can be related to additives (e.g., plasticizers, flame retardants, UV resistant agents, etc) that are introduced to the plastics during production (Rochman, 2015; Kühn et al., 2020) and to Persistent organic pollutants (POPs) adsorbed from the seawater. Many additives have been proven to be dangerous to animal and human health due to their genotoxicity, neurotoxicity, and hormonal endocrine disruptor abilities (Rochman, 2015; Aurisano, et al., 2021). Combined with other POPs that can bioaccumulate along the food chain, there has been an urge to classify plastics as hazardous to the marine environment to prevent their input (Rochman, 2015; Kühn et al., 2020).

Microplastics have been found to adsorb persistent bioaccumulative toxic substances (PBTS) such as trace metals, pharmaceuticals, and other POP from the surrounding environment (Rochman, 2015; Kühn et al., 2020). Microplastics have also been reported to leach chemical additives to the surrounding environment (Sørensen et al., 2021), however this process depends on factors such as gut retention time and partitioning coefficients (Koelmans et al., 2016; Kühn et al., 2020).

When plastics enter the marine environment, they can be colonised by various organisms on their surface to create biofilms (Oberbeckmann et al., 2015; Walkinshaw et al., 2020). The biofilm can alter the density of floating plastics (Kaiser et al., 2017), make it more appealing for other organisms to consume them (Rummel et al., 2017); and can act as a vector for spreading disease causing pathogens such as *Vibrio spp.* (Oberbeckmann et al., 2015; Kristein et al., 2016; Walkinshaw et al., 2020).

Microplastics are regularly referred to as a cocktail of chemicals because plastics have chemical additives introduced during the production phase (e.g., flame retardants, antioxidants, pigments, plasticizers, etc), and are likely to act as a kitchen sponge, adsorbing contaminants such persistent organic pollutants, pesticides, heavy metals and pharmaceuticals from the surrounding environment (Rochman, C., 2015; Prinz and Korez, 2020; Walkinshaw et al., 2020; Wang et al., 2020).

The previous section explored the impacts of microplastics on the lower trophic levels of the ocean in relation to climate and carbon sequestration. In this section, focus will be given to all marine life that is affected by microplastics pollution, particularly synthetic fibres, which are one of the main sources of this pollutant (figure 5).

PHYTOPLANKTON

Phytoplankton represents the basis of the marine food web (Lalli and Parsons, 1997). Microplastics have been shown to have effects on the growth, morphology, photosynthetic activity, reduced cell count and chlorophyll content of phytoplanktonic species (Bhattacharya et al., 2010; Besseling et al., 2014; Sjollema et al., 2016; Bergami et al., 2017; Zhang et al., 2017; Mao et al., 2018).

A 40% decrease in photosynthetic rate has been recorded when phytoplankton species are exposed to microplastics (Besseling et al., 2014, Mao et al., 2018); resulting in reduced **growth rates of up to 18%** - **25%** (Lagarde et al., 2016; Mao et al., 2018; Sjollema et al., 2016; Bergami et al., 2017; Canniff and Hoang, 2018). Phytoplankton can act as a potential sink for microplastics in the ocean, for example polystyrene microbeads of 2 µm were recorded to accumulate in the plankton aggregates (Long et al., 2015). Microplastic toxicity is often related to MP size, type, shape, and concentrations used (Wang et al. 2019), and it is assumed that toxicity increases with decreasing particle size. It is assumed that more studies with phytoplanktonic organisms will be carried out in the next decade to fully assess the scale of effects and impacts associated with microplastics.

ZOOPLANKTON

Zooplankton communities include copepods, krill, and fish larvae. They predominantly feed at the ocean's surface, where concentrations of floating microplastics tend to accumulate, therefore increasing exposure which has been shown to affect feeding, reproduction, and overall lifespan (Desforges et al., 2015; Sun et al., 2017; 2018). Zooplankton organisms are a direct link between phytoplankton and higher trophic organisms (Lalli and Parsons, 1997).

Ingested microplastics affect the feeding capacity, by causing gut blockages and decreasing energy inputs with a subsequent impact on growth, reproduction, and development of zooplankton (Cole et al., 2013, 2015; Cole and Galloway, 2015; Kaposi et al., 2014; Lee et al., 2013; Steer et al., 2017; Lo and Chan, 2018; Messinetti et al., 2018; Nobre et al., 2015). While nutritional deficiencies as a result of exposure to polystyrene microbeads over two consecutive generations of copepod *Tigriopus japonicus,* resulted in an increased mortality rate, a significant decrease in fecundity was also verified (Lee et al., 2013).

Feeding strategies and the abundances of microplastics recorded within zooplankton are site specific and not directly correlated to environmental concentrations for example omnivores with a non-selective feeding strategy, from the East China Sea, were found to bioaccumulate significantly higher microplastic abundances than herbivores and carnivores (Sun et al., 2018). However, a significant negative correlation was recorded between the abundance of zooplankton taxa and bioaccumulated concentrations of microplastics, often termed biological dilution (Desforges et al. 2015). This was particularly apparent for Copepoda where increasing population numbers competed for food resources, which included microplastics (Sun et al., 2018). An accidental spillage of microplastics resulting in localised high microplastics concentrations could result in short term decreases in both cell volumes and biomass of zooplankton such as *Strombidium sulcatum* (Geng et al., 2021).

Key species within the North Pacific marine food web, *Neocalanus cristatus* (copepod) and *Euphausia pacifica*, (North Pacific krill), were both found to ingest microplastics indicating potential risks to higher trophic levels including salmon (Desforges et al., 2015). In the Atlantic Ocean, along the Portuguese coastline, approximately 61% of zooplankton samples contained microplastics in relatively reduced concentrations: 0.036 MPs m^{-3} (Frias et al., 2014). In the same year, Setälä et al., reported that all 12 mesozooplankton species collected from glacial depressions in the Southwest coast of Finland showed ingestion of microplastics. Fish larvae recorded low ingestion rates of microplastics in the Western English Channel with a positive correlation found between low microplastic levels in the water and increasing densities of fish larvae with distance from the coast (Steer et al., 2017). Most of these fibres (66%) were blue, which is a prevalent microplastic colour.

Preference for different microplastic shapes was shown by *Calanus helgolandicus* (copepod) (fragments), *Acartia tonsa* (copepod) (fibres) and the larvae of *Homarus gammarus* (European lobster) (beads); ingesting significantly more when the microplastics were infused with algae-derived infochemicals (Hernandez-Fernandez and Ferrer-i-Cacho, 2016), suggesting that the shape of the microplastic particles influence bioavailability, which is likely to be dependent on the species biology and ecology. As zooplankton species, such as *Calanus finmarchicus* and *Acartia longiremis*, rely on chemosensory cues to find food and the presence of biofilms growing on aged microplastics, through both biofouling and weathering, represent an increased risk of ingestion mistaking the aged plastics for food (Vroom et al., 2017; Botterell et al., 2019; 2020).

In addition, under prolonged exposure to microplastics, the reproductive output for copepods is affected with the production of smaller eggs and lower hatch rates (Cole et al., 2015). When larvae in the zooplankton ingest microplastics, additional energy is required to egest these particles, which could result in an energy deficit during critical developmental life stages for example a decrease was recorded in growth rate and a premature settlement to the benthos of *Crepidula onyx* larvae (Lo and Chan, 2018). Juvenile *C. onyx* continued to show a slower growth rate even after microplastics were removed from the surrounding environment, (Lo and Chan, 2018).

Evidence of growth and reproduction effects are precursors of impacts that could lead to further effects at the population, community, and ecosystem level (Botterell et al., 2020).

INVERTEBRATES

It is estimated that over 98% of all animal species are invertebrates (Marine Bio, 2021). In the marine environment, invertebrates include worms, crustaceans, molluscs, etc. This section focuses on the impact of microplastics on macroinvertebrates (>1 mm), particularly those that are commercially relevant and have the potential to contribute to microplastic impacts on human health through ingestion.

Microplastics have been recovered in both commercially and ecologically relevant marine invertebrate species (Murray and Cowie, 2011; van Cauwenberghe et al., 2015; Blarer and Burkhardt-Holm, 2016; Phuong et al., 2018; Cau et al., 2019; Doyle et al., 2019; Piarulli et al., 2019; Maes et al., 2020; Hara et al., 2020; Walkinshaw et al., 2020) with additional evidence provided through laboratory assays (Horn et al., 2020; Rist et al., 2016; Setälä et al., 2016; Sussarellu et al., 2016). Some of the most commercially dominant species in Europe like **the Norwegian lobster (*Nephrops norvegicus*) was estimated to have a plastic occurrence of 1.75 ± 2.01 items per individual** (Hara et al., 2020), while the **blue mussel** (*Mytilus edulis*) **had an occurrence of 0.61 ± 0.56 items per individual** (Phuong et al., 2018), **the pacific oyster** (*Crassostrea gigas*) had **2.10 ± 1.71 items per individual** (Phuong et al., 2018) and the European brown shrimp (*Crangon crangon)* had 1.23 ± 0.99 microplastics per shrimp (Devriese et al., 2015). Ecologically relevant species, such as Arenicola *marina,* a lugworm, was reported to have 1.2 ± 2.8 microplastic particles per gram of organism (Cauwenberghe et al., 2015). Several other polychaetes such as *Hediste diversicolor*, *Sabella pavonina* and Oweniidae sampled in Norway and Portugal were reported to have ingested microplastics (Lourenço et al., 2017; Bour et al., 2018; Knutsen et al., 2020).

Marine invertebrates have been recorded actively ingesting microplastics that resemble natural food due to factors such as a similar size to their food, surface chemistry, presence of biofilm or info-chemicals (Trestrail et al., 2019). Filter-feeding bivalves inadvertently consume microplastics due to their generalist feeding strategy (Trestrail et al., 2019). Scavengers, detritivores, herbivores, or deposit feeders can ingest microplastics accidentally, if microplastics are present on their natural foods (Trestrail et al., 2019). As a result, microplastics can be transferred to higher trophic levels in the food chain by incidental ingestion (Trestrail et al., 2019).

