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Mapping of global plastic value chain and plastic losses to the environment: with a particular focus on marine environment

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Addressing Marine Plastics
A Systemic Approach

Mapping of global plastics value chain and plastics losses to the environment

With a particular focus on marine environment

Acknowledgements

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List of Acronyms

CIS	Commonwealth of Independent States
C&D	Construction and Demolition
EoL	End-of-Life
ELV	End-of-life vehicles
ETRMA	European Tyre & Rubber Manufacturers' Association
EU	European Union
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GDP	Gross Domestic Product
kg	Kilograms
Mt	Million tonnes
MMF	Morgan-Mercer-Flodin model
m3	Cubic meters
MSW	Municipal Solid Waste
NAFTA	North American Free Trade Agreement
NGO	Non-Governmental Organization
OECD	Organisation for Economic Co-operation and Development
PBDE	Polybrominated diphenyl ether
POP	Persistent Organic Pollutants
UN	United Nations
UN Environment	United Nations Environment Programme
USD	United States Dollar
UV	Ultraviolet
WEEE	Waste Electrical & Electronic Equipment
WWTP	Wastewater treatment plant

Types of plastics

ABS	Acrylonitrile butadiene styrene
AKD	Alkyd
ASA	Acrylonitrile styrene acrylate
CA	Cellulose acetate
EPS	Expanded polystyrene
HDPE	High density polyethylene
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
PA	Polyamide
PAN	Polyacrylonitrile
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
POM	Polyoximethylene
PP	Polypropylene
PS	Polystyrene
PMA	Poly methylacrylate
PUR	Polyurethane
PVA	Polyvinyl alcohol
PVAc	Polyvinyl acetate
PVC	Polyvinylchloride
SAN	Styrene-acrylonitrile
SBR	Styrene-Butadiene Rubber

Executive summary

Plastics have become one of the most ubiquitous materials used globally, and global production has on average increased by about 9% per year since 1950.The plastic industry has become a major economic actor with revenue of about 1,722 billion Euros in 2015. The issue of plastics ending up in the oceans and harming marine lifeforms has been known since the 1970s. Research focusing on the impacts associated with exposure of organisms to marine micro- and macroplastics has been ongoing for years. However, studies linking the processes in the plastic value chain to plastics being released to the oceans are only starting to emerge.

Plastics losses from the plastics value chain

This report provides a comprehensive global mapping of plastic losses to the environment throughout the plastic value chain using 2015 as the reference year. This mapping covers plastics production and processing, use of plastics or plastic containing products, and disposal of the products. It differentiates 23 types of plastics and 13 plastic applications, including division between macro- and microplastics (incl. microbeads and microfibers). Global production was about 388 million tonnes (Mt) in 2015. Plastics are primarily produced and consumed in China, North America, and Western Europe. The majority of plastics are used for packaging (30%), building and construction (17%), and transportation (14%). The most used plastic polymers are polypropylene (PP; 16%), low density polyethylene & linear low density polyethylene (LDPE, LLDPE; 12%), polyvinylchloride (PVC; 11%), high density polyethylene (HDPE; 10%), and polyethylene terephthalate (PET; 5%) which in total account for more than 50% of total plastics usage.

It was found that approximately 3.0 and 5.3 million tonnes of micro- and macroplastics, respectively, are annually lost to the environment. The largest sources of microplastic losses were from abrasion of tyres, and city dust, which include abrasion of plastics from e.g. shoe soles, exterior paints, and road markings. The primary sources of macroplastic losses stem from mismanaged municipal solid waste (i.e. open dumping and inadequate landfilling), accounting for about half of the macroplastics lost to the environment. Littering of plastic waste and loss of fishing gears and other equipment related to maritime activities were also major sources of macroplastic losses.

Hotspots with regard to potential impact on the marine environment

Measurements or models providing a link between losses to the environment and subsequent releases of plastics to the oceans are lacking. However, a comparison of the estimated losses to findings of plastics in the environment was conducted to identify possible correspondences between the lost plastic types and those found in the oceans.

The estimated sources of macroplastics losses (i.e. packaging and other consumer goods as well as fishing related equipment) corresponded well with the findings of macroplastics in and near the oceans. Moreover losses of macroplastics from marine activities are also often encountered in the marine environment.

The primary observations of microplastics types in the marine environment were identified to be PP, LDPE, HDPE and PET. The actual sources of these microplastics types are likely a combination of weathering of macroplastics and direct losses to the environment (i.e. as part of city dust, usage of cosmetics and personal care products, and textile washing). A notable exception are polymers related to tyres where, although estimated to be the largest loss of microplastics in this study, reports of observations of these plastics in the marine environment could not be retrieved.

The lost plastic types were also related to information on the potential impacts of micro- and macroplastics in the marine environment providing an indication of the importance of different plastic losses. This allowed for identifying the hotspots in the plastic value chain. Indeed, hotspots were defined based on the estimates of (i) plastic losses to the environment; (ii) a screening review of findings of plastics in the oceans; and (iii) a review of potential impacts of different plastics on the marine environment.Problems of macroplastics mainly relate to ingestion of and entanglement in the plastic pieces by marine animals. The most problematic macroplastics types are bags, fishing lines and nets, and ropes which all correspond well with the estimated losses related to mismanaged waste, littering, and losses from marine activities. These losses also correlate well with findings of macroplastics in the marine environment.

There are numerous potential impacts related to microplastics. Problems of microplastics relate to their ability to cause physical impacts, such as reducing activity/rate/capacity, inducing particle toxicity, adsorbing toxic pollutants, and transporting invasive species. Essentially all plastic types can cause physical impacts, where impacts are primarily related to particle size. PP, HDPE, LDPE and LLDPE, PP-fibers, and PET-fibers were found to be important in terms of microplastics lost to the environment. These microplastics are problematic due to their ability to cause physical impacts. Moreover, potential problems relate to intake of microplastics by marine organisms where potentially hazardous substances may be carried with the microplastic. For instance, residual monomers or additives in the plastic or other chemicals sorbed to the plastics from the surrounding environment. The losses of or introduction of microplastics to the marine environment cannot be related to a specific sector or region. The introduction of microplastics can stem from losses during production of the plastics, or during use of plastic products (e.g. losses of microbeads or microfibers). Moreover, microplastics can be introduced to the marine environment via degradation of macroplastics lost to the environment during their use or end-of-life stage.

Microplastics containing potentially hazardous additives or residual monomers were also identified as a hotspot. PVC, PUR and PAN were found to be the most problematic in terms of containing potentially hazardous residual monomers and additives. Moreover, toxicity from leachate from PVC and PUR has been evidenced in laboratory settings. PVC and PUR are primarily used in building and construction and PUR is additionally used in the transportation sector. Unfortunately, it was not possible to estimate the losses of plastics from these applications. Hence, more information on the disposal of construction and demolition waste and disposal of industrial and machinery waste is needed as losses of plastics, such as PVC and PUR, can pose a hazardous risk to the marine environment.

In summary, for both macroplastics and microplastics, the main hotspots, in terms of potential impacts on the marine environment, were related to the use stage and the end-of-life stage of the plastic value chain. To reduce losses and potential impacts of plastics on the marine environment, it was therefore recommended to prioritise:

i Focus on reducing loss of macroplastics from MSW, in particular plastic packaging. Initiatives should not be limited to the end-of-life stage; instead measures for reducing potential plastic losses at the end-of-life stage should be implemented along the entire plastic value chain. Particular focus should be on regions where the largest losses occur, i.e. Africa, Latin America and the Caribbean, and the Middle East

ii Focus on reducing microplastics losses from use of consumer-related applications. Initiatives should not be limited to the use stage; instead, measures for reducing potential plastic losses during the use stage should be implemented along the entire plastic value chain. Particular focus on the regions North America, China, Asia (excluding Japan, India, and China), and Western Europe which are responsible for the majority of microplastic losses

iii Focus on reducing direct plastic losses from marine activities (e.g. fishing, aquaculture, etc.).

iv Focus on reducing losses of plastics that have been identified to pose a hazardous risk to marine organisms

Technical summary

Project objectives and plastic value chain overview

Plastics have become one of the most ubiquitous materials used globally, and their production has on average increased by about 9% per year since 1950. Global plastics production was about 388 million tonnes (Mt) in 2015. Moreover, the plastic industry is a major economic actor with estimated revenue of about 1,722 billion Euros in 2015, corresponding to about 3% of the global economy. The issue of plastics ending up in the oceans and harming marine lifeforms has been known since the 1970s. Research focusing on the impacts and exposure of organisms to marine micro- and macroplastics has been ongoing for years. However, studies linking the processes in the plastic value chain to plastics being emitted to the oceans are only starting to emerge. This has given some information on the losses of plastics from mismanaged waste and littering in the coastal area, and on losses of microplastics along the global plastics value chain. Moreover, national assessments on losses of micro- and macroplastics to the environment and the oceans have been conducted for a handful of Western European countries (i.e. Norway, Germany, Denmark and Sweden). This report advances these initiatives in providing a comprehensive global mapping of micro- and macroplastic losses to the environment throughout the plastic value chain, as shown in Figure S1, using 2015 as reference year. The plastic value chain contains a number of key stakeholders which are also shown in Figure S1. Moreover, hotspots in the plastic value chain in terms of losses of plastics to the environment are highlighted.

With regard to identifying hotspots for potential impacts on the marine environment from the plastic value chain, this study consisted of two primary steps.

First, a top-down approach for estimating global losses of plastics to the environment across the plastics value chain. The top-down approach drew on relevant information from previous mapping studies about main sources of plastics losses. Specific models for deriving global estimates of plastic losses were developed to complement this approach, for instance, for predicting municipal solid waste generation and for estimating microplastics removal in wastewater treatment plants. As a second major step, the resulting losses from the top-down approach were compared to studies reporting findings of micro- and macroplastics in the oceans. That bottom-up attempt at validating the quantified losses fed into identification the most problematic micro- and macroplastics, in terms of potential impact on marine environment, using scientific literature.

Based on the estimates of (i) plastic losses to the environment; (ii) the brief review of findings of plastics in the oceans; and (iii) the review of impacts of different plastics on the marine environment, the potential key hotspots in terms of losses to the environment from the plastic value chain and potential impact on the marine environment could be indicated.

Global mapping of plastic production and consumption

Based on available statistics on plastics production, consumption, and usage retrieved from industry reports and scientific literature, the value chain characterisation was differentiated into 23 types of plastics (e.g. PS,

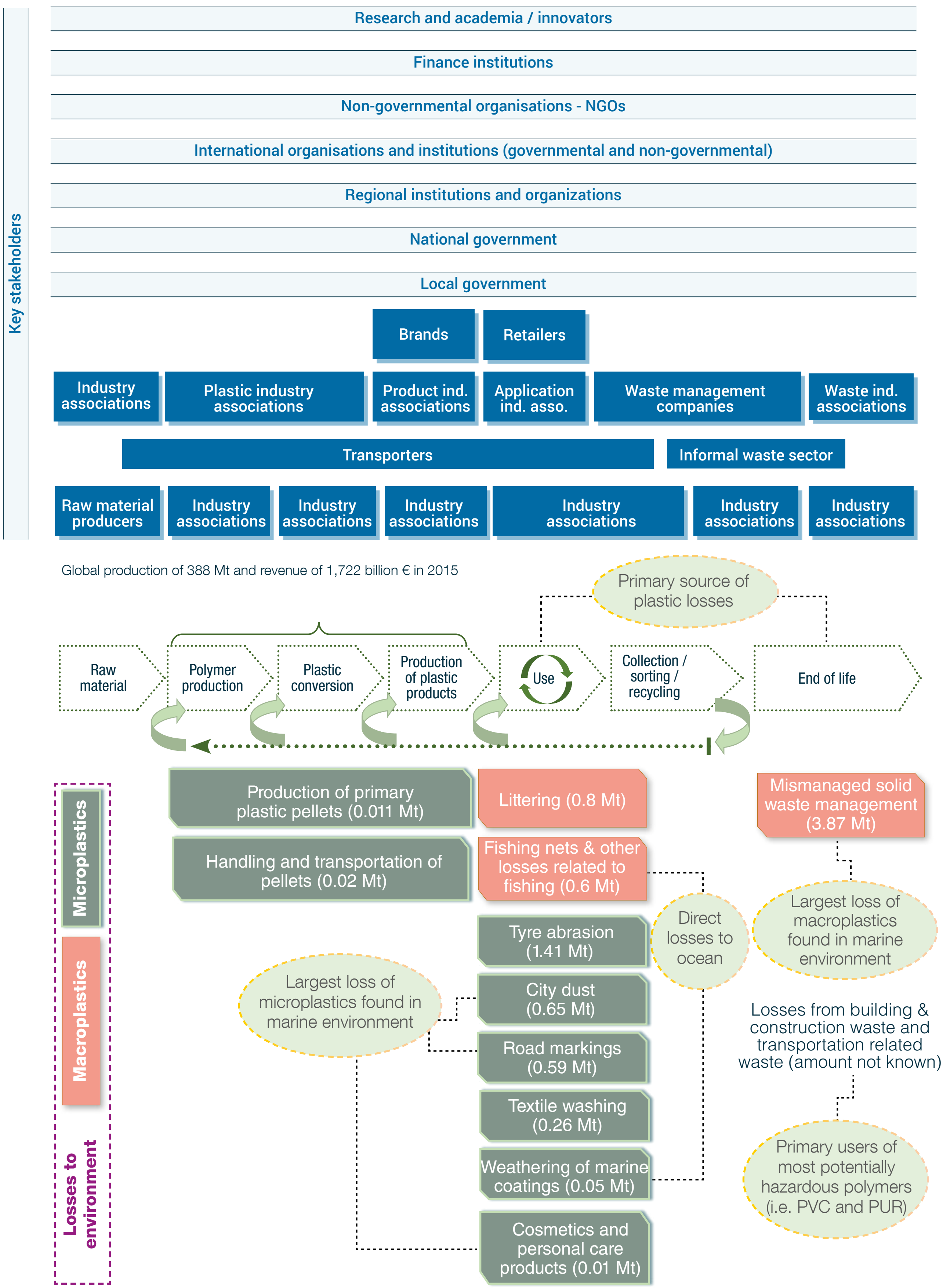

Figure S1. Overview of key value chain stages and stakeholders/interest groups associated with each value chain stage. Amounts of micro- and macroplastics lost to the environment are based on findings in Chapter 6. The identified key hotspots as presented in Chapter 9 are indicated with yellow circles.