Microplastic ingestion disrupts the energy flux in organisms by altering feeding ability and behaviour (Trestrail et al., 2019). Gut blockages, from fibre aggregates or fragments, and microplastics with sharp edges can lead to internal cuts or abrasions leading to inflammation (Trestrail et al., 2019). A significant reduction in assimilation efficiency was recorded in the amphipod *Gammarus fossarum* during feeding (Blarer and Burkhardt-Holm 2016). Pacific oysters (*Crassostrea gigas*) have been observed to increase food intake to compensate for the low nutritional and energy value from microplastics (Sussarellu et al., 2016). However, microplastic ingestion in clams (*Atactodea striata* and *Corbicula fluminea*) lead to a false sense of satiety and organisms reduced their ingestion rates (Oliveira et al., 2018; Xu et al., 2017)

Exposure of *Mytilus spp.* to environmentally relevant concentrations of polyethylene and polypropylene revealed microplastic accumulation in the digestive system only (Revel et al., 2019). At differing levels of microplastic contamination, mussels (*Perna viridis*) had reduced respiration and clearance rates and impaired byssal thread production (Rist et al., 2016). In the Pacific oyster, (*Crassostrea gigas*), exposure to microplastics saw an increase in mortality rates and negative effects on fecundity (decrease in sperm velocity, reduction in egg size, no viable larval produced) as a consequences of decreased energy reserves (Sussarellu et al., 2016). In addition, a decrease in lysosome cells results in reduced cell protection from xenobiotic agents, viruses, and bacteria (Maes et al., 2019). At environmentally unrealistic conditions mortality increased over time and had a negative impact on fecundity on species of amphipod and mysid shrimp (Au et al., 2015; Wang et al., 2017).

FISH

A total of **323 species of fish have been found to ingest microplastics (**Markic et al., 2020; Wang et al., 2020) of which, **262 are commercially relevant**.

Fish ingest microplastics through either curiosity or via prey resemblance, with yellow and blue bottles being attacked more frequently (Carson, 2013). Based on the shapes and size of the teeth marks in plastic litter items, it has been established a link that fish and sharks are attempting to eat plastics. Teeth marks have been recorded from 5.8% of the recovered litter (5,500 items). Fish can also unknowingly or accidentally ingest particles from the surrounding environment while foraging for food (McGoran et al., 2018), as for example flatfish species, who consume sediment along with their prey (Hurst et al., 2007; McGoran et al., 2018).

Secondary uptake or indirect trophic transfer via ingestion of other species has been demonstrated by a benthic fish (*Myoxocephalus brandti*) in Japan, which consumed 3 to 11 times more microplastics from prey than from the surrounding water (Hasegawa and Nakaoka, 2021).

Feeding strategy can determine the degree of exposure to plastics, for example, generalists will be exposed to larger amounts of plastics than selective feeders (Markic et al., 2018) and omnivorous fish will have significantly higher concentrations of microplastics when compared to herbivores and carnivores (Markic et al., 2018 and Mizraji et al., 2017). Pelagic fish, found in surface waters, have higher microplastic concentrations when compared to demersal species living near the sea floor (Digka et al., 2018; Güven et al., 2017; Markic et al., 2020; Rummel et al., 2016) as depicted by fish species found in the English Channel, in the Atlantic Portuguese Coast and in the NW Iberian Shelf (Lusher et al., 2013; Neves et al., 2015; Steer et al., 2017; Bessa et al., 2018; Filgueiras et al., 2020).

Most marine fish do not show a relationship between trophic level and plastic ingestion (Markic et al., 2020), which suggests that biomagnification of microplastics along the food chain is unlikely to occur (Walkinshaw et al., 2020). However, some lower trophic level species have recorded high microplastic abundances relative to their body weight (Walkinshaw et al., 2020). Microplastics can be considered transitory contaminants with limited residence time within fish, meaning once a fish ingests plastic, it will be excreted. Plastic ingestion can be reflective of environmental concentrations within the habitat however, this is dependent on life history and feeding strategies (Rummel et al., 2017; Güven, et al., 2017; Steer et al., 2017; Markic et al., 2018; Gove et al., 2019; Walkinshaw et al., 2020; Pagter et al., 2020b). An ecosystem-based approach looking at fish communities is often a better indication of the environmental levels of plastic within the surrounding water than any one individual species (Pagter et al., 2020b).

Fish larvae sampled from hotspots, such as convergence surface waters or slicks, with higher plastic densities, record more than double the microplastics than fish larvae outside of these zones (Gove et al., 2019). Incidence of microplastics in fish, such as tuna, mackerel, rosefish, and seabream, ranges from 10% to the North Atlantic Gyre (Pereira et al., 2020) to between 40% and 68% in the Mediterranean Sea (Romeo, et al., 2015; Nadal, Alomar and Deudero, 2016; Giani et al., 2019; Tsangaris et al., 2020; Pennino et al., 2020).

> Incidence of microplastics in fish, such as tuna, mackerel, rosefish, and seabream, ranges from 10% in the North Atlantic Gyre to between 40% and 68% in the Mediterranean Sea

Health impacts or toxicity associated with plastic particles in fish, depend on the additives and adsorbed contaminants to the particle itself. Chronic uptake of microplastics leads to bioaccumulation, gut blockages, decreased appetite, malnutrition, energy depletion and growth and reproductive effects (Galloway et al., 2017; Walkinshaw et al., 2020; Wang et al., 2020; Wright et al., 2013). For example, microplastic ingestion can lead to lethargy, reduced feeding activity, reduced swimming speed and range of movement in juvenile Korean rockfish (*Sebastes schlegelii*) (Yin et al., 2018). Such behavioural changes could decrease the overall fitness of the fish and affect their ability to avoid predators thus representing a cause for concern for marine food webs (Yin et al., 2018). A recent study established a direct link between chemicals in tyre wear run offs and the mass mortality of silver or coho salmon (Tian et al. 2021). The additive, 6PPD-quinone, to prevent damage to tyre rubber from ozone, was associated with the acute mortality in the salmon during their migration to creeks recorded to have lethal levels of the additive, introduced to the creek via stormwater (Tian et al. 2021).

Model organisms, such as Zebrafish (*Danio rerio*), after a 7-day exposure, accumulated 5 μm diameter microplastics in gills, liver, and digestive tract, with the 20 μm diameter microplastics only accumulated in the gills and digestive tract. In addition, inflammatory responses and metabolic changes to liver function were recorded (Laing et al., 2016; Lu et al., 2016). Chronic exposure to microplastics leads to deterioration of the structure and function of the intestines, within the European sea bass (*Dicentrarchus labrax*) (Peda et al., 2016). It is important to note that laboratory assays can differ in results to what is found in the environment, when environmental relevant concentrations of microplastics or different size ranges are used. Nonetheless, assessing environmental concentrations in commercial and ecological relevant species seems to provide a far more accurate snapshot in time, than to assess individual species.

SEABIRDS

Seabirds are particularly vulnerable to plastic pollution (Provencher et al., 2019) as entanglement and ingestion are a common occurrence (Kenyon and Kridler, 1969; Rothstein, et al., 1973; van Franeker et al., 2015; Kühn et al., 2015; Amélineau et al., 2016; Thiel et al., 2018; Provencher et al., 2019).

Diet, age, and distribution, in addition to their foraging behaviour on the surface of the ocean, all contribute to influence the incidence of plastics within their digestive tracts (Battisti et al., 2019; Provencher et al., 2019; Thiel et al., 2018).

It is estimated that plastic ingestion currently affects 180 seabird species (Kühn and van Franeker, 2020) with predictions stating that by 2050, about 99% of all seabirds will have plastic in their digestive systems (Wilcox et al., 2015).

Figure 16 – Microplastics in a Fulmar collected in Fanore beach, West coast of Ireland (Source: Heidi Acampora, 2018).

Similarly, to fish, seabirds ingest plastic directly, where the plastic resembles prey, or indirectly, via trophic transfer. It is thought that the presence of infochemicals (chemicals that create odours similar to those released by marine organisms), promotes, or mediates ingestion (Savoca et al., 2016). Dimethyl sulphide (DMS) is a marine infochemical that is produced by phytoplankton and absorbed by degrading polyethylene and polypropylene, which induces foraging among a variety of species, such as albatrosses, petrels, and shearwaters (Savoca et al., 2016).

Seabirds whose diet consists mainly of crustaceans are more likely to ingest higher amounts of microplastics when compared to species who feed on squid and fish (Auman et al., 1997; Kühn et al., 2015; Battisti et al., 2019; Roman et al., 2019). Seabirds with specialized diets are generally unlikely to mistake plastic with prey (Kühn et al., 2015), while generalist feeding strategies ingest the highest abundances of plastic (Kühn et al., 2020). For example, 93% of northern fulmars examined from the North Sea were reported to contain an average of 33 plastic particles per individual (van Franeker, 2017; Kühn et al., 2020).

Age and maturity are other deterministic factors for plastic exposure and interaction (Roman et al., 2020). Juveniles are particularly at risk to plastics, as they can be exposed to plastic debris at birth, through feeding from parents (Kühn and van Franeker, 2020) or from use of plastic in nest construction (Jagiello et al., 2019; Ryan, 2020) in addition to the potential entanglement of seabird chicks (Ryan, 2020; Votier et al., 2011). It has also been proposed that **nest monitoring can serve as an indicator of plastic environmental concentrations surrounding marine areas** (Ryan, 2020).

Plastic ingestion is known to cause a wide range of effects, from gut obstruction to appetite loss to death. These effects are likely to be magnified by contaminants associated with plastic debris (Rochman, 2015) therefore they would serve as a valuable bioindicator. Long term monitoring of plastic pollution in seabirds began in the 1980s, where high ingestion rates (90-97%) have been recorded for Laysan albatross (*Phoebastria immutabilis*) chicks (Fry et al., 1987; Auman et al., 1997) while northern fulmar chicks also recorded higher levels compared to adults (Kühn and van Franeker, 2020; van Franeker et al., 2011).

The presence of Persistent Bioaccumulative and Toxic Chemicals (PBTC), such as polybrominated diphenyl ethers (PBDEs), used in flame retardants added to plastics, have been recorded in the fatty tissue and gastrointestinal tract of short-tailed shearwaters (*Puffinus tenuirostris*) (Tanaka et al., 2013).

Preen oil, which serves as a proxy to identify environmental contaminants, is used by seabirds to clean their plumage, maintain feather lubrication, and protect them from ectoparasites (Ito et al., 2013). There is evidence for the transfer of environmentally relevant concentrations of chemical additives (flame retardants and ultraviolet stabilizers) from plastics within streaked shearwater chicks (*Calonectris leucomelas*) (Tanaka et al., 2020). Additives accumulated in the liver and fatty tissue had concentrations 10 – 100,000 times higher than the controls, highlighting plastics as a pathway for chemical contaminants (Tanaka et al., 2013; 2020).

> The presence of Persistent Bioaccumulative and Toxic Chemicals (PBTC), such as polybrominated diphenyl ethers (PBDEs), used in flame retardants added to plastics, have been recorded in the fatty tissue and gastrointestinal tract of short-tailed shearwaters (Puffinus tenuirostris)

Plastics can be grinded in the gizzard and fragment into microplastics (Kühn et al., 2020), which can increase the plastics' surface area, enhancing the leaching of chemicals from plastic (Kühn et al., 2020; Rochman, 2015). Leaching of chemicals in plastics is assumed to increase over time (Blastic, 2021), however gut retention time is quite varied amongst seabirds e.g., 1 month for northern fulmars, and several months to other species (van Franeker and Law, 2015; Ryan, 2015) where plastics are immediately excreted after ingestion, the leaching potential remains low. Harmful chemical additives from oceanic plastics were shown to leach from plastics into the stomach oil of Northern Fulmars, a common energy reserve in most Procellariiform seabirds (Kühn et al., 2020); highlighting that plastics can leach chemicals over environmentally relevant gut retention times (Kühn et al., 2020). Figure 16 shows an example of a fulmar necropsy and the microplastics retrieved.

TURTLES

Sea turtle populations have a wide range of anthropogenic threats from habitat destruction and fisheries bycatch to plastic and microplastic litter (ingestion, entanglement in ghost nets or by degrading key habitats) (Duncan, 2018, Nelms et al., 2016). Today there are a total of seven species of sea turtles and according to the IUCN, six of these are threatened by extinction (IUCN, 2021).

Plastic ingestion among marine turtles is a worldwide phenomenon (Digka et al., 2020; Duncan et al., 2019a; Pham et al., 2017; Ryan et al., 2016; Tourinho et al., 2010; Nelms et al., 2016), reported in all age groups (i.e., adults, juveniles, and post-hatchlings) and species (Duncan, 2018; Duncan et al., 2019a; 2019b). It is estimated that up to 52% of sea turtles globally have ingested plastic debris (Schuyler et al., 2016). Plastic ingestion can alter behaviour, lead to low energy levels and malnutrition, which further affects the fecundity and growth of the organism (Eastman et al., 2020; Nelms et al., 2016).

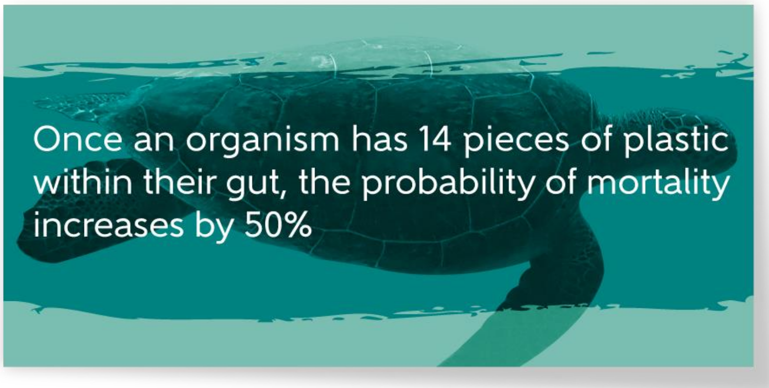
Plastic ingestion among sea turtles predominantly occurs in three ways i.e., direct, accidental or through trophic transfer. As many turtle species have been hypothesized to be visual feeders, individuals have been observed to misidentify plastic items such as plastic bags, plastic bottle caps and balloons as prey (Ex: jellyfish) and actively select and ingest these particles (Campani et al., 2013; Hoarau et al., 2014). Odours associated with biofouled marine plastic can deceive sea turtles into believing that plastic is potential prey and therefore enhances the chances of direct ingestion (Pfaller et al., 2020). Accidental ingestion can occur when plastic particles are either attached or mixed with their natural prey. For instance, juvenile green sea turtles (*Chelonia mydas*) were observed to feed on benthic microalgal banks that were infested with plastic debris (Di Beneditto and Awabdi, 2014). When turtles feed on prey which have previously ingested plastic, it results in trophic transfer (Nelms et al., 2016).

The extent to which marine turtles feed on plastic is influenced by factors including biology, feeding ecology, life history stage and the abundance of plastic litter in the surrounding environment (Santos et al., 2015; Schuyler et al., 2016). Turtles from the Mediterranean Sea were observed to have the highest abundances of plastic compared to their Atlantic and Pacific counterparts, due to the relatively high abundances of plastic debris within the Mediterranean basin (Duncan et al., 2018; Cózar et al., 2014; Duncan et al., 2019b). Where the geographical range of a turtle population overlaps regions such as the east Indian Ocean, South-east Asia and the east coasts of the USA, Australia, South Africa, and gyre systems then these species are at a higher risk of interacting with plastic debris (Schuyler et al., 2016; Pham et al., 2017, White et al., 2018).

Differences in the feeding ecology of species play a role in plastic ingestion rates. For example, the generalist feeding strategies employed by adult olive ridley turtles *(Lepidochelys olivacea)* along with their natural tendency to feed in the middle of the water column increase their chances of plastic ingestion (Schuyler et al., 2016). Species like Loggerhead turtles *(Caretta caretta)* and Kemp ridley turtles *(Lepidochelys kempii)* that feed on benthic organisms, such as crabs and molluscs, have lower chances of encountering floating plastics (Bjorndal et al., 1994; Nelms et al., 2016; Schuyler et al., 2016). Assessment of gut contents of 24 loggerhead turtles stranded in the North Atlantic showed that 83% had ingested plastic debris (Pham et al., 2017).

Life history stage can influence plastic ingestion among sea turtles (Schuyler et al., 2016). Post-hatchlings and early juveniles are among the most vulnerable age classes in terms of plastic ingestion (Eastman et al., 2020; Nelms et al., 2016). Post -hatchlings are exposed to large amounts of plastics immediately after birth, as coastlines and beaches around the world have been observed to accumulate plastic. Due to their small size and less robust digestive tracts, young sea turtles face a higher chance of mortality due to accidental plastic ingestion through the misidentification of plastics as prey (Nelms et al., 2016).

Ingestion of large plastic pieces of hard plastic fragments can lead to gut blockages, damage to the digestive system and internal injuries (Nelms et al., 2016). Blockages in the digestive tracts of two juvenile turtles from 0.5 g of plastics led to their death (Santos et al., 2015). Juvenile green turtles (*Chelonia mydas*) that died as a result of ingested debris were found to be emaciated or extremely underweight when compared to those that died as a consequence of fisheries bycatch (Santos et al., 2015). Once an organism has 14 pieces of plastic within their gut, the probability of mortality increases by 50% (Wilcox et al., 2018).



Post-hatchlings of loggerhead turtles *(Caretta caretta)* recorded plastic from almost all of the digestive tracts of 42 post-hatchlings from Florida and 60% from South Africa (Eastman et al., 2020; Ryan et al., 2016). In addition, plastics were reported to be responsible for the death of almost 16 out of 40 post-hatchlings from South Africa and plastics made up an average of 1.23% of their body weight in Florida (Eastman et al., 2020; Ryan et al., 2016). The plastic debris in the digestive tract from South Africa was made up of hard plastic fragments (77%), flexible packaging (10%), fibers (8%) and pellets (3%) while some post-hatchlings from Florida were found to have very high plastic loads, with as many as 287 plastic particles in one single individual (Eastman et al., 2020).

In their early juvenile stage, post-hatchlings are carried away from coastal waters by currents and can be transported to areas where marine productivity and floating anthropogenic debris are high, such as oceanic gyres, ocean fronts and downwelling areas (Nelms et al., 2016; Ryan et al., 2016). This overlap increases exposure to plastic debris and increases the vulnerability of juvenile sea turtles towards plastic ingestion (Nelms et al., 2016; Schuyler et al., 2016). The effect of plastic on young sea turtles, has the potential to threaten the future of sea turtle populations globally.

MARINE MAMMALS

Figure 17 – Seal entangled in plastic (Source: Heidi Acampora, 2018).

Marine mammal species are divided into Sirenia (e.g., dugongs and manatees), Carnivora (e.g., polar bear, sea otters, seals, sea lions and walruses) and Cetacea (e.g. whales, dolphins and porpoises) (Moore, 2008) and are regarded as indicators of ecosystem health (Zantis et al., 2021). Marine mammals are threatened by marine litter directly through injury and death or indirectly, through behaviour alterations leading to decreased fitness and productivity (Avila et al., 2018). As many are apex species at the top of marine food webs, they are more vulnerable to trophic transfer of aquatic contaminants through bioaccumulation and biomagnification (Avila et al., 2018; Nelms et al., 2018).

Anthropogenic marine debris, such as large plastic items such as plastic bags or ghost nets, pose a threat to marine mammals through ingestion or entanglement (Baulch and Perry, 2014; Williams et al., 2011). Microplastic research on marine mammals worldwide relies on non-invasive sampling techniques (i.e., stool samples and chemical loads) or opportunistic sampling (i.e., stranded, bycaught or hunted individuals) (Zantis et al., 2021; Besseling et al., 2015; Bravo Rebolledo et al., 2013; Nelms et al., 2018; Perez-Venegas et al., 2018). As microplastic studies in the case of marine mammals often relies on the availability of stranded or bycaught individuals, a few researchers have attempted to investigate the use of chemical loads as biomarkers to estimate levels of microplastic exposure. Another non-invasive way to estimate anthropogenic exposure including microplastic ingestion in marine wildlife is by using biomarkers of chemical loads such as phthalate concentrations in the sea water, plankton and in whale blubber (Baini et al., 2017; Fossi et al., 2016, 2012). Phthalates are common chemical plasticizers that can leach from a wide range of consumer goods and industrial processes, including plastics, into the environment and living organisms (Zantis et al., 2021). Because these chemical compounds exist in several sources, they are not a good indicator for plastic pollution.