PP, PVC, etc.), 13 types of applications (e.g. packaging, building and construction, and personal care products) and 11 geographical regions (e.g. Western Europe, North America, and China). The global mapping shows that the majority of plastics are produced in China, North America, and Western Europe with 28%, 19%, and 19%, respectively. These regions are also the major plastics consumers with 20%, 21%, and 18% for China, North America, and Western Europe, respectively. The most used plastic polymers are polypropylene (PP; 16%), low density polyethylene & linear low density polyethylene (LDPE, LLDPE; 12%), polyvinylchloride (PVC; 11%), high density polyethylene (HDPE; 10%), and polyethylene terephthalate (PET; 5%) which in total account for more than 50% of total plastics usage. The main applications of plastics are for packaging, building & construction, and transportation which cover 30%, 17%, and 14%, respectively, of total plastics usage in 2015.

Plastic losses from the plastic value chain

The estimations of plastic losses throughout the plastic value chain were based on available sources of information from the plastic industry and scientific literature. First, information on losses was drawn from the previous but more restricted (i.e. restricted to specific plastic type, location in value, chain or geographical location) assessments on plastic losses related to different value chain stages. To obtain a comprehensive global assessment, data gaps were filled using information from scientifically based literature to derive estimates of losses from other value chain stages.

Plastic losses related to polymer production and final plastic commodity production were assumed similar across regions as the plastic production technology was assumed to be independent of the country of production. Virgin plastic pellets are lost during production, handling, and transportation of the plastics. Losses occurring indoor as part of production, were modelled as going to the drain of the production facility while losses during handling and transportation were assumed to go directly to the environment. Macroplastic losses related to plastic usage included the littering of plastics, including loss of fishing nets, and other losses related to fishing and maritime activities. Microplastic losses related to plastic usage included microbeads from use of cosmetics and personal care products, rubber from tyre abrasion, weathering of marine coatings, microfibers from washing of textiles, abrasion of road markings, and city dust which include abrasion of plastics from e.g. shoe soles, exterior paints, and road markings. Losses were modelled using region-specific information, such as the share of population connected to wastewater treatment and wastewater treatment technology level.

Information on plastic losses related to the end-of-life treatment of plastic using applications was generally lacking and could only be estimated for plastic applications likely to be treated as part of the MSW fraction, i.e. packaging, electronics, consumer & institutional products (e.g. dinner and kitchenware, toys and sporting goods), and textiles (e.g. clothing). The annual MSW generation, the share of plastic in the MSW, and the waste treatment distribution were determined for each region. Mismanaged waste was defined as open dumping as well as landfilling in low income countries. Based on previous studies, it was assumed that 10% of the mismanaged plastic waste is lost to the environment. A number of potentially important sources of plastic losses could not be quantified due to lack of data. A potential key source is the loss of plastics related to use of floats and other equipment from e.g. marinas and aquaculture. These may be important in terms of micro- and macroplastics as these losses go directly to the oceans and are often made from polystyrene where potential leachate of residual styrene monomers pose a hazard risk to marine organisms.

Overall, it was found that about 3.0 and 5.3 Mt of micro- and macroplastics, respectively, are annually lost to the environment. The primary sources of microplastic losses can be attributed to abrasion of tyres and city dust, which include abrasion of plastics from e.g. shoe soles, exterior paints, and road markings. Figure S2 illustrates those trends through a Sankey diagram. It links the identified sources of micro- and macroplastic losses to their receiving environmental compartment, whenever that one could be specified (see dotted arrows, where no data could be retrieved).

For abrasion of tyres, the most contributing regions are North America, China, Asia (excluding Japan, India, and China), and Western Europe which account for 20%, 18%, 14%, and 13% of the total losses, respectively. Losses related to city dust are driven by population number and the regions most associated with losses of these microplastics are Africa, Asia (excluding Japan, India, and China), China, and India which account for 22%, 21%, 20%, and 14% of the total losses, respectively. The primary sources of macroplastic losses stem from mismanaged MSW which account for about half of all macroplastics lost to the environment. The macroplastics from mismanaged MSW lost to the environment primarily stem from Africa, Latin America and the Caribbean, and the Middle East which all have a high level of plastic consumption and harbor a large fraction of inadequately managed MSW. For microplastics, the most contributing regions were North America, China, Asia (excluding Japan, India, and China), and Western Europe which account for 16%, 20%, 14%, and 11% of the total microplastic losses, respectively. The losses of microplastics are mainly driven by large population and per-capita plastic consumption in these regions (more information on geographical contribution is provided in table S2).

Measurements and models providing a link between losses to the environment and subsequent releases of plastics to the oceans are lacking. As an alternative, a bottom-up approach was applied where findings of plastics in the environment were compared to the estimated losses of plastics to the environment. This bottom-up approach generally showed a good correspondence between the lost plastic types estimated in this study and those reported to be found in the oceans.

With regard to macroplastics, the majority of plastics-related findings in the ocean or in coastal areas can be attributed to general consumer goods for recreational activities and fishing- and maritime-related activities that have been lost through either littering or inadequate waste management. The plastics found corresponded well with the main sources of macroplastics that are related to maritime activities and short-lived consumer goods ending up in MSW systems, including packaging.

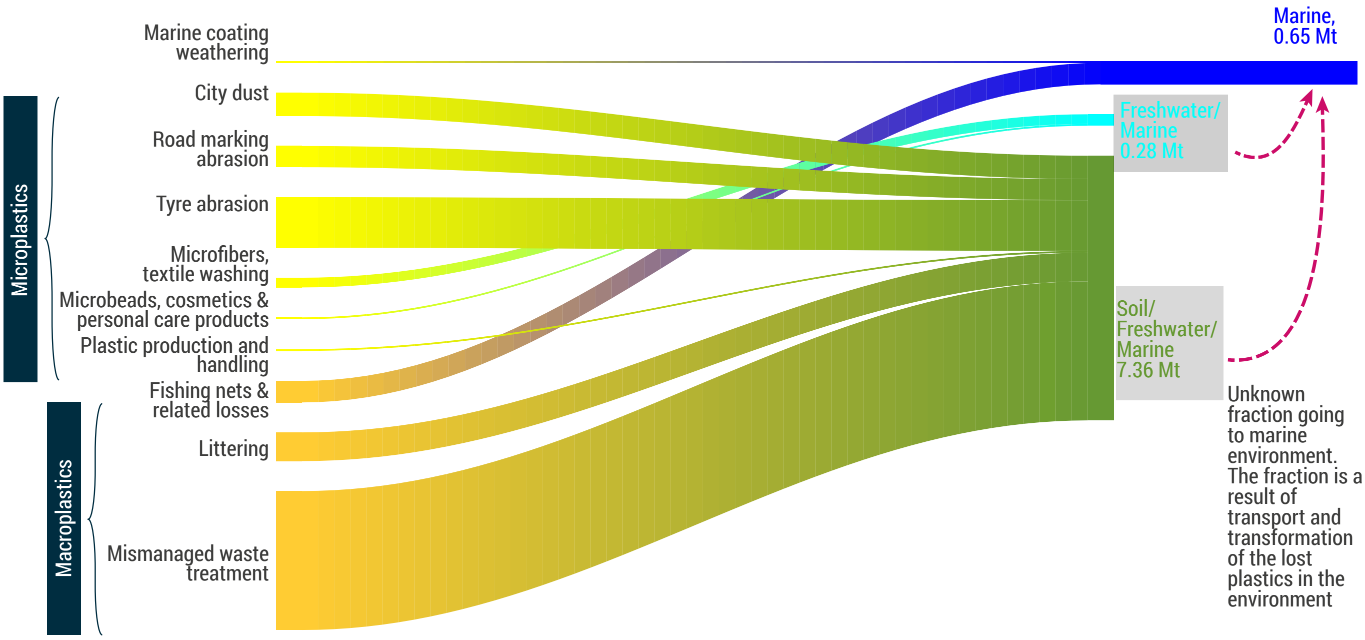

Figure S2. Sources of plastic losses and the environmental compartments to which the plastics are lost

With regard to microplastics, the primary findings of microplastics in the marine environment were PP, LDPE, HDPE and PET. These findings corroborate the theory that most microplastics stem from weathering of lost macroplastics as the identified plastic types are often used in macroplastics related to ocean/maritime activities and short-lived consumer goods part of MSW, such as packaging. The findings of microplastics also correspond well with the estimated losses of microplastics from city dust, use of cosmetics and personal care products, and textile washing. The reported findings of PP, nylon and PS are likely to also be a result of weathering of macroplastics from fishing nets, fishing gears, floats, and other equipment related to maritime activities which are directly lost to oceans. An exception was polymers related to tyres where, although estimated to be the largest loss of microplastics, reporting of these plastics in the marine environment could not be retrieved.

Effects of micro- and macroplastic on marine organisms

The unit of mass of macro- and microplastics in the oceans is not an appropriate indicator of impacts, as it does not capture the actual damages to environment and human health and their dependence on the type and properties of the plastics. A necessity when aiming to identify hotspots and make sound decisions is therefore to understand the impacts of different plastic types on the marine environment.

Macroplastics impact all types of marine animals such as invertebrates, fish, reptiles, birds, mammals, and amphibians. Macroplastics in the oceans are particularly problematic because the physical characteristics of the macroplastics can lead to animals being entangled in the plastic or ingesting the plastics, thus ending up by killing themselves. Most animals killed by marine plastics are undiscovered as the animals either sink to the bottom (e.g. fish) or are eaten by other animals making it near-impossible to observe and monitor the extent of the impacts, especially when considering the large ocean area over which the affected animals may spread. In addition, macroplastics can be degraded into microplastics in the oceans and, thereby, cause impacts as microplastics. The most problematic macroplastic types appear to be bags, fishing lines and nets, and rope. These all correspond well with estimated losses and with the dominating findings of macroplastics in the marine environment.

There are numerous potential impacts related to microplastics. Problems relate to intake of microplastics by the marine organisms where potentially hazardous substances may be carried with the microplastic. For instance, residual monomers or additives in the plastic or other chemicals sorbed to the plastics from the surrounding environment. The hazardous chemicals can potentially leach from the microplastics and be taken up by the marine organisms, thereby, causing adverse toxic effects. There are also potential physical impacts related to the microplastics, such as reduction in feeding activity/rate/capacity, moreover, the plastic particles may also be taken up in organs, cells and tissues (e.g. through uptake of nano-sized plastic particles) which can lead to particle toxicity. Essentially all plastic types can cause physical impacts, where impacts are primarily related to physical microplastic characteristics, such as particle size. With regards to hazardous chemicals, due to the potential leaching of additives from polymers, a particular focus should be on limiting losses of PVC as the majority of additives are used in PVC. Moreover, the monomers related to production of PUR, polyacrylonitrile (PAN; e.g. used as part of acrylic fibers and for production of ABS, SAN and ASA), and PVC plastics were ranked highest in terms of hazardousness. Hence, a particular focus should be on reducing residual monomer content when producing these plastics and to limit general losses of these plastics. Microplastic debris may also provide a substrate for organisms which may drift long distances and pose an ecological impact via transport of non-native species. In general, knowledge about the impacts on microplastics on the marine environment is still lacking and further research on the different potential impacts is required.

Hotspots in terms of potential impact on the marine environment

Hotspots in the plastic value chain were defined based on the estimates of (i) plastic losses to the environment; (ii) a screening review of findings of plastics in the oceans; and (iii) a review of potential impacts of different plastics on the marine environment. Table S1 provides an overview of the quantified losses to the environment, also indicating the main polymer types, plastic application categories, and potential impacts associated with the losses.

For macroplastics, in terms of potential impacts on the marine environment, bags, fishing lines, fishing nets and ropes where identified as being the most problematic as animals are affected via ingestion of or entanglement. These macroplastics types can all be attributed to losses during the end-of-life and use stage of the plastic value chain and are also commonly found in the marine environment. Another potentially important hotspot is the direct losses of macroplastics from marine activities. Although the amounts are relatively low compared to other losses, plastics are lost directly to the environment and often reported in samples of marine plastics. Moreover, losses from marinas and aquaculture, in particular polystyrene floats, were not quantified due to lack of data. However, float and buoys are often found as part of marine debris (see Table 20) and the emissions are judged too important because they are lost directly to the marine environment and because leaching of styrene monomers and oligomers from polystyrene has been shown, thus, also posing a potential hazard risk to marine organisms.

PP, HDPE, LDPE and LLDPE, PP-fibers, and PET-fibers were found to be important in terms of microplastics lost to the environment. These microplastics are problematic due to their ability to cause physical impacts, such as reducing activity/rate/capacity, inducing particle toxicity, adsorb toxic pollutants, and transport invasive species. The actual source of these microplastic types found in the marine environment is likely a combination of weathering of macroplastics and directly lost microplastics (i.e. as part of city dust, usage of cosmetics and personal care products, and textile washing). Microplastics containing potentially hazardous additives or residual monomers were also identified as a hotspot. PVC, PUR and PAN were found to be the most problematic in terms of containing potentially hazardous residual monomers and additives. Moreover, toxicity from leachate from PVC and PUR has been shown in laboratory settings. PVC is primarily used in building and construction and PUR is primarily used in building and construction and transportation. Unfortunately, it was not possible to make estimates on the losses of plastics from these applications. Hence, more information on the disposal of construction and demolition waste and disposal of industry and machinery waste is needed as losses of plastics, such as PVC and PUR, can pose a hazardous risk to the marine environment.

In conclusion, for both macroplastics and microplastics, the main hotspots, in terms of losses and potential impacts on the marine environment, are related to the use stage and the end-of-life stage of the plastic value chain. The macroplastics related to losses from these stages are important in terms of impacts on marine organisms. The microplastics lost are primarily PP, HDPE, LDPE and LLDPE, PP-fibers, and PET-fibers which, although not hazardous, are important with regards to physical impacts related to microplastics in the marine environment.

To reduce losses and potential impacts on the marine environment, it was therefore recommended to:

i Focus on reducing the loss of macroplastics from MSW, in particular plastic packaging. Initiatives should not be limited to the end-of-life stage; instead measures for reducing potential plastic losses at the end-of-life stage should be implemented along the entire plastic value chain. Particular focus should be on regions whether the largest losses occur, i.e. Africa, Latin America and the Caribbean, and the Middle East

ii Focus on reducing microplastics losses from use of consumer-related applications. Initiatives should not be limited to the use stage; instead, measures for reducing potential plastic losses at during the use stage should be implemented along the entire plastic value chain. Particular focus on the regions North America, China, Asia (excluding Japan, India, and China), and Western Europe which are responsible for the majority of microplastic losses

iii Focus on reducing direct plastic losses from marine activities (e.g. fishing, aquaculture, etc.)

iv Focus on reducing losses of plastics that have been identified to pose a hazardous risk to marine organisms

Table S1. Summary table of sources of plastics losses to the environment and the life-cycle stages related to the loss, indicating the amounts lost to the environment and whether micro- or macroplastics are lost. Moreover, the main polymer types, plastic application categories, and potential impacts associated with the loss are indicated. The table is sorted as after macro- and microplastics lost and, hereafter, sorted in descending order based on amount lost.

Sources of plastic losses to the environment	Related life-cycle stage	Amount lost	Micro- and/or macroplastics lost	Main polymer types associated with loss	Plastic application categories associated with loss	Main potential impacts associated with plastic losses to marine environment
Mismanaged waste treatment	End-of-life stage	3.87 Mt	Macroplastics	PP, LDPE & LLDPE, HDPE, PET, PP fibers	Packaging, Electrical/ Electronic, Consumer & Institutional Products, Textile (Clothing and Others)	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from weathering of macroplastics
Loss of plastic from littering	Use stage	0.8 Mt	Macroplastics	PP, LDPE & LLDPE, HDPE, PET, PP fibers	Packaging, Electrical/ Electronic, Consumer & Institutional Products, Textile (Clothing and Others)	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from weathering of macroplastics
Fishing nets and other losses of fibers related to fishing	Use stage	0.6 Mt	Macroplastics (0.0003 Mt of microplastics from abrasion of dolly ropes)	Only possible to quantify losses for PA fibers	Marine/maritime related activities	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from dolly ropes and weathering of macroplastics
Loss of rubber from tyre abrasion	Use stage	1.41	Microplastics	Tyre elastomers (e.g. SBR)	Transportation - Tyres	Physical impacts related to microplastics. Likely more related to impacts of very small (likely micro and nano-sized) particles
City dust	Use stage	0.65	Microplastics	• Losses are likely to occur for all polymer types. Top five polymers lost are believed to be PP, • LDPE & LLDPE, PVC, HDPE, and not specified thermosets	• Paints and protective coatings for exterior use. • Textiles and other dust generating applications. Clothing with relation to shoe ole abrasion. • Road use (related to road wear)	Physical impacts related to microplastics
Road markings	Use stage	0.59	Microplastics	Road markings (specific polymer types are unknown)	Road marking application	Physical impacts related to microplastics
Loss via washing of textiles	Use stage	0.26	Microplastics	PP fibers, PET fibers, PA fibers	Clothing and textile application	Physical impacts related to microplastics (synthetic fibers)
Loss through weathering of marine coatings	Use stage	0.05	Microplastics	Marine coatings (specific polymer types are unknown)	Marine coating application	Physical impacts related to microplastics. Potential hazardous impacts for certain coatings, e.g. epoxy coatings (Lithner et al., 2012)
Loss of plastic during upstream plastic production (Virgin plastic pellets)	Production stage	0.03	Microplastics	All polymer types. Top five polymers lost are PP, LDPE & LLDPE, PVC, HDPE, and not specified thermosets	Not relevant. Loss occurs before application	Physical impacts related to microplastics. Potential toxic impacts related to losses of virgin microplastics containing hazardous additives or residual monomers.
Microbeads lost to environment from use of cosmetics and personal care products	Use stage	0.01	Microplastics	PP, PE, HDPE, PA	Cosmetics and personal care products	Physical impacts related to microplastics

Table S2. Source of losses of macro- and microplastic to the environment distributed into geographical regions

Micro- or macro-plastic	Source of loss	Share of total loss [%]											Total loss [Mt]
		NAFTA (incl. rest of North America)	Western Europe	WJapan	Central Europe & CIS	Asia (excl. Japan, India, and China)	Africa	Latin America & Caribbean	Oceania	India	China	Middle East	
Macroplastics	Loss of plastic to environment from mismanaged waste treatment	0%	0%	0%	0%	13%	24%	23%	0%	10%	10%	19%	3.87
	Loss of plastic from littering	11%	17%	3%	7%	18%	6%	18%	1%	3%	7%	9%	0.80
	Fishing nets and other losses of fibers related to fishing	Global estimate, no information about the regions where losses occur											0.60
	Total macroplastics	2%	3%	1%	1%	14%	21%	22%	0%	9%	9%	18%	5.27
Microplastics	Microbeads lost to environment from use of cosmetics and personal care products	10%	3%	1%	6%	17%	16%	8%	1%	9%	22%	6%	0.01
	Loss of rubber from tyre abrasion	20%	13%	2%	12%	14%	3%	6%	1%	6%	18%	5%	1.41
	Loss through weathering of marine coatings	22%	18%	4%	4%	6%	6%	10%	0%	4%	19%	5%	0.05
	Loss via washing of textiles – clothing	13%	3%	1%	8%	20%	3%	5%	1%	12%	27%	6%	0.26
	Road markings	22%	18%	4%	4%	6%	6%	10%	0%	4%	19%	5%	0.59
	City dust	3%	1%	0%	5%	21%	22%	8%	0%	14%	20%	6%	0.65
	Loss of plastic during upstream plastic production (Virgin plastic pellets)	17%	15%	4%	2%	9%	6%	5%	0%	11%	28%	2%	0.03
	Total macroplastics	16%	11%	2%	9%	14%	8%	7%	1%	8%	20%	5%	3.01

1

Introduction

The problems of marine plastic debris and its impact on the marine environment has been acknowledged as a major concern at least since 1984 (Shomura and Yoshida, 1985). In spite of being aware of the problem since the 1970s, e.g. Baltz and Morejohn (1976), Carpenter et al. (1972), and Carpenter and Smith (1972), the problem remains and research on the impacts and drivers of the problem is still ongoing trying to close the knowledge gaps that still exist.

Marine plastic debris can generally be classified into two types of plastics, i.e. microplastics and macroplastics. Microplastics are tiny plastic particles smaller than 5 mm in size (Arthur et al., 2009). Two types of microplastics exist.

- Primary microplastics are plastic particles which were originally manufactured to be that size (i.e. primary) and purposely used for particular industrial or domestic application such as exfoliating facial scrubs, toothpastes and abrasive blasting (GESAMP, 2015). Thus, microplastics are released into the environment in the form of small particulates.
- Secondary microplastics are microplastics originating from the breakdown of larger plastic items (i.e. secondary) either in the ocean or during transport from where it is lost to the ocean. Degradation occurs through weathering of the plastic pieces from e.g. sunlight, wind, and water (Auta et al., 2017; Boucher and Friot, 2017; GESAMP, 2015).

The other type of plastic is macroplastics which are all plastics above 5 mm. In a global coastal clean-up, the majority of litter types were found to be cigarette buds (cellulose acetate) and various packaging types, incl. plastic packaging (Ocean Conservancy, 2011). Indeed, macroplastics are easily visible and pose a large aesthetic problem as it is washed up on beaches and coastal areas. Besides the aesthetic problems, macroplastics are harmful to animals living in or near the ocean because the animals may ingest or be entangled in the plastics (CBD & STAP - GET, 2012; Laist, 1997)

During the last five years a number of studies on the anthropogenic sources of marine debris have been conducted. National assessments on the losses of plastics to the environment and to oceans have been conducted for Germany (Essel et al., 2015), Denmark (Lassen et al., 2015), Sweden (Magnusson et al., 2016), and Norway (Sundt et al., 2014). Moreover, global assessments have been made on the plastic losses related to waste treatment (Jambeck et al., 2015) and on microplastics across the entire plastic value chain (Boucher and Friot, 2017). Studies on the transport of plastics from rivers to oceans have also been conducted (Cable et al., 2017; Lebreton et al., 2017; Schmidt et al., 2017). These assessments have contributed to a better understanding of the amounts of plastics released to oceans and which stages in the plastic value chain that contributes to the largest releases of plastics to the oceans.

1.1. Objective

The primary objective of this study is to provide a global mapping of the plastic value chain and quantify the global losses of plastic across the value chain to the environment using 2015 as reference year.

The mapping will draw on and combine information from previous assessments on plastic losses which are either restricted to national scale or only focus on specific subsets of the total value chain and associated losses (i.e. waste management and primary microplastics). However, this study will go one step further in providing a comprehensive mapping of global scale losses of both macro- and microplastics across the plastic value chain. The estimates of losses to the environment were conducted as an iterative process where initial estimates were made to get an idea of the magnitude of the losses from different activities in the plastic value chain. The most important losses were, hereafter, re-visited and additional information was collected to obtain a more solid estimate of the plastic losses.

Moreover, the findings on plastic releases to the environment will be complemented with a qualitative assessment of the types of plastic found in the oceans and the impacts of micro- and macroplastics on marine organism to identify the most important stages of the plastic value chain where losses occur and to identify the most critical plastic types lost from the value chain. The findings of the study are used to provide recommendations aimed at decision-makers in governments and industry on where to place focus and possible measures for reducing effects of plastics on the marine environment.

1.2. General methodology

The study consist of two primary steps with regards to quantifying the global losses of plastic across the value chain to the environment and identifying the most important stages of the plastic value chain in terms of potential impact on the marine environment.

First, a top-down approach for estimating global losses of plastic to the environment across the plastics value chain. Second, comparison of the estimated losses with studies reporting findings of micro- and macroplastic in the oceans was made. Finally, an identification of the most problematic micro- and macroplastics, in terms of potential impact on marine environment, was conducted based on scientific literature.

Top-down approach for estimating losses of micro- and macroplastics

The top-down approach was used for estimating the losses of micro- and macroplastics along the plastics value chain. Here, information on global plastics production and usage, differentiated on plastic types, were combined with information on regional plastic consumption to derive a global regionally differentiated indication of plastic production, use, and end-of-life. The was primarily derived based on Geyer et al. (2017) but coupled with more specific data on processes and plastic types that were deemed important in relation to marine plastics (see Chapter 3 and Chapter 4).

Based on the global estimate of plastic production, use, and end-of-life, information from the previous studies on losses of plastics (i.e., Boucher and Friot, 2017; Essel et al., 2015; Jambeck et al., 2015; Lassen et al., 2015; Magnusson et al., 2016; Sundt et al., 2014) were used to identify the main sources of losses. With regards to the sources of losses found in the previous studies, the methodologies applied in those studies as well as new models specifically made for this study were used to derive global estimates of plastic losses (described under the relevant section in Chapter 6).

The models derived in this study, for instance includes modelling of treatment of wastewater and microplastics removal efficiency, and modelling of generation of municipal solid waste and treatment of the solid waste. Indeed, a number of assumptions were necessary to derive global estimates of plastic losses along the full plastics value chain, for instance, extrapolation of regional data to global scale. Hence, the data used, calculations, and choices for deriving global estimate in this study are provided in the report and described when first used.

It needs to be stressed that this report only provide an indication of the total global losses and that these estimates comes with a large degree of uncertainty. To reduce this uncertainty, more specific information is needed. For instance, specific data on waste treatment were not available at an aggregated level and such data is likely only available at local levels. Obtaining data at such high resolution for all processes for which plastics are lost was not within the scope of this project. Nevertheless, this study provides a realistic estimate of the global losses and a very valuable result of this project is to identify the main sources of plastic losses. This allows for focusing on retrieving detailed data for processes which are actually relevant in terms of plastic losses, thereby avoiding focusing on getting very detailed data for processes that in the bigger picture do not contribute significantly to the problem of marine plastic.

Comparison of losses with findings of plastics in marine environment and potential impact on marine environment

To get an idea about the plastic types lost to the environment which actually reach the marine environment, the estimated losses to the environment were compared with retrieved information about the primary plastic types found in marine environment (Chapter 7). This comparison between the estimated losses and reporting of plastics in the ocean was done because it was not possible to estimate the share of the plastics lost to the environment that are eventually lost to the marine environment. However, in this way, it was possible to indicate the plastic losses actually ending up in the ocean and, therefore, indicate which sources of plastic losses to focus on with regard to reducing losses to the oceans. The information on findings of plastics in the marine environment does not provide complete coverage of all plastics found in the marine environment. However, it does provide a good indication of the main types of plastics, thereby, allowing better understanding of the most important losses.

The mass of macro- and microplastics released to the oceans are not an appropriate indicator of impacts, as it does not reflect the actual damages to the environment. Hence, information on the potential impacts on marine environment of different macro- and microplastics was retrieved to facilitate an assessment of the most problematic plastic losses from the value chain and findings of plastics in the marine environment (see Chapter 8). Although, a complete understanding of the impacts of micro- and macroplastics on the marine environment is still lacking, we base this indication on scientifically based literature on the potential impacts of micro- and macroplastics on the marine environment. This allows for indicating which types of plastic are most problematic and, thus, which losses that should be reduced.

1.3. Report structure

The report is structured in a logical manner where **Chapter 1 and 2** provides a general introduction to the plastic value chain and the problem with marine plastics. Chapter 2 also provides information on the central actors related to the global plastics value chain.

Chapter 3 to 5 provides a comprehensive overview of global plastics production, use, and end-of-life. Information on the plastics is distributed into 23 plastic types, 13 plastic applications, and 11 geographical regions.

Chapter 6 provides detailed calculations and estimates on the losses of plastics to the environment related to production, use, and end-of-life stage of the plastic value chain. Section 6.4 gives a full overview of all losses and the magnitude of the different losses relative to total losses to the environment.

Chapter 7 provides an overview of studies reporting findings of plastics in the oceans. The findings are related to the losses estimated in Chapter 6 to get an idea about the plastic types lost to the environment which actually reach the marine environment.