Microplastic occurrence has been recorded in scat from harbour seals, grey seals, fur seals (Hudak and Sette, 2019; Hernandez-Milian et al., 2019; Eriksson and Burton, 2003). Plastics in the scat of grey seals were similar in abundance and type to the microplastics that were isolated from the gastrointestinal tracts of the wild-caught Atlantic mackerel (prey items) highlighting that trophic transfer is likely to be a pathway for microplastics to transfer to top predators (Nelms et al., 2018; Zantis et al., 2021).

Microplastics were recorded from all digestive tracts of cetacean species and pinniped species, for example grey seals (*Halichoerus grypus*), True's beaked whales (*Mesoplodon mirus*) (adult females and a calf), and beluga whales *(Delphinapterus leucas)* (adult males) (Lusher et al., 2015; Moore et al., 2020; Nelms et al., 2018). However, microplastics were also recorded from the faeces of beluga whales indicating that the organisms were capable of egesting these particles and could have ingested them while seawater entered during feeding or through trophic transfer (Moore et al., 2020;).

Based on feeding behaviour it is most likely that consumption of contaminated prey results in plastic ingestion in mammals (Nelms et al., 2018). Filter-feeding baleen whales such as humpback whales *(Megaptera novaeangliae)* and fin whales *(Balaenoptera physalus)* (Besseling et al., 2015; Egbeocha et al., 2018; Fossi et al., 2012) consume large quantities of seawater and its associated contaminants in the process (Zantis et al., 2021). Consequently, these species may consume comparatively higher quantities of microplastics.

Where species are foraging in areas with high concentrations of microplastics in the surrounding waters, the uptake of microplastic debris is unavoidable (Egbeocha et al., 2018; Fossi et al., 2012; Zantis et al., 2021). For instance, it is estimated that surface feeding fin whales could inadvertently ingest almost 3653 particles per day (Fossi et al., 2014; 2016), while a blue whale could ingest anywhere in between 332 and 1245 million microplastic particles per mouthful (Zantis et al., 2021). While the levels of microplastics within prey species, rather than the surrounding water, could be used as a better indicator for microplastics uptake by the cetaceans Common minke whale (*Balaenoptera acutorostrata*) and Sei whale (*Balaenoptera borealis*) (Burkhardt-Holm and N'Guyen, 2019).

Figure 18 – Common dolphin entangled in plastic
(Source: Simon Berrow, 2017).

IMPACT ON HUMAN HEALTH

Microplastics can enter the human body either through ingestion or inhalation (Rist et al., 2018; Campanale et al., 2020). It is hypothesized that translocation is a possible pathway where microplastics are <10 microns (Campanale et al., 2020; Zarus et al., 2021;). Research findings have confirmed the presence of microplastics within the human body, with their recovery from human stool samples (Schwabl et al., 2019) and the placenta (Ragusa et al., 2021). Additionally, the wear and tear of medical implants (Zarus et al., 2021), synthetic clothing and makeup (Prata et al., 2020) and anthropogenic secondary organic aerosols such as those sourced from tyre wear (Daellenbach et al., 2020) represent other sources of microplastics for the human body.

Microplastics are prevalent in commercial seafood, for example shellfish such as mussels, clams, and oysters; crustaceans like shrimp, prawn, crab, and lobsters; and fish, as already described. Based on the number of extracted microplastics from mussels and oysters targeted for human consumption, European shellfish consumers were estimated to ingest up to 11,000 microplastic particles every year (Van Cauwenberghe and Janssen, 2014).

The Dublin Bay prawn (*Nephrops norvegicus*) contains relatively high concentrations of microplastics (Cau et al., 2019; Hara et al., 2020; Welden and Cowie, 2016) while fish species such as Skipjack tuna (Rochman et al., 2015), Atlantic cod (Bråte et al., 2016), striped bass (Rochman et al., 2015), Pacific chub mackerel (Neves et al., 2015; Rochman et al., 2015), and Japanese anchovy (Tanaka and Takada, 2016) have varying concentrations of microplastics.

Research on microplastics is largely focused on the digestive tracts of commercial species where it is assumed the ingested plastics will pass through or potentially bioaccumulate. In Europe, the visceral organs are largely removed before consumption, as in fish species, therefore microplastic transfer to humans is considerably lower (Rist et al., 2018). However, there is the potential for very small microplastics to translocate to the tissues and organs, which was observed in seabass and salmon respectively (Gomiero et al., 2020; Zeytin et al., 2020).

In addition to food as a direct source of microplastics, atmospheric microplastics can further contaminate food through cooking and lifting of dust particles during ingestion.

Exposure to household dust (13,731–68,415 microplastic particles per year per capita) is significantly higher when compared to the exposure of microplastics from mussels (123 microplastics per year per person), as suggested on study conducted in the UK (Catarino et al., 2018). Several common consumable items used for cooking, such as drinking water, tea, honey, sugar, sea salt, and beer have all been found to be contaminated with airborne microplastics (Hernandez et al., 2019; Kosuth et al., 2018; Liebezeit and Liebezeit, 2013; Wright and Kelly, 2017; Yang et al., 2015; Wright and Kelly, 2017; Peixoto et al., 2019).

Phthalates are responsible for making plastics more flexible and pliable and are used in seafood packaging (Campanale et al., 2020). This additive has been reported to be carcinogenic and it is found to be responsible for endocrine disruption and developmental abnormalities (Halden, 2010). Additionally, phthalates were found to affect human development during puberty, male and female reproductive health and to affect pregnancies (Campanale et al., 2020; Meeker et al., 2009; Rist et al., 2018; Rudel et al., 2011). Nonetheless, because there are other sources of this contaminant rather than solely plastics, they cannot serve as a sole proxy for plastic contamination.

Research presented here has a marine microplastic focus and is not considered a comprehensive study on all known microplastic impacts on humans. It is important to also realise that this particular field of research is in its infancy. At present, adverse health effects from environmental microplastic exposure is limited to worker related studies. For example, workers employed in flocking industries, are exposed to high levels of airborne microplastics, (Zarus et al., 2021) and have recorded health effects such as respiratory ailments (for example pulmonary inflammatory response, fibrosis-induced lung remodelling and pneumonia or asthma) as a consequence of inhaling dust laden with microplastics (Burkhart et al., 1999; Zarus et al., 2021). While in textile factories, workers exposed to synthetic fibers reported respiratory problems along with colorectal cancer in some patients (Pimentel et al., 1975; Zarus et al., 2021).

CHAPTER 3

MONITORING BASED UPON EXPERT OPINION

A series of qualitative interviews with 23 marine litter and microplastic pollution experts from 15 countries were conducted to support this report. Their expertise ranged from microplastic research to recycling, and they were academics, members of non-governmental organisations, of governmental institutions and of private corporations. One of the questions was related to policy recommendations to mitigate microplastic pollution globally. Before listing the proposed policy recommendations in chapter 4, it is important to highlight a few common recommendations that were advocated by the experts. These were:

1. Addressing the **MACRO-plastic** issue will significantly decrease the occurrence, concentration and impacts of microplastics

2. **Reusing** products, **reducing waste**, and **repairing equipment** are more effective strategies than recycling single-use products

3. Recycling plastic is currently not effective, feasible or economically efficient. Several experts highlighted that exporting plastic waste to countries with emerging economies often accounts as part of the recycling cycle. Adequate waste management systems that account for such fluxes throughout the system need to be disclosed to ensure true circular economy approaches on waste management

4. Implementing Extended Producer Responsibility (EPR) and Corporate Social Responsibility (CSR) schemes while redesigning plastic products in circular economy approaches is fundamental to reduce plastic pollution and

5. Banning non-essential single-use plastics, wherever sustainable and carbon-neutral alternatives are available, are essential.

Outreach and awareness raising campaigns on plastic pollution based on these 5 cross-sector recommendations will further reduce inputs of marine anthropogenic litter and microplastics into the ocean.

Below is a series of questions that focus on relevant environmental concerns associated with microplastic pollution and monitoring, and the expert replies.

Q1: In your opinion, what are the most relevant or biggest environmental concerns associated with microplastic pollution?

Most experts interviewed identified toxic effects (30%) and uptake, ingestion, and entanglement (22%) to be the most significant environmental concerns associated with microplastic pollution (figure 19). About 12% of the participants referred impacts to human health as a reason for concern. Other concerns included the lack of standardised methodologies to assess microplastics, which can contribute either to under- or over-estimations of concentrations currently in the environment. Degradation of plastics in the marine environment, which can contribute to microplastic concentrations increasing over time, was another of the concerns highlighted.