Chapter 8 provides a brief review of potential environmental impacts related to macroplastics and microplastics in the oceans. The chapter presents they main effects related to macro- and microplastics. Moreover, the most problematic types of microplastics and macroplastics are indicated.

Chapter 9 provides an overview of the hotspots in the plastic value chain. Hotspots were defined based on the estimates of (i) plastic losses to the environment; (ii) a screening review of findings of plastics in the oceans; and (iii) a review of potential impacts of different plastics on the marine environment. Hence, Chapter 9 draws on the findings of Ch. 6, Ch.7, and Ch. 8.

Chapter 10 presents further research needs required for improving the assessment. This includes improved data for quantifying losses of plastics to the environment. The need for models to characterize the fate and effect of plastics on the marine environment are also highlighted.

Chapter 11 provides recommendations on how to reduce losses of plastics and potential impacts on the marine environment based on the findings of the report.

2

Global plastics value chain

Chapter highlights

- The global plastics industry had an estimated annual revenue of 1,722 billion Euro in 2015
- Main stakeholders are plastic producers, consumers and waste managers. Other important stakeholders are industry associations and regional, national, and international governmental and non-governmental institutions

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The Global plastics value chain ranges from the extraction of raw materials for plastics production to final disposal of the plastic- or plastic containing products. Figure 1 provides a schematic overview of the Global plastics value chain and indicates the key stakeholder associated with plastic production, consumption and end-of-life (EoL). Key actors are the plastic producers and processors, as well as the plastic industry associations, such as PlasticsEurope. Annual revenue for the plastics industry in EU28 (PlasticsEurope, 2016a) and USA (The Plastics Industry Trade Association, 2016) was extrapolated to global level based on the market share of EU28 and USA. Thereby, the Global plastics industry was estimated to have an annual revenue of 1,722 billion Euro in 2015 which correspond to about 3% of the total world economy in 2015 (Janßen et al., 2016).

With regards to the plastic- and plastic containing products, industries and consumers who use the products are key actors who can influence and put pressure on plastic producers and processors based on their consumption choices. The EoL actors are the companies and governments responsible for managing the plastic waste. Plastic waste management is likely to be dominated by public waste management for consumer-citizen plastic waste, which is often collected as part of the municipal solid waste (MSW) either as part of mixed residual waste or as a separate plastic fraction. Private companies are more likely to be dominating waste management from industries where the plastic fraction often consists of only few plastic types while impurities from other waste fractions is also low compared to citizen waste, thus, making it more suited for recycling. Running across the entire value chain is national and international governmental bodies as well as other non-governmental institutions. These can influence all parts of the plastic value chain (i.e. production, consumption, and EoL) through different measures. This can, for instance, be by implementing legislation, setting targets that should be met or otherwise applying pressure on the involved actors.

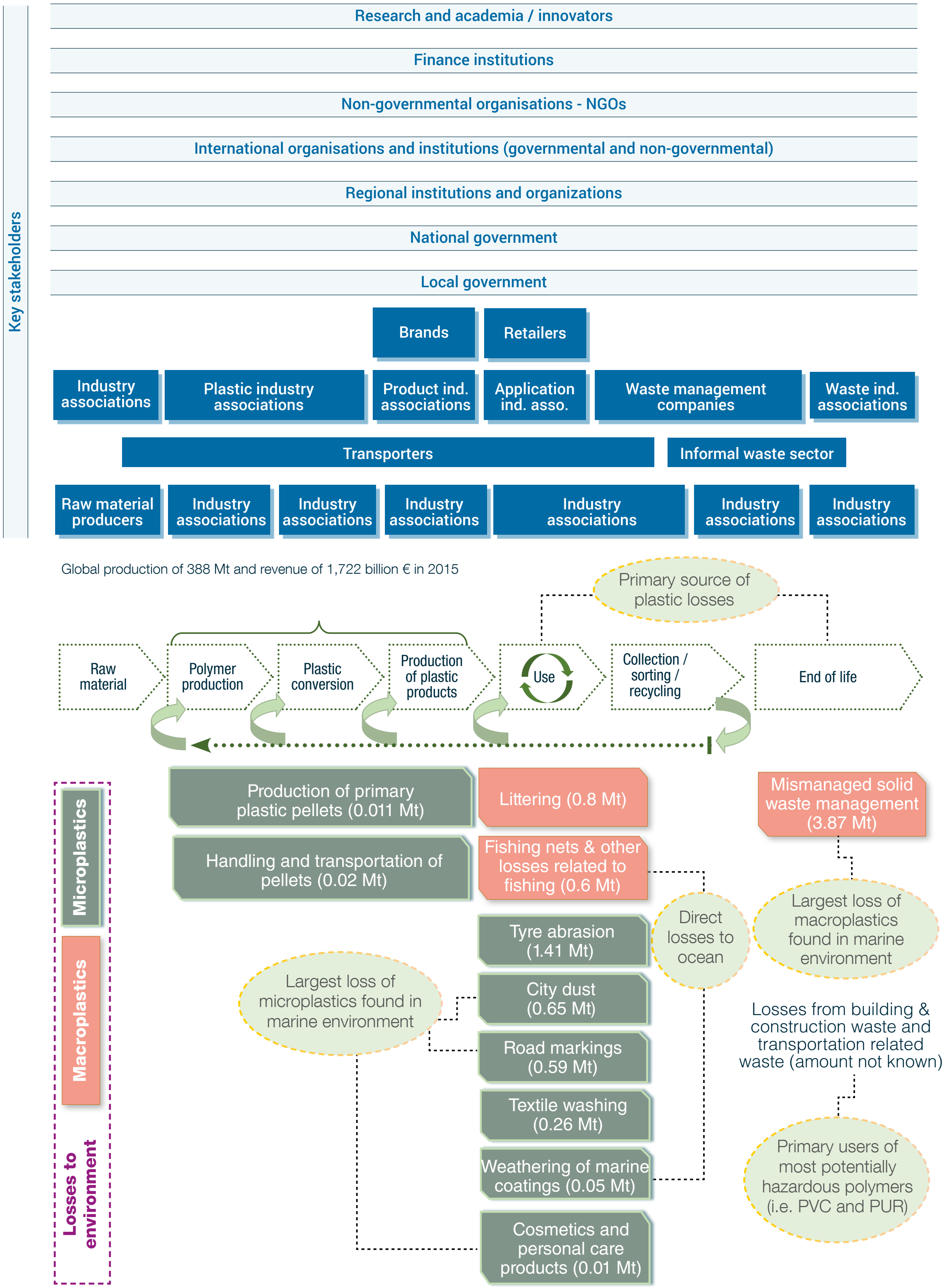
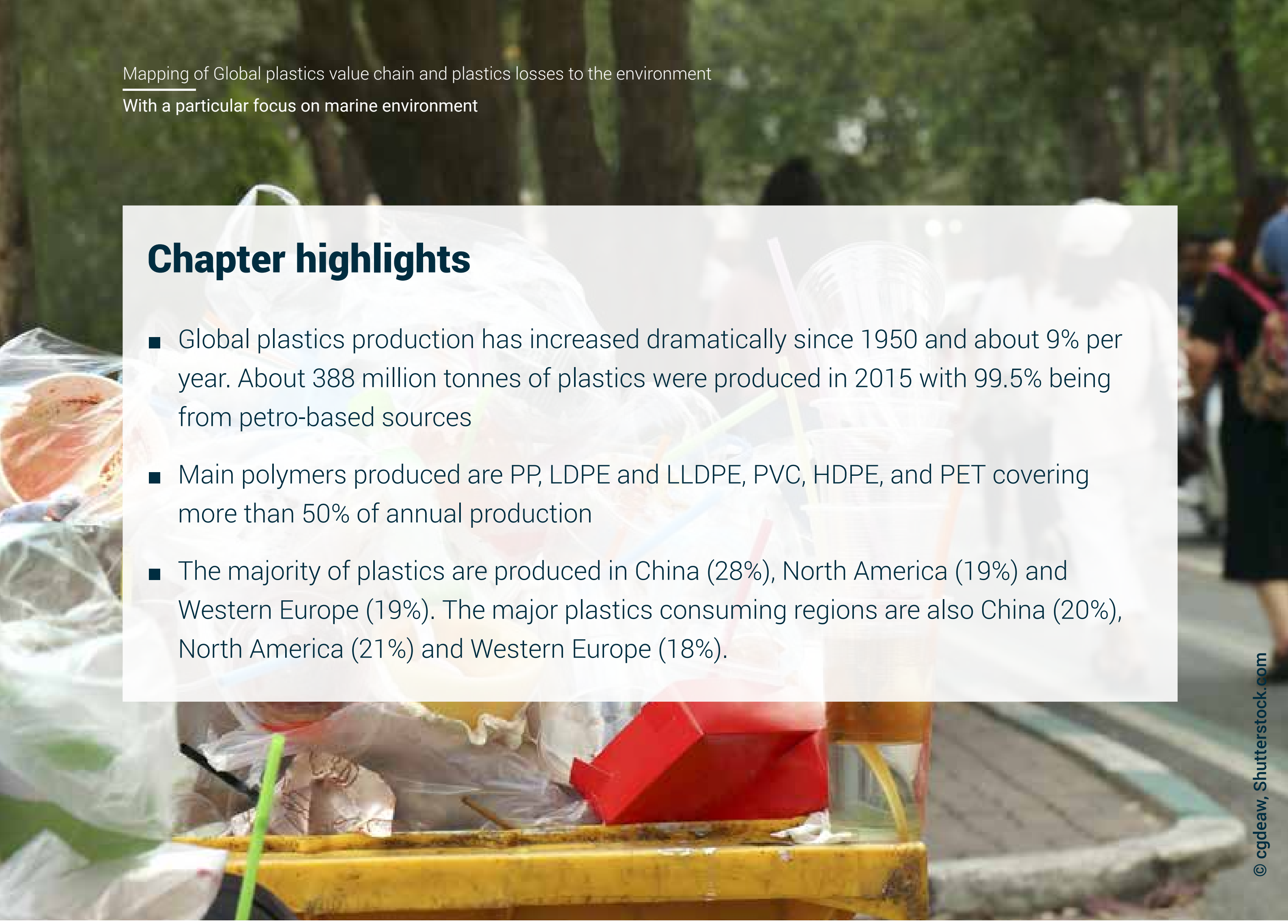


Figure 1. Overview of key value chain stages and stakeholders/interest groups associated with each value chain stage. Amounts of micro- and macroplastics lost to the environment are based on findings in Chapter 6. The identified key hotspots as presented in Chapter 9 are indicated with yellow circles.

3

Global plastics production and consumption



Chapter highlights

- Global plastics production has increased dramatically since 1950 and about 9% per year. About 388 million tonnes of plastics were produced in 2015 with 99.5% being from petro-based sources
- Main polymers produced are PP, LDPE and LLDPE, PVC, HDPE, and PET covering more than 50% of annual production
- The majority of plastics are produced in China (28%), North America (19%) and Western Europe (19%). The major plastics consuming regions are also China (20%), North America (21%) and Western Europe (18%).

Global plastics production has increased dramatically with an average yearly increase of about 9% between 1950 and 2015 (Figure 2) (Geyer et al., 2017).

In 2015 about 322 million tonnes (Mt) of plastics were produced globally (PlasticsEurope, 2016a). These values exclude PP fibers, PET fibers, PA fibers, and elastomers. When including them, i.e. production of fibers (Credence Research, 2016; Maddah, 2016; plastemart, 2010) and elastomers (ETRMA, 2017, 2011), the total amounts to about 388 Mt of plastics. Table 1 shows the global mass production and its distribution between different plastic polymer types.

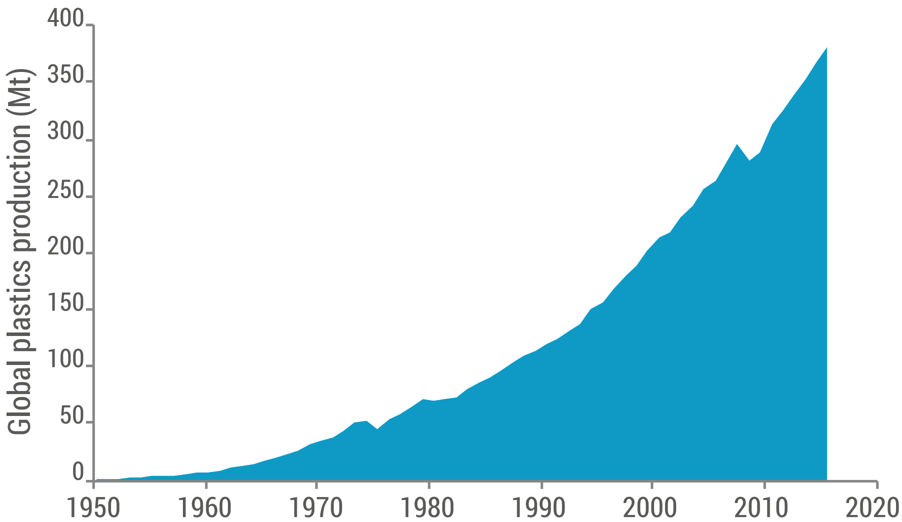


Figure 2. Annual global polymer resin and fiber production in million metric tonnes from 1950 to 2015

Table 1. Global polymer production and share of total demand, divided into different polymer types

Polymer	Tonnes	Share of total demand	Reference
Polypropylene (PP)	61,870,000	16%	(PlasticsEurope, 2016b)
Low density polyethylene, Linear low density polyethylene (LDPE, LLDPE)	45,730,000	12%	(PlasticsEurope, 2016b)
Polyvinylchloride (PVC)	43,040,000	11%	(PlasticsEurope, 2016b)
High density polyethylene (HDPE)	40,350,000	10%	(PlasticsEurope, 2016b)
Polyethylene terephthalate (PET)	18,830,000	5%	(PlasticsEurope, 2016b)
Polystyrene, Expanded polystyrene (PS, EPS)	18,830,000	5%	(PlasticsEurope, 2016b)
Polyurethane (PUR)	16,140,000	4%	(PlasticsEurope, 2016b)
Other Thermoplastics	10,760,000	3%	(PlasticsEurope, 2016b)
Acrylonitrile butadiene styrene, Acrylonitrile styrene acrylate, Styrene-acrylonitrile (ABS, ASA, SAN)	8,070,000	2%	(PlasticsEurope, 2016b)
Polycarbonate (PC)	2,690,000	1%	(PlasticsEurope, 2016b)
Polyamide (PA)	2,690,000	1%	(PlasticsEurope, 2016b)
Elastomers (non tyres)	7,931,413	2%	(ETRMA, 2017)
Thermosets	33,740,000	9%	(prnewswire, 2015)
Adhesives	9,390,000	2%	(Grand View Research, 2015a)
Sealants	1,840,000	0.5%	(Grand View Research, 2015a)
Coatings	2,828,905	1%	(Sinograce chemical, 2017)
Marine coatings	452,000	0.1%	(Boucher and Friot, 2017)
Road marking coatings	588,000	0.2%	(Boucher and Friot, 2017)
PP fibers	30,061,649	8%	(Maddah, 2016; PlasticsEurope, 2016b)
PET fibers	18,830,000	5%	(Credence Research, 2016; PlasticsEurope, 2016b)
PA fibers	4,388,947	1%	(plastemart, 2010; PlasticsEurope, 2016b)
Elastomers (tyres; mainly Styrene-Butadiene Rubber)	7,068,587	2%	(ETRMA, 2011)
Bioplastics (e.g. Polylactic acid)	2,054,000	0.5%	(European Bioplastics, 2017)
Total	**388,173,501**	100%	

A schematic overview of the plastic production chain is shown in Figure 3 (a more detailed flow chart of the plastic production chain for the different plastic types is provided in Appendix 3). Polymer production can generally be classified into a relatively few number of production and processing steps. However, the additives and processes required for production during refining and polymerization of the specific polymer type may vary greatly. The majority of plastics are petro-based and produced from crude oil and/or natural gas; only about 0.5% is derived from bio-based sources – see Table 1 (European Bioplastics, 2017).

The global distribution of plastics production and consumption is shown in Figure 4 (see Appendix 1 for more information). The majority of plastics are produced in North America, Western Europe, and China which are also the primary consumers of plastics. In general, there is a good proportionality between plastic production and consumption in the regions. In terms of plastic consumption, for North America and Western Europe the large consumption is primarily due to the high per-capita plastic consumption. For China it is predominantly a result of the large population, although, the per capita plastic consumption has increased from about 25 kg/capita in 2000 to currently about 45 kg/capita (Panda et al., 2010; Plastindia Foundation, 2014).

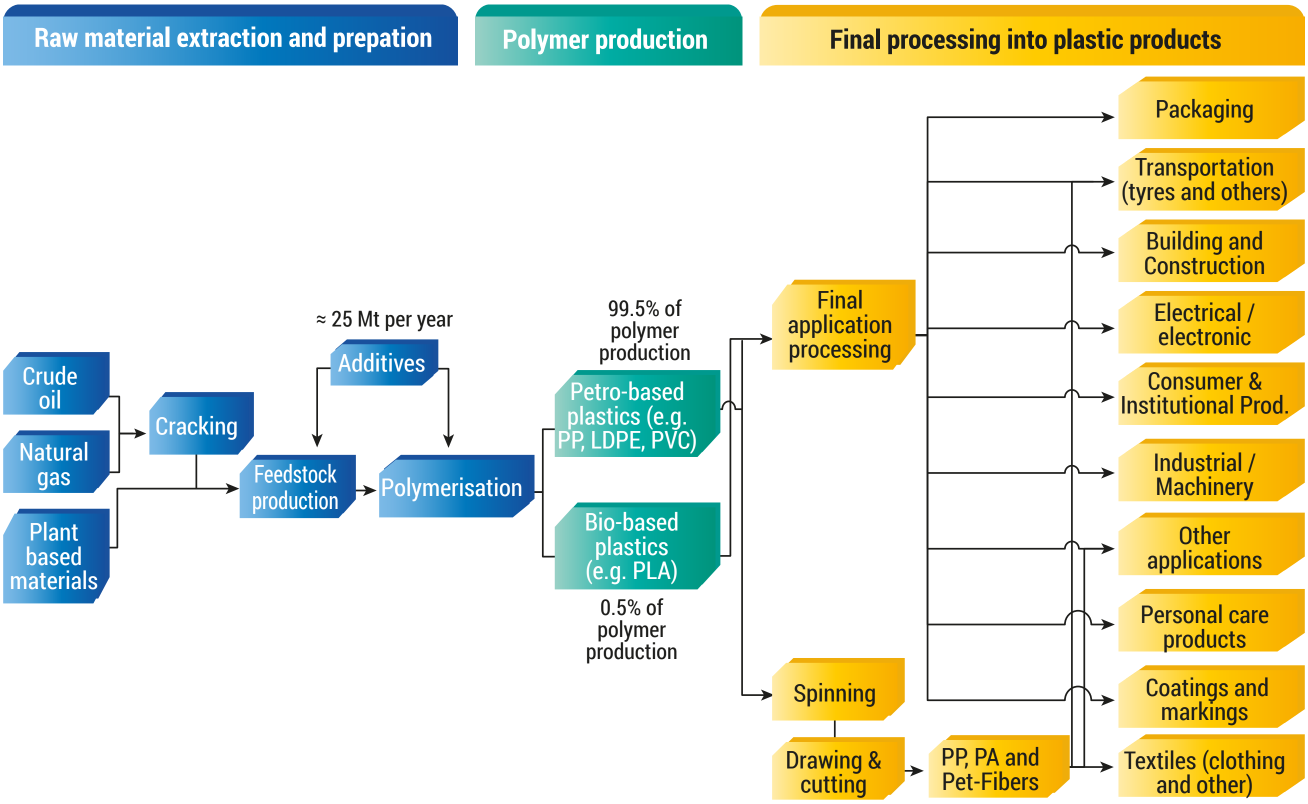


Figure 3. General polymer production value chain indicating the main processes in plastic production

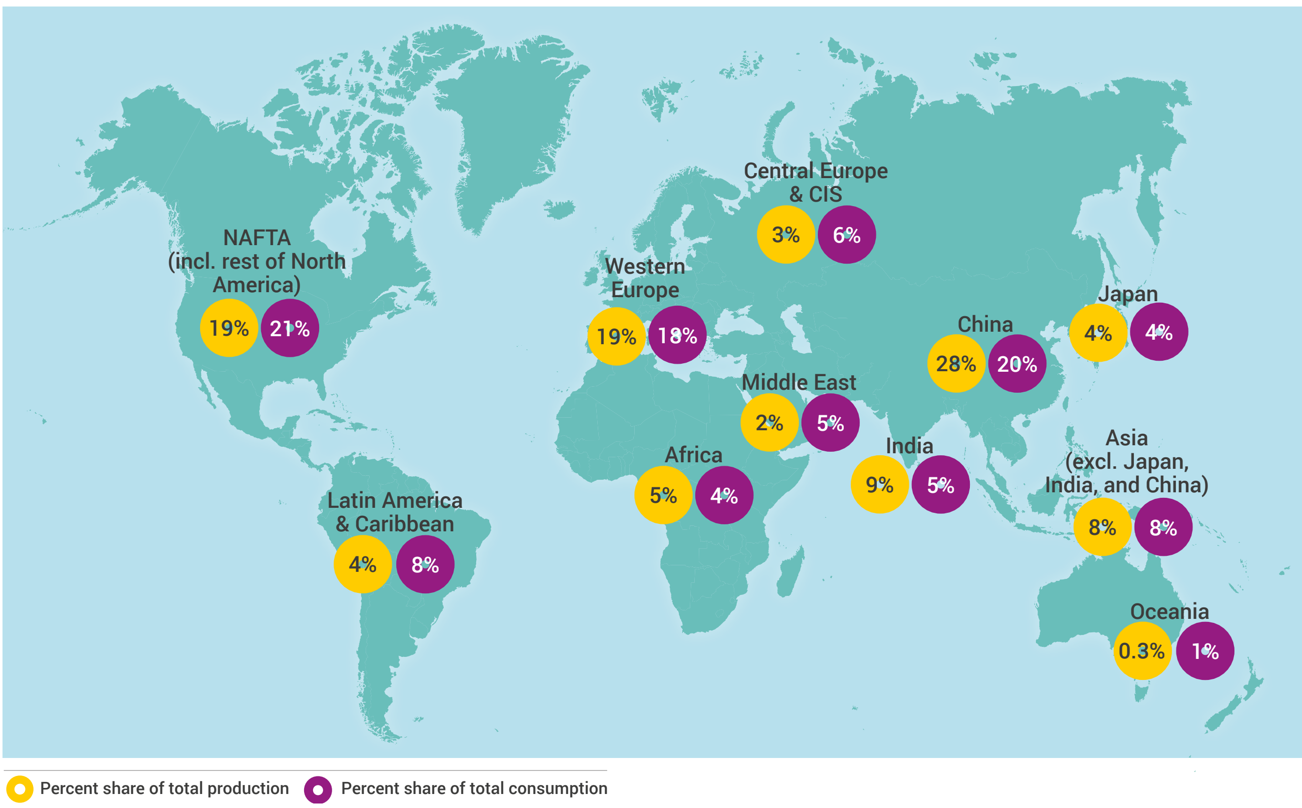


Figure 4. Share of total plastics production and consumption for the different world regions in this mapping

4

Global plastics usage

Chapter highlights

The main plastic using applications are packaging, building and construction, and transportation using 30%, 17%, and 14% of total annual plastic production, respectively.

4.1. Distribution of plastics applications

Plastics are used for a variety of different purposes and in different application categories. In this mapping, the plastics used were distributed in to a number of applications as shown in Table 2. Table 2 also provides a list of examples of the typical plastics products in the category.

The relative plastic usage for different applications as derived in Table 3 are primarily based on a study by Geyer et al. (2017). The initial distribution by Geyer et al. (2017) was expanded to differentiate between tyres in transportation and other transportation. Plastics for personal care products was isolated from the 'consumer & institutional products' category and marine coatings, and road markings were also isolated from the 'other' category. Although the amounts of plastics in these three applications are small relative to the total plastic consumption, these were found to be major sources of microplastic losses (Boucher and Friot, 2017) and, thus, were deemed important to distinguish in the current assessment. The largest fraction of plastic is used for packaging while substantial shares are also used for building and construction, transportation, textiles, and embedded in consumer & institutional products.

A distribution on the different plastic types used for the different applications is given in Table A3 in Appendix 2. That distribution of plastic types was developed assuming a same pattern for all regions in the world. This assumption appears reasonable given that plastics are not necessarily produced in the country where they are used; hence the different plastic types entering plastic products are likely to be similar for same products across regions.

Table 2. Overview of the application categories used in this mapping and examples of the typical products included within each application category

Application	Examples of products in included in the application category
Transportation - Other	Motor vehicles and parts (including autos, trucks, buses, motorcycles and bicycles), railroad equipment, travel trailers, campers, golf carts, snowmobiles, aircraft, military vehicles, ships, boats and recreational vehicles (American Chemistry Council, 2008)
Transportation - Tyres	Plastics related to tyres for vehicles
Packaging	Bottles, jars, vials, food containers (excl. disposable cups), flexible packaging (excl. household and institutional refuse bags and film), tubes, tape, strapping, drums, caps, closures, baskets, trays, boxes, pallets, shipping crates and cases, pails, buckets, and blister and bubble containers (American Chemistry Council, 2008)
Building and Construction	Pipe, conduit and fittings (including drainage, irrigation, plumbing fixtures and septic tanks), siding, flooring, insulation materials, panels, doors, windows, skylights, bathroom units, agricultural film, gratings and railings (American Chemistry Council, 2008)
Electrical/Electronic	Home and industrial appliances (including electrical industrial equipment), wire and cable coverings, communications equipment, resistors, magnetic tape, records and batteries (American Chemistry Council, 2008)
Consumer & Institutional Products	Disposable food service ware (including disposable cups), dinner and kitchenware, toys and sporting goods, household and institutional refuse bags and film, health care and medical products, hobby and graphic arts supplies (including photographic equipment and supplies), apparel, footwear, luggage, buttons, lawn and garden tools, signs and displays, and credit cards (American Chemistry Council, 2008)
Industry/Machinery	Engine and turbine parts, farm and garden machinery, construction and related equipment, fishing and marine supplies, machine tools, ordnance and firearms, fishing and marine supplies, and chemical process equipment (American Chemistry Council, 2008)
Other	(American Chemistry Council, 2008)
Marine coatings	Marine coatings
Personal care products	Personal care products and cosmetics
Road marking	Road markings
Textile sector - clothing	Clothing textiles
Textile sector - others	All other textiles except for clothing

Table 3. Global plastics consumption distributed on different plastic applications

Application	Amount [tonnes]	Share [%]	Reference
Transportation - Other	4.75E+07	12%	(Geyer et al., 2017; Grand View Research, 2017)
Transportation - Tyres	7.07E+06	2%	(ETRMA, 2011; Geyer et al., 2017)
Packaging	1.15E+08	30%	(European Bioplastics, 2017; Geyer et al., 2017)
Building and Construction	6.41E+07	17%	(European Bioplastics, 2017; Geyer et al., 2017)
Electrical/Electronic	1.57E+07	4%	(European Bioplastics, 2017; Geyer et al., 2017)
Consumer & Institutional Products	4.06E+07	10%	(European Bioplastics, 2017; Geyer et al., 2017)
Industrial/Machinery	2.01E+06	0.5%	(Geyer et al., 2017)
Other	5.66E+07	15%	(European Bioplastics, 2017; Geyer et al., 2017)
Marine coatings	4.52E+05	0.1%	(Boucher and Friot, 2017)
Personal care products	2.54E+04	0.01%	(Boucher and Friot, 2017; Geyer et al., 2017; Gouin et al., 2015)
Road marking	5.88E+05	0.2%	(Boucher and Friot, 2017)
Textile sector - clothing	2.49E+07	6%	(Geyer et al., 2017; Grand View Research, 2017)
Textile sector - others	1.35E+07	3%	(Geyer et al., 2017; Grand View Research, 2017)

4.2. Plastics consumption distributed into geographical regions and plastics applications

Total plastics consumption values differentiated into geographical regions and plastic applications (Table 4) were derived based on Figure 4 (i.e. plastic consumption differentiated on regions) and Table 3 (i.e. plastic consumption differentiated on application categories). It was generally assumed that distribution of plastic applications was the same across geographical regions.