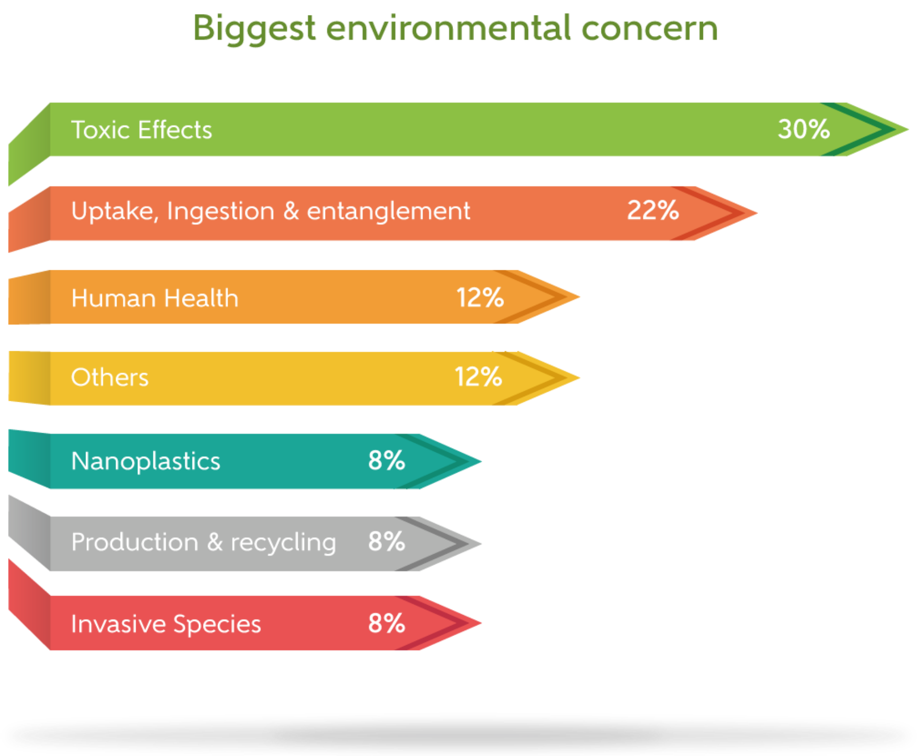


Figure 1937 – Biggest environmental concerns associated with microplastic pollution

Environmental monitoring of plastics and microplastics is crucial to understand long-term effects and impacts of these pollutants in the environment. Because of the diverse background of experts, and countries where they are based, the interviews focused on monitoring according to their experiences.

Q2: In your opinion, what environmental compartments should be monitored, and how often?

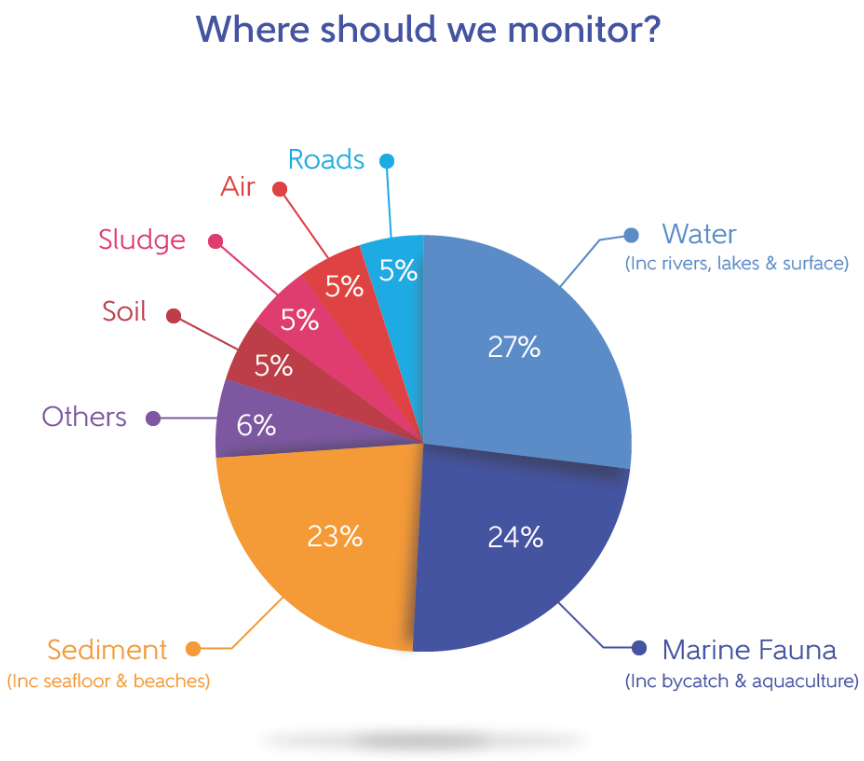


Figure 20 – Matrices to sample according to experts

From the experts' opinions, the main environmental compartments to be monitored are aquatic systems (27%) followed by biota (24%) and sediment (23%) (Figure 20). Water refers to rivers, lakes, bays, surface waters, and underground waters. Consistent monitoring of these systems will allow them to identify sources and pathways and create mitigation strategies before plastics and microplastics are released into the sea.

Biota includes bycatch and the aquaculture industry. Bycatch is a particularly relevant way to assess microplastics in the environment, as it could be easily incorporated into fisheries surveys already taking place in Europe. Not included in biota, but similarly relevant is nest monitoring, which was already highlighted in the seabird chapter, and that can contribute to understanding the levels of plastics and microplastics in coastal and marine regions using non-invasive techniques on seabirds.

Sediment monitoring mainly refers to benthic sediments and to beaches, not including soil. Soil is often part of terrestrial systems. Underwater benthic sediments are the ultimate sink for microplastics in the seafloor, therefore many experts mentioned the importance of monitoring this environmental compartment. Other compartments of prospective importance include road runoff, air, sludge, and soil. These compartments are likely to be the focus of scientific research in upcoming years.

Research shows microplastics resulting from the wear and tear of tyres and brakes and from road runoff are one of the main sources of microplastics in the environment. Recent studies suggest that particles identified as styrene: butadiene using Fourier-transform infrared spectroscopy (FTIR) analysis are likely to be a proxy for tyre wear. Most of the tyre wear particles, due to their colour are not quantifiable in FTIR analysis, so other techniques to quantify microplastic concentrations from road run-off and tyre and brake wear are required and likely to be suggested in upcoming years, as many research projects are focusing on them.

Air monitoring, an emerging compartment, is likely to become a priority policy area after the discovery of microplastic pollution in the Arctic, Alps, and Mount Everest. Sludge (WWTP solids) and terrestrial soil monitoring should occur in parallel, as many experts pointed out, as several European countries use sludge as a fertilizer in agricultural land. Other relevant categories include city dust, macroplastic satellite observations at sea and drinking water.

Regarding frequency of monitoring (figure 21), 65% of the experts advocate for seasonal monitoring programs, as highlighted in many publications. Seasonality varies with geographical area and corresponds either to two seasons (wet and dry) or to four seasons (spring, summer, autumn, and winter). Experts highlighted the need to collect samples from snow melts and immediately after extreme climatic events, as these provide maximum concentration values entering the environment or reaching coastal areas. Including microplastic monitoring to already established monitoring programs is a cost-effective way to collect data on this pollutant as OSPAR guidelines already recommend seasonal monitoring.

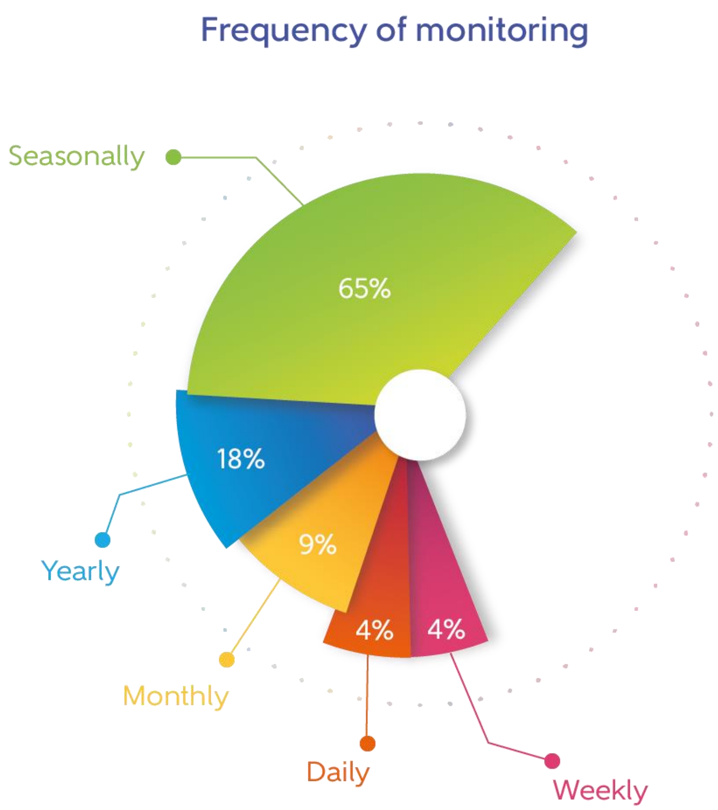


Figure 21 - Frequency of monitoring

The monitoring of the seafloor sediment should occur once a year, recommended by 18% of the experts, as sedimentation rates are usually low. For countries with regular monitoring programmes, experts (4%) suggested microplastic monitoring occur once per month.

Q3: What indicators or bioindicators are currently being used in your country to monitor microplastic pollution?

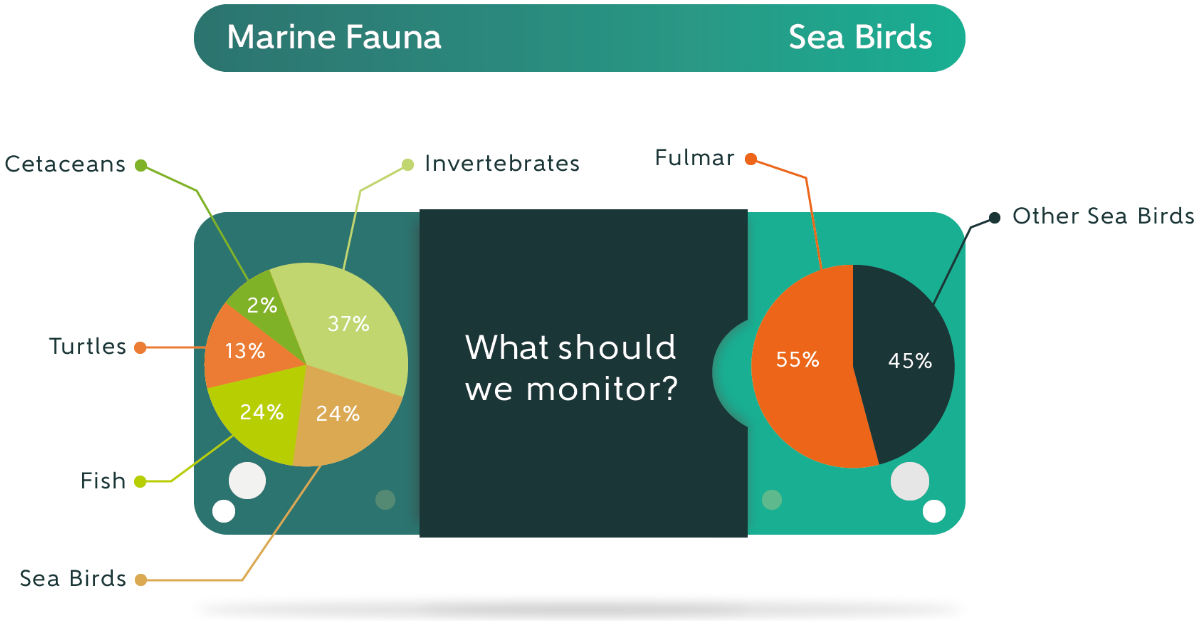


Figure 22 – Marine fauna and seabird species to monitor

All experts recommended bioindicators to monitor microplastic pollution, particularly invertebrates (37%), seabirds (24%), fish (24%), sea turtles (13%) and cetaceans (2%) (Figure 22). Invertebrates are often used as bioindicators for a given region due to their sessile lifestyle or limited movement. Suggested invertebrates to monitor were mussels (42%), planktonic organisms (33%), and worms (25%) (figure 23). Mussels are already widely used as a model species in Europe to monitor several pollutants. Experts highlighted that some monitoring programmes could be updated to include microplastic monitoring.