However, specific geographical distributions were derived and used for certain plastic applications based on available industry-specific data, for example on the annual consumption of vehicles and tyres as retrieved from the European Tyre & Rubber Manufacturers' Association (ETRMA). To maintain a fit with the overall geographical plastic consumption distribution, the other plastic applications were proportionally adjusted within each region.

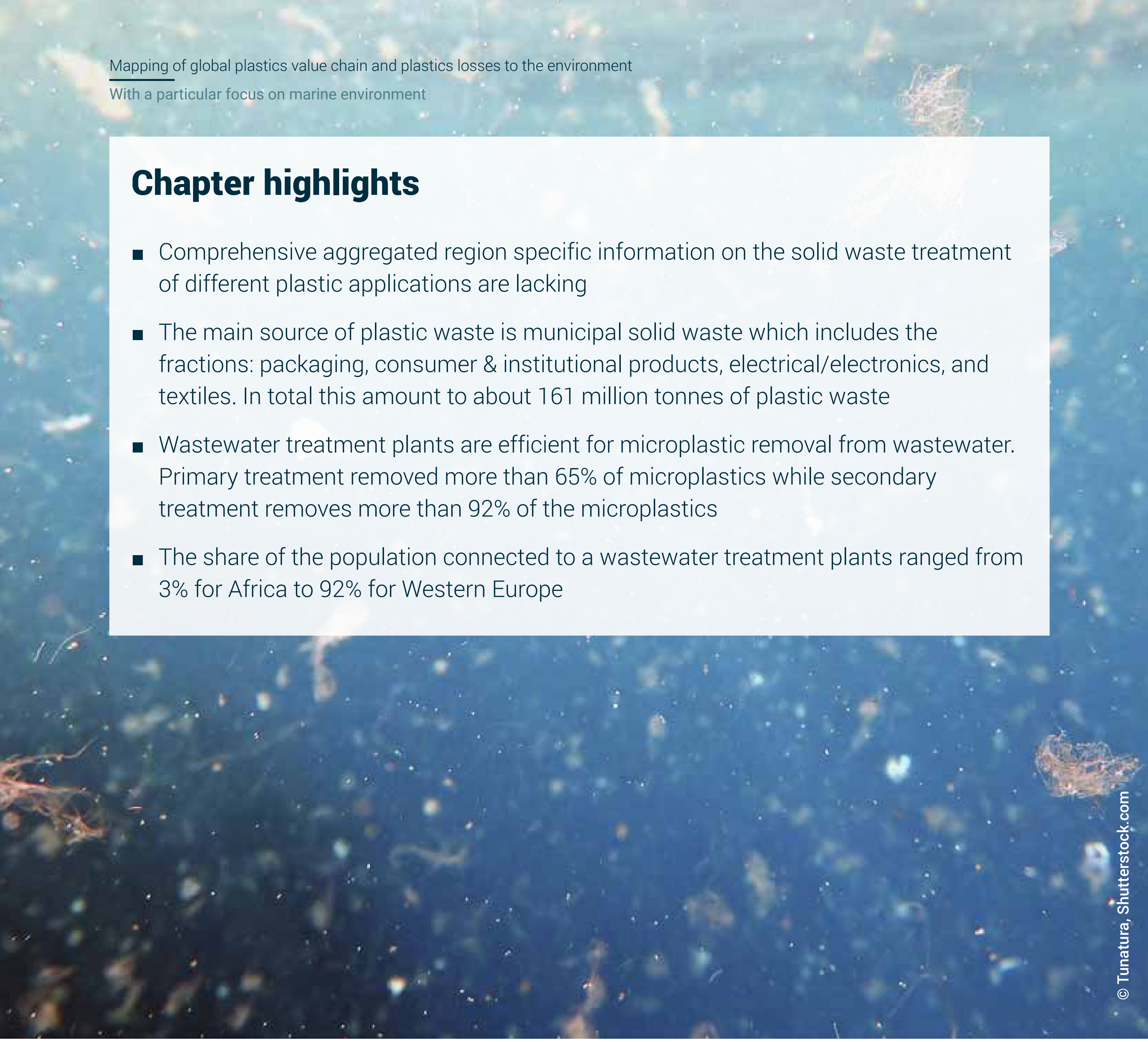
Table 4. Global mass based plastics consumption differentiated into geographical regions and applications

Region	World	NAFTA (incl. rest of North America)	Western Europe	Japan	Central Europe & CIS	Asia (excl. Japan, India, and China)	Africa	Latin America & Caribbean	Oceania	India	China	Middle East	Reference for distribution of applications between regions
Share of total consumption	100%	21%	18%	4%	6%	8%	4%	8%	1%	5%	20%	5%	1
Transportation - Other	12%	2.5%	1.6%	0.2%	1.5%	1.7%	0.3%	0.7%	0.2%	0.7%	2.2%	0.6%	2
Transportation - Tyres	2%	0.4%	0.2%	0.0%	0.2%	0.3%	0.0%	0.1%	0.03%	0.1%	0.3%	0.1%	2
Packaging	30%	6.6%	5.4%	1.1%	1.3%	1.8%	1.8%	3.0%	0.09%	1.3%	5.7%	1.4%	1
Building and Construction	17%	2.4%	4.0%	1.4%	1.0%	1.1%	0.1%	0.8%	0.464%	0.8%	3.5%	0.8%	3
Electrical/Electronic	4%	0.9%	0.7%	0.2%	0.2%	0.3%	0.2%	0.4%	0.01%	0.2%	0.8%	0.2%	1
Consumer & Institutional Products	10%	2.3%	1.9%	0.4%	0.5%	0.6%	0.6%	1.1%	0.03%	0.5%	2.0%	0.5%	1
Industrial/Machinery	0.5%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.002%	0.0%	0.1%	0.0%	1
Other	15%	3.3%	2.7%	0.5%	0.6%	0.9%	0.9%	1.5%	0.04%	0.6%	2.8%	0.7%	1
Marine coatings	0.1%	0.03%	0.02%	0.00%	0.01%	0.01%	0.01%	0.01%	0.0004%	0.01%	0.02%	0.01%	1
Personal care products	0.01%	0.001%	0.001%	0.0003%	0.0003%	0.001%	0.001%	0.0004%	0.0001%	0.001%	0.001%	0.000%	1
Road marking	0.2%	0.03%	0.03%	0.01%	0.01%	0.01%	0.01%	0.02%	0.0005%	0.01%	0.03%	0.01%	1
Textile sector - clothing	6%	1.4%	0.6%	0.2%	0.4%	0.8%	0.1%	0.3%	0.1%	0.9%	1.3%	0.3%	4
Textile sector - others	3%	0.8%	0.6%	0.1%	0.2%	0.3%	0.2%	0.3%	0.04%	0.2%	0.7%	0.2%	1

1 To fit the overall geographical plastic consumption distribution (i.e. Share of total consumption), these plastic applications were proportionally adjusted within each region according to Global plastics applications distribution,
2 (ETRMA, 2017),
3 (IHS Economics, 2013),
4 (FAO/ICAC, 2011)

5

Plastics end-of-life



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Chapter highlights

- Comprehensive aggregated region specific information on the solid waste treatment of different plastic applications are lacking
- The main source of plastic waste is municipal solid waste which includes the fractions: packaging, consumer & institutional products, electrical/electronics, and textiles. In total this amount to about 161 million tonnes of plastic waste
- Wastewater treatment plants are efficient for microplastic removal from wastewater. Primary treatment removed more than 65% of microplastics while secondary treatment removes more than 92% of the microplastics
- The share of the population connected to a wastewater treatment plants ranged from 3% for Africa to 92% for Western Europe

The amounts of plastic waste treated in one year is not necessarily equal to the amount of plastic produced in the same year due to differences in plastic product lifetimes , in-use plastic stocks, and annual variations in plastics production and demand. Hence, the mapping of plastic waste treatment was developed independently of the production and consumption mapping.

Aggregated region specific information about the EoL treatment of different plastic applications was not adequate for some regions which restricted the option for providing a comprehensive overview of the different waste management systems in the different regions. More detailed information about the EoL treatment may be available at regional to local level (e.g. municipal level). However, such detailed retrieving of waste information and subsequent extrapolation to the scale of the regions used in this study was outside the scope of the study. Instead, Table 5 provides an overview of the common treatment option the different applications may undergo in different regions, such as developed or developing countries. Moreover Table 5 provides information on the annual amount of total waste and plastic waste generated for each application.

Table 5. Common end-of-life treatment options for the different applications where plastic is a component. The total annual amounts of waste generated as well as the annual amounts of plastic waste generated are also given from the table.

Application	Common treatment options	Amounts generated
Transportation – Other	In developed countries, End-of-life vehicles (ELV) are primarily disassembled where part of the ELV is recycled while the remaining part is shredded and landfilled (Sakai et al., 2014)their background and present situation, outcomes of related policies and programs, the framework of recycling and waste management, and case studies on related topics in several countries and regions, as well as the essential points of the comparison. Legislative ELV recycling systems are established in the EU, Japan, Korea, and China, while in the US, ELV recycling is managed under existing laws on environmental protection. Since automobile shredding residue (ASR. For developing countries, data on ELV treatment is scarcer, but, recycling is less common and most ELVs are landfilled after dismantling and shredding using non-standardized operations or are being dumped directly in the environment (Cruz-Rivera, 2008).	40,176,051 vehicles/yr (Sakai et al., 2014)their background and present situation, outcomes of related policies and programs, the framework of recycling and waste management, and case studies on related topics in several countries and regions, as well as the essential points of the comparison. Legislative ELV recycling systems are established in the EU, Japan, Korea, and China, while in the US, ELV recycling is managed under existing laws on environmental protection. Since automobile shredding residue (ASR. About 12-15% of car mass is plastic (PlasticsEurope, n.d.). Assuming average car/vehicle weight of 1500 kg this gives between 7.2 – 9 Mt of plastic.
Transportation – Tyres	In EU in 2013, used tyres were recovered as energy recovery (52%) or material recovery (48%) (ETRMA, 2015). In the EU, end-of-life tyre treatment is managed through Extended Producer Responsibility, a Liberal system, or a Tax system (Government responsibility, financed through a tax) (ETRMA, 2015). These three models are likely to be applicable for the rest of the world as well. Treatment of used tyres in more developing economies is less effective and the majority of used tyres are disposed of in open dumps (Connor et al., 2013). In United States and Japan, less than 15% and 11%, respectively, of the tyres are disposed by landfilling or similar treatment (Connor et al., 2013)	For EU about 2.8 Mt of tyres are discarded per year (EU27 plus Norway, Switzerland and Turkey) (ETRMA, 2015). Based on information from ETRMA (ETRMA, 2017, 2011), Europe account for about 26% of global tyre usage. By extrapolating the end-of-life tyres using global tyre usage, we estimate that about 11 Mt of tyres are discarded each year. With an elastomer content of about 47% (Evans and Evans, 2006), this amounts to 5.2 Mt of polymer per year.
Packaging	Considered treated together with other MSW fractions or source separate (and then recycled). As part of MSW and depending on the waste management system in the given country, treatment can be recycling, incineration, landfilling or dumping.	Part of general MSW. About 161 Mt of plastic MSW is generated per year (Table 6).
Building and Construction	Construction and demolition (C&D) plastic waste is traditionally being landfilled as inert waste (or dumped). However, there is an increasing focus on recycling/reuse of the C&D waste (Christensen and Andersen, 2010).	Plastic (primarily PVC) constitute about 5-6% of C&D waste (Christensen and Andersen, 2010). About 13 Mt of plastic C&D waste is generated per year (Geyer et al., 2017)
Electrical/ Electronic	Electrical/Electronic waste is generally being recycled either through take back systems, as a source separated fraction, or via informal waste handling (e.g. waste pickers). Otherwise the Electrical/Electronic is likely to be mixed with other MSW fraction and undergo the same treatment as other MSW. Depending on the waste management system in the given country, treatment can be recycling, incineration, landfilling or dumping.	About 35 Mt of WEEE is generated per year (Breivik et al., 2014; Cao et al., 2016)but it is difficult to assess the significance of this issue without a quantitative understanding of the amounts involved. The main objective of this study is to track the global transport of e-wastes by compiling and constraining existing estimates of the amount of e-waste generated domestically in each country M GEN , exported from countries belonging to the Organization for Economic Cooperation and Development (OECD with a plastic content of about 10-30% (Taurino et al., 2010)and then in the recycling of post-consumer plastic of WEEE there is a pressing need for rapid measurement technologies for simple identification of the various commercial plastic materials and of the several contaminants, to improve the recycling of such wastes.This research is focused on the characterization and recycling of two types of plastics, namely plastic from personal computer (grey plastic. This amount to about 7 Mt of plastics in WEEE.
Consumer & Institutional Products	Consumer & Institutional Products are likely to either be treated as bully waste where the waste is either recycled or disposed via incineration or landfilling. Otherwise Consumer & Institutional Products are likely to be mixed with other MSW fractions and undergo the same treatment as other MSW. Depending on the waste management system in the given country, treatment can be recycling, incineration, landfilling or dumping.	Part of general MSW. About 161 Mt of plastics MSW is generated per year (Table 6).
Industrial/ Machinery	Considered treated in the same way as "Transportation – Other" where the machines are disassembled where part of the ELV is recycled while the remaining part is shredded and landfilled/dumped.	About 1 Mt of plastic waste from Industrial/Machinery is generated per year (Geyer et al., 2017)
Other	Not known, but the waste is likely to be treated as part of other MSW	Not known
Marine coatings	No treatment	Not relevant
Personal care products	Either treated in waste water treatment plant or directly discharged to environment	Not relevant
Road marking	No treatment	Not relevant
Textile sector – clothing	Considered treated together with other MSW fractions or source separate (and then recycled). As part of MSW and depending on the waste management system in the given country, treatment can be recycling, incineration, landfilling or dumping.	Part of general MSW. About 161 Mt of plastic MSW is generated per year (Table 6).
Textile sector – others	Considered treated together with other MSW fractions or source separate (and then recycled). As part of MSW and depending on the waste management system in the given country, treatment can be recycling, incineration, landfilling or dumping.	Part of general MSW. About 161 Mt of plastic MSW is generated per year (Table 6).