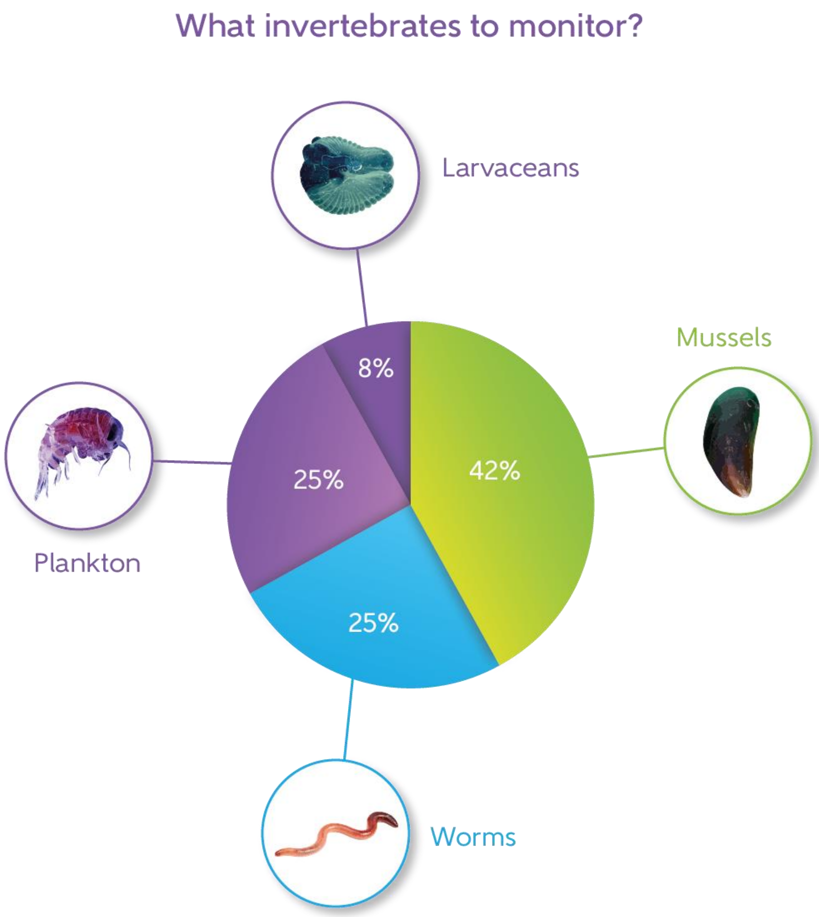


Figure 23 - Invertebrates to be monitored for microplastics

Seabirds are reliable bioindicator species for floating plastics and microplastics in the ocean. Fulmars were recommended by 55% of the experts recommended as a bioindicator for Europe as they are opportunistic surface feeders that tend to consume large amounts of floating plastics. As fulmars are geographically limited to Northern Europe, 45% of the experts recommended that other species should be included. One relevant aspect related to seabirds from the interviews is the fact that most experts believe that gulls are not a suitable bioindicator, as they feed on urban areas on land, and would be misleading in assessing microplastic concentrations floating in the ocean.

Most experts expressed a difficulty in finding one common species that could be used for monitoring purposes throughout Europe. Experts always alluded to the fact that different species should be used for comparison purposes as long as they lived in similar habitats (epipelagic, mesopelagic, pelagic, benthopelagic), have similar feeding strategies, or similar behaviour. One of the frequent suggestions was to use bycatch as a way to assess microplastics in both commercial and ecologically relevant species, in already established fishery surveys.

Sea turtles, migratory animals that are found in the Macaronesia region, in the North Atlantic and in the Mediterranean Sea, have the potential to be bioindicators as well, particularly species such as loggerhead turtle, which is being proposed as a suitable microplastic bioindicator in monitoring programmes. Cetaceans, large migrating marine mammals, are difficult to monitor, as recommendations for these organisms follow the current state of sampling described in the marine mammal section. Beach stranding can serve as a way to assess plastic ingestion and entanglement of abandoned, lost or otherwise discarded fishing gear.

Q4. Considering your study area, have you noticed increasing, decreasing or stable concentrations of microplastics?

Trends in figure 24 refer to matrices from biota to surface waters, including sediments. Half of the experts stated that the microplastic concentrations in their study sites and/or species are increasing over time, 25% mentioned that no significant trends can be estimated, 17% mentioned that microplastic concentrations are actually decreasing and only 8% mentioned that they were stable across time. No consistent temporal trends have been estimated in overall research to date, even though increasing amounts of microplastics can be found in remote areas (Galgani et al., 2021).

Perceptions on trends of microplastic accumulation in the ocean

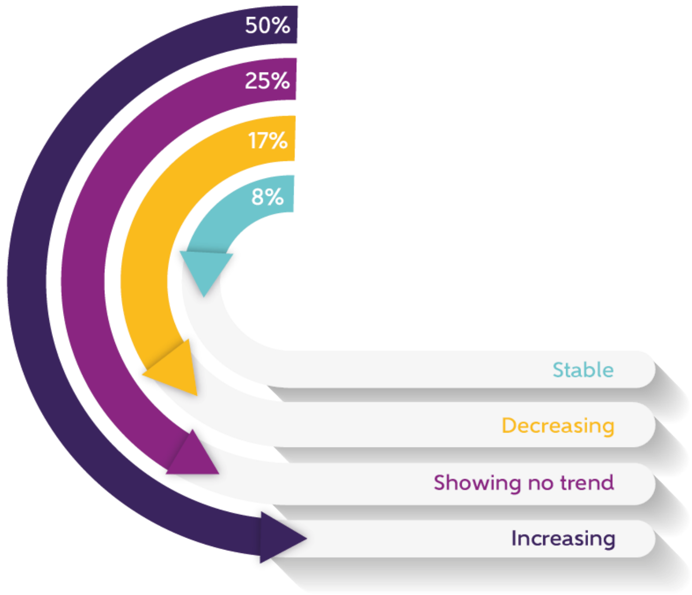


Figure 24 – MP concentration trends in the expert's study area of country

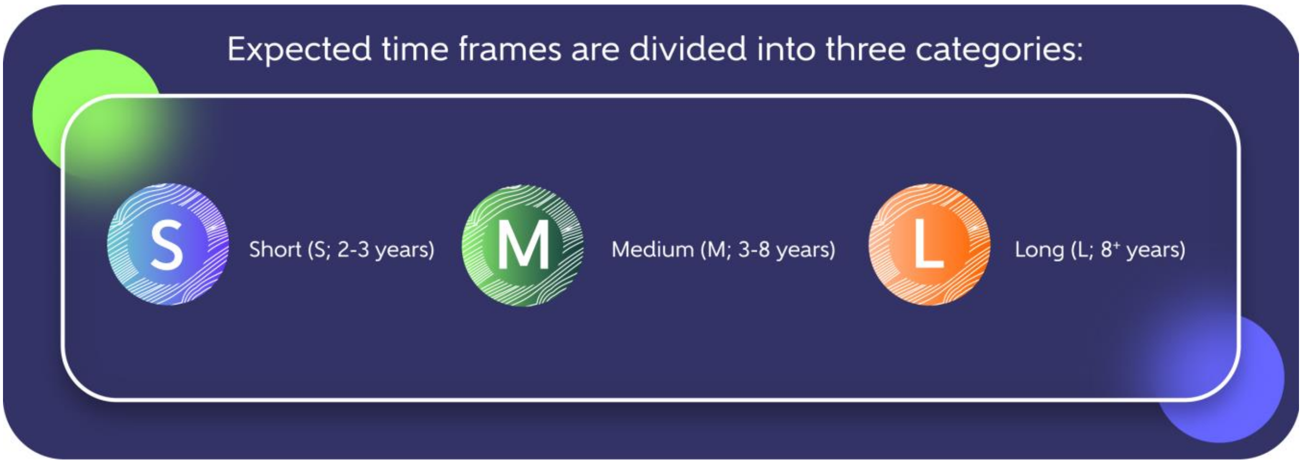
CHAPTER 4

RECOMMENDATIONS

Supported by strong scientific evidence, policy recommendations provided here target decision-makers both at the EU and national level. Following the identification of sources, routes of entry, pathways and overall magnitude and impact of microplastics pollution on ecosystems, it is important to identify ways to minimize the effects or mitigate consequences. The policy recommendations below aim to propose upstream solutions that effectively address the plastic problem at its source. Upstream solutions and systemic change require strong commitments and considerable amounts of time and efforts of all stakeholders involved. Thus, recommended measures are to be transitory to tackle this global issue. Additionally, this report also identifies opportunities to reinforce other marine litter policy frameworks that are currently in place to better tackle the problem.

Policy recommendations

Recommendations here are focused on Europe and organised by sectors (Chen, 2015) which were identified as a source or a pathway for marine microplastics in this report.



Agriculture & tourism

Research

S Fund research to identify the minimum admissible concentrations of microplastics in terrestrial systems (soil, run-off, groundwater), taking into consideration the upcoming EU Zero Pollution Action Plan (2021) and the EU Soil Strategy

Current practice

S Introduce legislation to phase out the use of intentionally added microplastics in fertilizers, seed and crop protection products in agriculture and horticulture

S Promote and incentivise alternative materials to plastic mulch, as well as other soil-pollutant microplastics (e.g. geosynthetics).

M Introduce legislation to phase out the use of synthetic polymers in agriculture and horticulture

Tourism

S Enforcing of the current littering fines across European member states

S Creation of a coastal tourism tax to fund beach, riverine, sub-aquatic and terrestrial clean-ups, monitoring and pollution awareness raising campaigns

Personal care products & consumer goods

Intentionally added microplastics

S Introduce legislation to ban intentionally added microplastics from all personal care products and household cleaning products in Europe.

S Financially incentivise the promotion of a) bulk and refill areas in supermarkets and b) national/regional bulk sale and packaging free networks

M Build on existing plastic bans to include bans on plastic glitter, sequins and microbeads from all consumer products such as carpets, plastic flowers, flocking plants, clothes, makeup, children's toys, etc

Single-use plastics

S Systematic identification of single-use products remaining on the market with a label sign a) to inform consumers of environmental impacts, recyclability and b) generate adequate disposal of such products.

M Phase-out non-essential single use plastics, across Europe

Greywater

M Introduce legislation to ensure that all washing and drying appliances machines in all domestic and industrial applications but also in all ships and vessels (commercial, transport, research,etc) have systems to filter greywater

L Regulate to ensure that new buildings have microplastic filtering systems installed between the greywater and sewage systems

Textiles and Fashion industry

Research

M Identify the materials and garments that release higher quantities of microfibres and phase out those materials and fibres at the design and production stages (selecting for the best performing fabrics)

L Assessment of the environmental impacts of 3D printing of garments at domestic and industrial level, as this technique might increase the sources and a widespread release of microplastics into the environment

Design stage

M Establish mandatory minimum eco-design requirements for textiles and associated manufacturing techniques to help reduce textiles as a source of microplastics

M Incentivise the expansion of reuse/recycling of clothing at both national and European levels (for example rental schemes for formal wear).

L Fund and/or subsidize the creation of textiles from 100% natural fibres

Production

M Legislate to ensure that all industrial washing machines have a microplastic collection system (e.g. filters that collect microplastics).

Plastic supply chain

Raw materials

S — Introduce two levels of mandatory containment for all raw material handling facilities (pellets, powders and flakes). A primary containment barrier around each site and a secondary containment of all identified hotspots within those facilities, using capture equipment to prevent spillage (e.g. protect sewage grates)

M — Introduce audits for plastic supply chains, making it mandatory for all plastic manufacturers, converters, recyclers and pellet handling companies to implement best practices for handling and managing plastic pellets, to prevent, reduce and phase out pellet loss.

Plastic additives

M — Ensure that there is an open access database to all plastic additives, including concentrations and CAS numbers.

Alternative to conventional plastics

S — Alternatives to conventional plastics, namely biobased, biodegradable or compostable plastics to be clearly labelled and include the specific information on the conditions where each are biodegradable and/or compostable.

M — Introduce command and control regulation on mislabelling to ensure that Corporate Social Responsibility and accountability (polluter pay principle) is enforced

L — Use of innovation and research to introduce facilities that biodegrade/compost all new single use plastic alternatives

Packaging

S — Phase out the use of easily fragmentable plastic materials such as oxo-plastics and synthetic polymers in foam

S — Reduction of excessive packaging in products and in delivery services throughout Europe

Recycling

S — Promotion and/or creation of a mandatory national and European deposit refund schemes for plastic bottles, metal cans and glass bottles throughout Europe (e.g. Pfand systems)

Additives

M — Phase out potentially toxic polymers from food packaging, such as PVC, while promoting suitable safe materials in contact with food, that are either reusable or recyclable

L — Ban colourants intentionally added to plastic packaging as part of the EU sustainable product initiative

L — Regulate food packaging to ensure they are toxic-free by design before and after use, i.e. free from all potentially hazardous substances including phthalates, bisphenols, mineral oils, Per- and polyfluoroalkyl substances (PFAs),tNon-intentionally added substances (NIAs), etc.

Transport

Research and design

S — Fund research for a) alternative tyre designs that help to reduce abrasion and sources of microplastics and b) tyre-fitted devices to collect airborne microplastic particles.

S — Tyres that exceed microplastic emission threshold limits to be removed from the market

S — Fund research for alternative brake pads, and friction equipment for all land vehicles (cars, buses, trucks, trains, metros, etc), to reduce the emission of fine particles to the atmosphere

Alternative uses

M — Prohibit the use of tyres in underwater activities, such as aquaculture seeding or artificial reefs

Fisheries and aquaculture

Fishing gear

S Mark fishing gear to reduce discarding of nets and to enable location, identification, recovery and reuse, in line with the Food and Agriculture Organization (FAO) voluntary guidelines

S Systematically reporting of gear lost to public authorities to facilitate data collection and recovery of lost gear

Research and design

M Encourage technological innovations towards developing low impact solutions for systematic tracking of large fishing gear which are more prone to loss and drifting. Similar systems should be in place for aquaculture facilities, particularly after extreme climatic events

Recover and recycle

M Introduce tax incentives to professional fishers who are part of Fishing for Litter schemes in Europe. These programmes shall not incentivise active fishing for litter activities

M Subsidise the recycling of ghost nets and other ALDFG into predetermined standard products, as long as they do not contribute to the spread of toxic chemicals. Risk assessments should be conducted to all materials retrieved from the ocean

M Promote circular design of fishing gear through innovation e.g. through the use of low impact and durable materials or return to use natural fibres in fishing gear

Aquaculture products

L Assess and monitor microplastic concentrations in aquaculture and fishing products

Shipping and Cruise industry

- Establish regulations that prevent the overloading of cargo ships and mandate quality stowage of pellets containing containers below deck onboard ships
- Regulate the release of microplastics in greywater for all ships and vessels (commercial, transport, research, etc)
- European-wide ban on intentionally added microplastics to marine coatings, sealant joints and cleaners used for the scrubbing of hulls.
- Develop a systematic reporting of containers lost at sea through the use of tracking devices on maritime containers and create an open access international database on container loss.
- Apply "Polluter Pays" principle to shipping companies holding them accountable for the clean up and retrieval of containers lost at sea, where non-retrievable a considerable fine is imposed.

Water and wastewater treatment plants

S — Regulate the systematic reporting of biomedia spills

M — Include an amendment to the Urban Wastewater Directive to incorporate the assessment of microplastics in future regulations

M — Set reduction targets for release of microplastics from effluents and any other by-products (fats, sludge, etc) from WTPs and WWTPs into the environment

L — Legislate and introduce regulations to achieve zero emissions of microplastics in WTPs and WWTPS, in all the effluents and any other sub-products (fats, sludge, etc).

Research

S — Regulate the monitoring of WTPs and WWTPs to ensure that microplastics are not released into the environment (e.g. properly sealed pipelines; secured external tank walls; grating system at influent and effluent stages, etc)

Import and export of waste

S — Ban the export of plastic waste outside the EU

M — Create a tracking system for the import and export of waste (e.g. customs form)

M — Facilitate the circular economy model through regulating the sorting of waste by material before exporting

L — Create a custom fee per metric ton of plastic material exported (e.g. €0.01 per metric ton) to facilitate the development of infrastructures in ports and harbours for Fishing for Litter schemes

Recycling

S Mandate the containment of recycling facilities to prevent pellet and microplastic loss

M Set reduction targets for release of microplastics from shredded microplastics from recycling facilities into the environment

L Legislate and introduce regulations to achieve zero emissions of microplastics in recycling facilities

M Create an open access database for all the chemical additives introduced to recycled plastic, including concentrations and CAS numbers

Research

M Fund I&D research into recycling of plastic product to ensure market longevity under a circular economy approach

Solid waste management

- **S** Create low impact collection systems for rivers and freshwater streams for Macroplastics.
- **S** Facilitate and fund deposit-return schemes throughout Europe
- **M** Legislate to mandatory implement deposit-return schemes throughout Europe
- **M** Invest in solid waste management infrastructure across all platforms, including collecting systems (trucks, bins, landfills, etc) to lower the waste generated per capita to 1 kg/day
- **M** Implement non-combustion techniques for the treatment of plastic waste before they are safely landfilled

Monitoring and research

S — Fund inter-calibration exercises focused on different environmental matrices to improve quantification and identification of microplastics in the environment

S — Continue funding long-term environmental monitoring programmes with the recommendation to include indicators to assess microplastic pollution

M — Adapt fisheries monitoring research programmes to assess microplastic accumulation in organisms and use of bycatch

M — Fund microplastics research with the recommendation of taking an ecosystem-based approach for monitoring and to assess impacts, sources, pathways, mitigation and restoration.

Education and outreach

- **S** Incorporate ocean literacy principles, including microplastic pollution, in education curriculums
- **S** Fund and promote citizen science monitoring projects associated with marine litter and microplastic pollution
- **S** Create a forum to allow participation from science experts, civil society groups and non-governmental organisations in national policy-making processes
- **S** Contribute to the establishment of a public access repository for microplastics research (e.g. current methodologies, legislation, reports, and mitigation measures)
- **S** Develop awareness-raising campaigns at the national level on key plastic pollution issues (e.g. reducing consumption, reusing and repairing items, and use of biodegradable, compostable and recycled plastics)
- **M** Include consequences of plastic pollution on anti-litter signage around urban rivers, and coastal and riverine beaches across Europe
- **M** Support national and local public authorities to provide financial incentives or tax reduction to citizens and local businesses who regularly participate in beach, coastal, riverine or terrestrial low impact clean-up activities. The clean-up initiatives should also collect data on the litter collected to help in pollution monitoring

Concluding remarks

It is undeniable the countless socio-economic benefits of plastics in modern society. This versatile material enables global productivity rates and helps to save countless lives every day in hospitals. Nonetheless, as this report highlights, there are many consequences, effects and impacts associated with the use of this material, particularly when our waste management systems are not able to capture plastics, or when these reach microscopic scales in the marine environment.