5.1. Municipal solid waste generation

It was assumed that plastic applications related to packaging, consumer & institutional products, textile sector – clothing, and textile sector – others is treated as part of the MSW. The generation of MSW within each region was estimated according to a statistically-derived linear model based on information for 143 countries, covering 73% of global population including countries from all regions in this mapping. The variables used for predicting MSW generation were the region in which the county is located, gross domestic product (GDP) per capita (World Bank, 2016a), and country population (World Bank, 2017). The model equation is shown in Eq. 1 and the model gave a modest r^2 of 0.586. However, when plotting the predicted values against the actual values a reasonable fit was observed and the low r^2 was primarily caused by an inability to predict MSW generation for small island states, which generally show a high per-capita MSW generation (Figure 5). This is also indicated by the higher Spearman rank correlation test, which is less influenced by outliers, where the coefficient was 0.752.

Where ***a*** is a statistically derived fitting parameter of 0.24 and ***b*** is a region specific fitting parameter being -0.07, 0.01, -0.43, 0.24, 0.04, 0.18, 0.18, and 0.08 for Asia (excl. Japan, India, and China), Central Europe & CIS, China, Latin America & Caribbean, Middle East, NAFTA (incl. rest of North America), Oceania, and Western Europe, respectively.

Eq. 1 $$MSW_{capita} = Intercept + a \log_{10}(GDP_{capita}) + b \times \text{Region}$$

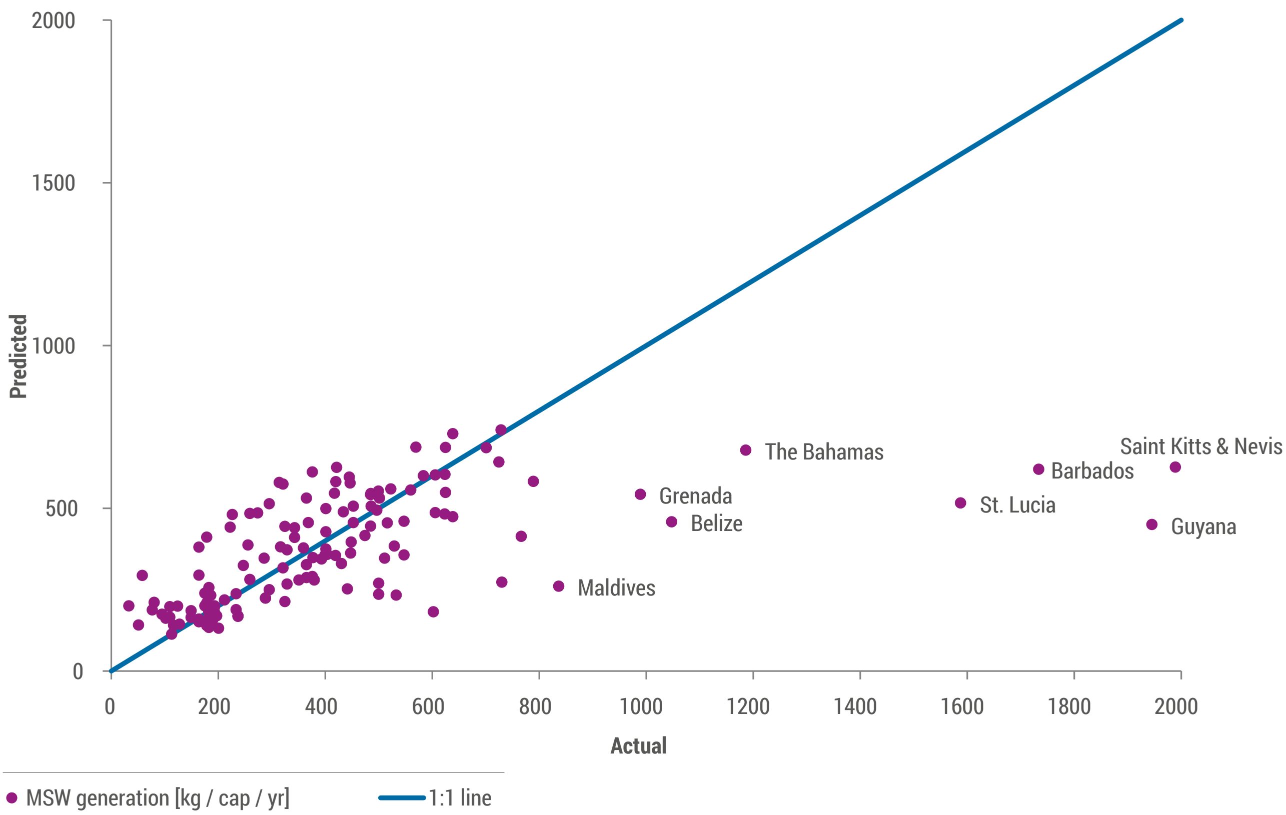


Figure 5. Scatterplot showing correlation between actual MSW per capita data and predicted MSW per capita with an r^2 of 0.586

Based on the derived model, the annual per-capita values for MSW generation were estimated for each region, which led to region-specific total amounts of MSW generated once combined with population data (Table 6).

Table 6. Overview of MSW generation and the part of MSW that is plastic differentiated between regions used in this study

Regions	MSW per capita generated [kg/cap/yr]	Total MSW generated [million tonnes/yr]	Share of plastic waste in MSW	Amount of plastic MSW generated [million tonnes/yr]
NAFTA (incl. rest of North America)	691	333	5%[1]	17.8
Western Europe	534	229	12%[1]	27.5
Japan	449	57	9%[1]	5.1
Central Europe & CIS	307	123	9%[1]	10.7
Asia (excl. Japan, India, and China)	215	246	12%[1]	29.4
Africa	203	224	5%[1]	10.2
Latin America & Caribbean	525	266	11%[1]	28.7
Oceania	670	26	5%[1]	1.3
India	206	269	2%[3]	4.3
China	113	159	7%[4]	11.6
Middle East	336	139	10%[1]	14.2

1 Hoornweg and Bhada-Tata (2012)environmental impacts and costs vary dramatically, solid waste management is arguably the most important municipal service and serves as a prerequisite for other municipal action. Currently, world cities generate about 1.3 billion tonnes of solid waste per year. This volume is expected to increase to 2.2 billion tonnes by 2025. Waste generation rates will more than double over the next twenty years in lower income countries. Globally, solid waste management costs will increase from today\u2019s annual $205.4 billion to about $375.5 billion in 2025. Cost increases will be most severe in low income countries (more than 5-fold increases

2 Zhang et al. (2010)

3 UN Stat (2016)

5.2. Wastewater treatment

In terms of loss of microplastics to the environment, the wastewater management is important for microplastics related to, e.g. cosmetics and personal care products and textile washing where microplastics are washed out with the wastewater.

The wastewater may have four different fates: (i) to be collected as part of the sewage network and treated in a wastewater treatment plant (WWTP), (ii) to be collected as part of the sewage network and emitted directly to either freshwater or seawater without treatment (either due to lack of wastewater treatment in a WWTP or due to overflow in the WWTP during e.g. flooding), (iii) to be released directly to the environment because no connection to a sewage network exists, or (iv) to be treated independently (e.g. septic tanks) while not being collected as part of the sewage network. Information about the share of national population connected to the public sewage network and also on the share of the wastewater generated that is treated was obtained from various databases (OECD stat, 2017; UN Stat, 2011).

Because the population covered by the data on the share of population connected to sewage network and share of population with wastewater treated in WWTP was less than 50% for some regions or because the data were simply not representative (e.g. only for urban population or based on a single city) other sources of data were identified and a correlation between the share of population connected to sewage system and the share of population connected to wastewater treatment and GDP/capita was derived. The share of population connected to sewage system and wastewater treatment (fr_{WWTP}; %) was estimated using data from UN Stat (2011). The dataset from

UN Stat (2011) contains information on the share of the population connected to wastewater treatment for 82 countries. A model fit analysis was performed between the share of persons connected to wastewater treatment and GDP per capita (GDP_{capita}; USD). The model best describing the relationship was the sigmoidal Morgan-Mercer-Flodin (MMF) model with an r^2 of 0.712. Using the derived model, the share of persons connected to WWTP for the regions included in this study was determined (see Table 7 for shares).

A model fit analysis was performed between the share of persons connected to a sewage system (fr_{Sewage}; %) and GDP per capita (GDP_{capita}; USD). The model best describing the relationship was an exponential model with an r^2 of 0.626. Thereby, using the derived model, the share of persons connected to a sewage system for the regions included in this study was determined (see Table 7 for shares).

Table 7. Share of population connected to public sewage network and share of population whose wastewater is treated

	NAFTA (incl. rest of North America)	Western Europe	Japan	Central Europe & CIS	Asia (excl. Japan, India, and China)	Africa	Latin America & Caribbean	Oceania	India	China	Middle East
Share of population connected to wastewater collection system	75%	92%	78%	51%	46%	42%	55%	86%	60%	46%	52%
Reference	1	1	1	2	2	2	1	1	5	1	2
Share of population connected to sewage system with WWTP	74%	92%	90%	36%	15%	3%	33%	77%	60%	33%	38%
Reference	1	1	1	2	3	4	1	2	5	1	2

1 OECD stat (2017)
2 Correlation between WWTP connection and GDP/capita
3 WWAP (2017)
4 Actual share is unknown but estimate of 3% has been calculated for Addis Ababa which is used as proxy for general situation in Africa (WWAP, 2017)
5 Kalbar et al. (2017)WW LCI 2.0, which on many fronts represents considerable advances compared to its previous version WW LCI 1.0. WW LCI 2.0 is a novel and complete wastewater inventory model integrating WW LCI 1.0, i.e. a complete life cycle inventory, including infrastructure requirement, energy consumption and auxiliary materials applied for the treatment of wastewater and disposal of sludge and SewageLCI, i.e. fate modelling of chemicals released to the sewer. The model is expanded to account for different wastewater treatment levels, i.e. primary, secondary and tertiary treatment, independent treatment by septic tanks and also direct discharge to natural waters. Sludge disposal by means of composting is added as a new option. The model also includes a database containing statistics on wastewater treatment levels and sludge disposal patterns in 56 countries. The application of the new model is demonstrated using five chemicals assumed discharged to wastewater systems in four different countries. WW LCI 2.0 model results shows that chemicals such as diethylenetriamine penta (methylene phosphonic acid

The level of wastewater treatment technology for the share of the wastewater that is treated was derived based on OECD stat (2017). This provides information on the level of treatment, i.e. preliminary treatment, primary treatment, secondary treatment, or tertiary treatment. Independent (non-public) treatment (such as septic tanks) was included and the treatment level was assumed similar to primary treatment in a conventional WWTP. The treatment level is important as it determines the removal of microplastics from the wastewater before release to environment (Michielssen et al., 2016). Microplastic removal efficiencies were calculated for different wastewater treatment options and for different microplastic types (i.e. microbeads, fibers, and others) based on a study assessing the removal of microplastic types at the different wastewater treatment stages for two full scale WWTPs in the United States (Michielssen et al., 2016). The resulting efficiencies are reported in Table 8. The exact fate of the microplastics in the wastewater sludge removed after wastewater treatment is not known. However, the sludge is likely to be deposited into dumpsites, applied as fertilizer on land, incinerated, or used for compositing or anaerobic digestion. Depending on the disposal of the sludge, a fraction of the microplastics in the sludge will be released to the environment. Incineration would remove most of the microplastics while use of the sludge as fertilizer on agricultural land could lead to a large fraction of the microplastics being lost. Further investigation into the treatment of wastewater sludge is needed to provide a better estimate; however, such detailed assessment was not within the scope of this project.

Table 8. Microplastic removal efficiency for different wastewater treatment options and for different microplastic types

Microplastic type	Preliminary treatment	Primary treatment	Secondary treatment	Tertiary treatment
Microbeads	62.3%	85.6%	92.2%	99.3%
Fiber	58.0%	87.0%	92.2%	96.5%
Other	30.7%	68.6%	95.8%	98.7%

Due to the lack of representative data, other sources of information were used for India (Kalbar et al., 2017) and China (Zhang et al., 2016). Because information on wastewater treatment level for "Asia (excl. Japan, India, and China)" and "Africa" were not available, the wastewater treatment level was assumed to be the same as in India for those two regions. The levels of wastewater treatment technologies for the share of treated wastewater, differentiated between regions, are documented in Table 9.

Overflows of the sewage piping system and the WWTP occur, for example, as a result of heavy rain falls. Based on Magnusson et al. (2016), it was assumed that 100% of plastic in the sewage piping system will be lost to the environment during overflow, while only 50% of plastic in the WWTP will be lost during overflow because part of the wastewater often undergo, at least, primary treatment even during overflow. The share of total wastewater in the WWTP lost to overflow was estimated to be 2.4% by using an average of the values reported in the national microplastics assessments (Lassen et al., 2015; Magnusson et al., 2016; Sundt et al., 2014). The share of total wastewater in sewage piping system was assumed to be 0.6% (Magnusson et al., 2016).