The sources, pathways, sinks, and hotspots of microplastics in the environment are relatively well studied and it is important that action is taken to minimise, mitigate or reduce their input into the environment. In some cases, it is important to completely rethink their use.

The set of carefully thought recommendations aim precisely at that, reducing inputs and minimising impacts. Predictions and future scenarios can drastically change, as a consequence of societal behaviour changes and political action. For a considerable amount of time, experts have reflected that the use of market-based instruments can be quite beneficial to regulate plastic production and recycling operations, while incentivising consumers to change consumption habits. As mentioned in the foreword, the purpose of this report is to stimulate debate and dialogue among stakeholders and decision-makers, so that European values such as innovation and progress, are reflected in environmental protection, as described in the New European Green Deal.

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Chapter 3 - Monitoring based on expert opinion

See Report information.

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Appendix

Legal frameworks

Legal frameworks, regulations and market-based instruments are essential mechanisms to regulate the use of plastics. The first attempts to regulate all aspects of the ocean, including its resources and uses was made in 1982 with the United Nations Convention on the Law of the Sea (UNCLOS), which focused on a wide range of topics from territorial sea limits, economic jurisdiction, and conservation to management of marine resources (United Nations, 1982). This convention came into force in 1994, and although it did not addressed specifically plastic pollution, it considered plastic as an hazardous material for the marine environment, stating in its Article 210 that the convention obliges member states to develop frameworks to 'prevent, reduce and control pollution of the marine environment by dumping' (Da Costa et al., 2020).

Under the guidance of the International Maritime Organisation (IMO), another international regulatory instrument, the Convention for the prevention of Pollution from ships (MARPOL) came into effect in 1983. OSPAR contains a series of five annexes to address specific problems related to the marine environment. Among them, the first three annexes aim to prevent and eliminate pollution from land-based sources, offshore sources and by dumping or incineration (OSPAR, 2021). One of the most important aspects of this convention was the objective of its Annex V, revised in 2012, aimed at reducing pollution at sea by preventing pollution from ships (UNEP, 2017, Da Costa et al., 2020). Both UNCLOS and MARPOL are legally binding instruments that are guided by the "polluter pays principle", a principle based on the belief that "the costs of preventing, controlling and remedying any pollution is to be borne by the polluter" (UNEP, 2017).

The International Oceanographic Commission (IOC) and the Food and Agriculture Organization (FAO) also developed complementary guidelines on monitoring marine litter and lost, abandoned, or discarded fishing gear (FAO, 2009).

Most action plans include waste management (both solid and liquid waste), fishing for litter schemes, educating communities about marine litter, creating outreach programs, and establishing better Port Reception facilities (Marine litter – descriptor 10 – EU Commission, 2021).

The United Nations Environment Programme (UNEP) has also established a resolution on marine litter and microplastics, based on initiatives that took place in 2015 (UNEP, 2017). And two years later, the United Nations announced a new programme, the Decade of Ocean Science for Sustainable Development, aimed at the sustainable management of coastal areas and oceans, which include marine litter and microplastics (United Nations, 2020). The relevance of this issue is so broad that the G7 recognised plastic pollution as a global threat, and action plans were established to address it (G7, 2018).

In the European context, there are many frameworks established to address the problem of plastic litter in the environment. To promote collaborative action, the UNEP's Regional Seas Convention (RSC), established in 1974, aims to engage neighbouring countries to develop comprehensive actions that are aimed at safeguarding the shared marine environment (Da Costa et al., 2020). Around Europe there are 4 RSCs that have been established:

1. The Barcelona Convention to the Mediterranean Sea
2. The Oslo-Paris Convention (OSPAR) for the Northeast Atlantic
3. The Helsinki Convention (HELCOM) for the Baltic Sea
4. The Bucharest Convention for the Black Sea and

with 22, 15, 10 and 6 member states respectively (Regional Seas Convention - EU Commission 2021). These conventions set up specific objectives to protect the marine environment by preventing and eliminating pollution at regional and national levels (EU Parliament – Think Tank 2020; Regional Seas Convention - EU Commission 2021).

Several other EU regulations have been established to address different aspects of plastic pollution. One of the best tools to keep track and progress of European legislation is the Legislative Train of the European Parliament, as it reflects the progress of the several policy options in Europe. Several initiatives and directives addressing waste management and prevention of marine litter and microplastics have been developed since 2008, particularly the Waste Directive (2008/98/EC), amended in 2018 (2018/851); the Marine Strategy Framework Directive (2008/56/EC), the European Strategy on Plastics in a Circular Economy (2018/2035(INI)), and more recently the new European Green Deal (2019) and the Directive on the reduction of the impact of certain plastic products in the environment (2019/904), often referred to as the Single-Use Plastics Directive.

Among these, the Marine Strategy Framework Directive (MSFD) is one of the most important frameworks, as it was the first of its kind and was aimed at achieving and maintaining Good Environmental Status (GES) in the marine environment by 2020. This legally binding framework came into effect in 2008 (UNEP, 2017), including 11 descriptors focusing on different aspects of the marine environment, of which descriptor 10 exclusively addressed marine litter. Actions under this directive include assessment of marine litter, setting up targets, establishing monitoring protocols, reporting and executing protocols (Marine litter – descriptor 10 – EU Commission, 2021). The activities undertaken by Descriptor 10 of the MSFD are guided by the MSFD Technical group on Marine Litter, where a group of experts assess the effectiveness of action plans and provide guidance on issues such as monitoring and assessments (EU Commission, 2021).

Marine litter is estimated to cost the European economy approximately €630 million yearly in beach clean-up campaigns and around €105 billion in failure to recycle (EU Parliament, 2020). Preventive measures that address single use plastics have the potential to reduce the amount of waste generated and lessen the environmental impact (EEA, 2019).

Considering that plastic packaging accounts for 60% of post-consumer waste in the EU (EU Commission – Strategy for plastics in a Circular Economy), the Union has invested in reducing single-use plastic bags and other single-use products (EU Parliament – Think Tank 2020). Market-based instruments such as the plastic bag levy substantially contribute to significant reductions (Brink et al., 2009; Luís and Spínola, 2010; Schuyler et al., 2018).

The 2019/904 Directive proposed a set of bold measures including bans on selected single-use plastic items (straws, cotton bud sticks, plates and cutlery) as well as in oxo-degradable materials, while establishing measures to decrease the use of food and liquid containers, ensure appropriate labelling of plastic products (concerning recyclability and compostability) and set up "Extended Producer Responsibility Schemes" for products such as tobacco filters and fishing gear (EU Commission, 2021).

Following the implementation of the 2015 EU Plastic Bags Directive (EU Directive 2015/720), taxation on plastic bags is one of the most common and successful market-based instruments that has been established by many national governments.

In 2002, Ireland was the first country to impose a levy on plastic bags. It also witnessed one of most drastic reductions up to 90% in the use of plastic after the enforcement of this legislation (Luís and Spínola, 2010; OECD, 2021). Several European countries gradually followed this tendency and implemented levy's either on the consumer of plastic bags or on the suppliers. The Welsh government introduced in 2011 a mandatory fee on all carrier bags, regardless of the type of material the bag was made. A study from Portugal analysed the influence of the plastic bag fee on the behaviour of consumers using a symbolic fee of €0.02 cents per bag (Luís and Spínola, 2010), which reported a 37% increase in bag reuse and a 52% increase in filling the bags, compared to 17% when the bags were free (Luís and Spínola, 2010). Such findings clearly demonstrate the importance of market-based instruments to change behaviour. Additionally, it is believed that taxes and gradual bans are effective particularly in emerging economies where waste collection and management systems are relatively inefficient (EU Parliament - Think Tank 2020).

In 2018, the European Union adopted an Action Plan for Plastics in a Circular Economy. Circular Economy is a paradigm shift from a traditional linear economic system, where the principle "from cradle to cradle" is upheld. Under the EU strategy for plastics in a Circular Economy, the Commission established targeted measures to make the use of plastics more sustainable (CEAP 2020). In this regard, the Commission proposed guidelines for recycling, establishing measures to reduce waste production especially for products such as packaging, construction and vehicles (CEAP 2020). In the case of packaging waste, the Commission mandates that by 2030 all packaging in the European market should either be reusable or recyclable in an economically practical manner (CEAP 2020). Furthermore, the Commission aims to push for appropriate labelling for plastic packaging, set up protocols for the safe recycling of materials that are used for food packaging and make drinking water more accessible in public spaces to decrease our reliance on packaged water.

Regarding drinking water, a review of the directive that regulates water intended for human consumption is underway, and it is expected to include monitoring of the levels of microplastics (European Parliament, 2021).

In the case of microplastic litter, the Commission aims to restrict intentionally added microplastics to products (ECHA, 2019), implement measures to enhance microplastic capture during the life cycle of the product and establish harmonized protocol to quantify the release of microplastics into the environment, primarily from textiles and tires and finally generate scientific knowledge on the presence and risk of microplastics in food, drinking water and our environment (CEAP 2020).

Finally, the new European Green Deal (EC, 2021) provides an action plan to make EU's economy sustainable based on three principles:

1. No net emissions of greenhouse gases by 2050,
2. Economic growth is decoupled from resource use and
3. No person and no place is left behind.

The Green Deal highlights product eco-design and circular economy approaches to production systems to reduce the amount of generated litter into the marine environment. Although this is the most recent set of policy initiatives in Europe to enable sustainability, a long way has already been made with international conventions and European regulations.

These legal instruments all address plastic pollution by prevention, removal, mitigation and/or education strategies. Prevention of focusses of the 3R rule: reduce at the source, reuse materials, and recycle; removal addresses cleanup actions on beaches, rivers or terrestrial sites; mitigation refers to development of discharge regulations and litter disposal and finally education covers awareness campaigns and economic incentive approaches (Chen, 2015).

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