Table 9. Overview of distribution of wastewater treatment in terms of fraction going for preliminary, primary, secondary, or tertiary treatment in the wastewater treatment plant

	NAFTA (incl. rest of North America)	Western Europe	Japan	Central Europe & CIS	Asia (excl. Japan, India, and China)	Africa	Latin America & Caribbean	Oceania	India	China	Middle East
Share of population covered in (OECD stat, 2017)	100%	93%	100%	9%	4%	0%	14%	12%	0%	0%	21%
Share going to Preliminary treatment	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Share going to Primary treatment	17%	8%	13%	5%	65%	65%	53%	18%	65%	3%	30%
Share going to Secondary treatment	46%	21%	57%	20%	35%	35%	28%	32%	35%	97%	39%
Share going to Tertiary treatment	37%	72%	30%	75%	0%	0%	18%	50%	0%	0%	31%
Reference	1	1	1	1	4	4	1	1	2	3	1

[1] OECD stat (2017)
[2] Kalbar et al. (2017)
[3] Zhang et al. (2016)
[4] Due to lack of better data the treatment share was assumed to be same as in India

6

Losses of plastics to environment from plastic value chain

Chapter highlights

- Primary annual losses of macroplastics are from (i) mismanaged solid waste treatment, i.e. open dumping and inadequate landfilling (3.9 Mt); (ii) littering as e.g., plastics being thrown away by citizens and not correctly disposed of (0.8 Mt); and (iii) loss of fishing nets and other fishing related activities (0.6 Mt)
- Primary annual losses of microplastics are from abrasion of tyres (1.4 Mt), general city dust (0.65 Mt), and abrasion of road markings (0.6 Mt)
- Microplastic losses through use of cosmetics and personal care products are limited due to the relatively low use of plastics in cosmetics and personal care products. The limited losses are also a result of efficient removal of microplastic beads in wastewater treatment plants. This is particularly the case for developed countries that have a comprehensive treatment coverage of wastewater in wastewater treatment plants
- Plastic losses (as microplastics) from plastics production and handling are generally limited due to historical focus on limiting these losses e.g. as a result of the "Operation Clean Sweep" and "Zero Pellet Loss" initiatives
- A number of potential losses could not be accounted due to insufficient data. The likely most important losses not accounted for are from floats and other similar losses from marinas and aquaculture where losses are directly to the marine environment

6.1. Production

Macroplastic

Pre-production plastic pellets qualify as microplastics, as the plastic pellets are normally between 2 and 5 mm in size (PlasticsEurope, 2017). Hence, macroplastic are generally not considered to be lost during the production of plastics.

Microplastic

Losses during production, processing and handling of plastic

Losses of microplastics during production and processing of plastic is generally low as there have been a number of initiatives focusing on reducing these losses and increasing the overall material efficiency of plastic production. For instance "Operation Clean Sweep" initiated in the 1990s by the main plastic organizations and the "Zero Pellet Loss" initiative founded by PlasticsEurope (Magnusson et al., 2016). These initiatives have helped raising awareness on minimizing losses of virgin pellets during plastics production.

However, losses of virgin pellets still occur, although, primarily as a result of accidental spills of plastic pellets during the production and handling of the plastic materials. Studies quantifying these losses are scarce. The only available data, which could be retrieved, relate to a Norwegian polystyrene plant where a loss of 0.4 g/kg PS produced was reported (Sundt et al., 2014). This value was used for estimating the losses from production and processing of plastic pellets. The microplastics lost during production and processing will most likely go to the drain as drainage in industrial facilities is common (Magnusson et al., 2016). It is assumed that plastics lost during production will be treated in a WWTP. Using a general loss of 0.4 g / kg plastics produced, the plastic lost to environment during production was calculated using the global production distribution (Figure 4) coupled with the regional distribution in WWTP treatment technology level (Table 9) and the microbeads removal efficiency for the different WWTP treatment levels (Table 8). This gave a total loss of 0.01 Mt of plastic lost to the environment from production.

With regard to handling and transport of the plastic pellets, we rely on estimates by Magnusson et al. (2016), who estimate that the true value ranges between 0.0005% and 0.01%.The average value, i.e. 0.005%, was used for estimating losses during loading, reloading and transportation of the pellets. As the majority of these losses will occur outside, it is assumed that all losses from handling and transport of the plastic pellets are to the environment; this amount to a loss of 0.02 Mt of plastic to the environment during handling and transport.

6.2. Use

Macroplastics

Littering

Studies on the magnitude of littering are generally lacking which renders any estimate of the losses of plastic as a result of littering very uncertain. Indicators for expressing the risk of littering include population density; magnitude of tourism and recreation; port activities; solid waste management (i.e. level of collection and treatment of municipal waste, management of waste from dump sites located near coasts or riverbanks/rivers, management of plastic packaging waste, management of commercial and industrial waste, and management of agricultural plastic waste) (Mehlhart and Blepp, 2012).

The only estimate on littering, which could be retrieved, was reported by Jambeck et al. (2015). They estimated that ca. 2% of the mass of total waste generated was littered and that about 25% of this waste was not captured during street sweeping, catchments or pump stations (Jambeck et al., 2015). The total amount of plastic MSW generated for the different regions (i.e. 161 Mt; see Section 5.1 on MSW generation) were derived assuming the following plastic waste fractions to be part of the overall MSW: packaging, electrical/ electronic, consumer & institutional products, and textiles (both clothing and others). To estimate the types of plastic lost as part of mismanaged MSW the regional distribution of applications was used. It was assumed that the distribution of each application in consumption as reported in Table 4 was equal to the distribution in the MSW. The regional application distribution as given from Table 4 was combined with the share of plastic types included for each application as given from Table A3 in Appendix 2. Assuming 2 % littering, from which 25% is not captured, this gave a total loss of 0.8 Mt of plastics to the environment.

Ocean based losses (i.e. discarded fishing nets and dolly rope abrasion and floating devices)

Most fishing gear used, such as nets or dolly ropes are made from plastic, mainly polyamide/nylon or polyethylene (PE), polypropylene (PP). Due to a lack of information on the distribution of different polymers, we assumed that all fishing nets are made from polyamide fibers. Floats which are essential in fishing, aquaculture and marinas are often made from expanded polystyrene (EPS) (Magnusson et al., 2016). The loss of these products is mainly a problem in terms of macroplastic while formation of microplastic may also occur, especially for dolly ropes which are used to protect the cod-end of trawling nets against wear and tear, where the dolly ropes are being teared instead. Information on loss related to abrasion of floating devices could not be estimated due to lack of data. Quantitative data on the loss of discarded fishing nets or other discarded fishing gear is also generally lacking. As a proxy for the annual loss of plastic nets, we apply an estimate of 0.6 Mt per year (Boucher and Friot, 2017).

For dolly ropes, according to the Dutch organization (DollyRopeFree, n.d.), about 0.1 Mt of dolly rope is used in the European Union (EU) during fishing activities. Approximately 15-25% of the dolly rope is lost during its functioning. The EU dolly rope use was extrapolated to global level using the share of fish caught from marine fishing in EU (i.e. 5.4 Mt; Eurostat, 2017) relative to global capture, i.e. 81.5 Mt (FAO, 2016). This is equivalent to assuming that ca. 6.6% of global marine fish capture stem from EU. Based on this, we estimated that 1,514 tonnes of dolly rope is used globally per year. With a loss of about 20% (average of the range 15-25%), this amounts to 303 tonnes of dolly rope directly lost to oceans per year.

Microplastics

Use of cosmetics and personal care products

Microplastics originating from cosmetics and personal care products used by consumers and lost in wastewater are termed microbeads. Microbeads are primarily made from PE, PP, PET, and PA (Beat the microbead, 2018). Based on Gouin et al. (2015), it was assumed that 93% of microbeads cosmetics and personal care products are PE (as HDPE) while the last 7% was equally distributed between PP, PET, and PA. The geographical distribution in usage of cosmetics and personal care products was predicted by collecting information on the per-capita purchases on cosmetics and personal care products in different countries [USD/ capita] and relating this to the countries' per-capita GDP [USD/capita]. This data was collected for 41 countries (ITA, 2016; L'Oréal, n.d.; Statista, 2017, 2014) and a linear correlation between these two per-capita indicators was derived with an obtained r^2 value of 0.75. By retrieving the GDP per capita for the regions used in this study, the distribution in consumption of cosmetics and personal care products was derived (see Table 10). This estimation assumes an equal distribution between costs of cosmetics and personal care products and amounts of microbeads in the cosmetics and personal care products.

Table 10. GDP per capita and per capita purchases on cosmetics and personal care products distributed on regions included in this mapping. Share of total purchases on cosmetics and personal care products in region relative to global purchases on cosmetics and personal care products

Region	GDP per capita [USD]	Per capita purchases on cosmetics and personal care products [USD]	Share of global purchases on cosmetics and personal care products
NAFTA (incl. rest of North America)	43,484	171.9	17%
Western Europe	37,720	153.5	14%
Japan	38,894	157.3	4%
Central Europe & CIS	7,648	57.3	5%
Asia (excl. Japan, India, and China)	3,981	45.5	11%
Africa	1,634	38.0	9%
Latin America & Caribbean	8,306	59.4	6%
Oceania	35,674	147.0	1%
India	1,709	38.3	10%
China	8,199	59.0	17%
Middle East	8,556	60.2	5%
World average	10,113	65.2	

Based on information on the amount of microplastics from consumer and personal care products (as microbeads), information on the share of population connected to a wastewater collection system, the share of population with wastewater treatment, and the distribution of wastewater treatment technology level, the mass of microplastics lost to the environment were estimated. The total loss of microplastics in cosmetics and personal care products to the environment was estimated as:

Eq. 2
$$m\_lost\_env_{microbeads} = \sum_i m\_consumed_{microbeads,i} \times \left(fr_{WWTP,i} \left(1 - WWTP_{eff,microbead,i}\right) + \left(1 - fr_{WWTP,i}\right)\right)$$

Where m_lost_env$_{microbeads}$ [tonnes] is the mass of plastic microbeads lost to the environment. m_consumed$_{microbeads,i}$ [tonnes] is the mass of plastic microbeads in consumed cosmetics and personal care products in region *i*. WWTP$_{eff}$ [-] is the microbeads removal efficiency in the WWTP in region *i*.

Based on the regional consumption of consumer and personal care products, the associated loss to wastewater and the treatment of the wastewater, the amounts of microplastics loss to the environment from use of consumer and personal care products is given in Table 11.

Table 11. Total consumption of microbeads in consumer and personal care products, share of wastewater treated in wastewater treatment plant, removal rate of microbeads in the waste water treatment plant, and the amount of microbeads lost to the environment

Region	Share of total purchases	Absolute microbeads amount from consumer and personal care products [tonnes]	Share of regions where waste water is treated in WWTP	Microbeads removal rate in WWTP	Absolute microbeads amount lost to environment [tonnes]
NAFTA (incl. rest of North America)	17%	4,356	74%	93.7%	1,408
Western Europe	14%	3,447	92%	96.8%	441
Japan	4%	1,049	90%	93.4%	183
Central Europe & CIS	5%	1,201	36%	97.2%	791
Asia (excl. Japan, India, and China)	11%	2,741	15%	87.9%	2,385
Africa	9%	2,196	3%	87.9%	2,139
Latin America & Caribbean	6%	1,577	33%	90.0%	1,122
Oceania	1%	305	77%	94.5%	86
India	10%	2,629	60%	87.9%	1,264
China	17%	4,345	33%	92.0%	3,054
Middle East	5%	1,306	38%	92.4%	851
Total		25,153			13,724

Loss via washing of textiles – Clothing

About 2% of microplastics in clothing are lost via washing during the lifetime of the clothing (Boucher and Friot, 2017). With an annual consumption of about 25 Mt of plastic fibers for clothing and assuming that the annual consumption is constant over time, this amount to about 0.5 Mt of fibers entering wastewater. We assume the distribution of fiber types lost (i.e. PP, PET, and PA fibers) is equal to the distribution in annual fiber production.

Based on information on the amount of microplastics lost from washing of textiles (as fibers), information on the share of population connected to a wastewater collection system, the share of population with wastewater treatment, and the distribution of wastewater treatment technology level, the mass of microplastics lost to the environment were estimated. The total loss of microplastics from textile washing to the environment was estimated using Equation 3. Table 12 reports the results differentiated by region.

Eq. 3

$$m\_lost\_env_{fibres} = \sum_i m\_lost\_washing_{fibres,i} \times \left(fr_{WWTP,i} \left(1 - WWTP_{eff,fibres,i}\right) + \left(1 - fr_{WWTP,i}\right)\right)$$

Where $m\_lost\_env_{fibres}$ [tonnes] is the mass of plastic microfibers lost to the environment. $m\_lost\_washing_{fibres,i}$ [tonnes] is the mass of plastic microfibers lost during washing of the textiles in region i. $WWTP_{eff}$ [-] is the microfiber removal efficiency in the WWTP in region i.

Table 12. Total loss of microfibers to wastewater from washing, share of wastewater treated in wastewater treatment plant, removal rate of microfibers in the waste water treatment plant, and the amount of microfibers lost to the environment

Region	Regional distribution of plastic fibers for clothing	Absolute plastic microfiber amount from textiles [tonnes]	Share of wastewater treated in WWPT	Plastic microfiber removal in WWTP	Absolute microfibers amount lost [tonnes]
NAFTA (incl. rest of North America)	22%	107,880	74%	92.9%	35,487
Western Europe	9%	45,858	92%	94.9%	6,645
Japan	4%	17,612	90%	92.8%	3,173
Central Europe & CIS	6%	31,347	36%	95.2%	20,848
Asia (excl. Japan, India, and China)	12%	59,963	15%	88.8%	52,107
Africa	2%	8,628	3%	88.8%	8,402
Latin America & Caribbean	4%	19,849	33%	90.2%	14,109
Oceania	2%	10,277	77%	93.4%	2,973
India	14%	68,427	60%	88.8%	32,568
China	21%	102,655	33%	92.0%	72,138
Middle East	5%	24,868	38%	91.9%	16,247
Total		497,364			264,696

Tyre abrasion

Microplastics are also lost to the environment from abrasion of tyres during vehicle use. The primary elastomer lost is styrene butadiene rubber (SBR) (Sundt et al., 2014). Based on Boucher and Friot (2017), about 20% of the synthetic rubber in the tyre is lost over the tyre's lifetime. With an annual consumption of about 7 Mt of synthetic rubber for tyres and assuming that the annual consumption is constant over time, this amount to about 1.41 Mt of microplastic lost to the environment per year. Tyre abrasion generally depends on a number of factors, such as driving style, weather, and tire and road characteristics. The tyre abrasion rate has been found to higher in cities due to the increased need for acceleration, braking, and cornering (Wik and Dave, 2009). Hence, it is also likely that the majority of tyre elastomer particles will run-off to the sewage system. If a combined sewage system is used, then the particles will likely be captured in the WWTP, if separate sewage system is used, then the particles will likely be emitted to freshwater or marine waters. However, this aspect could not be adequately quantified due to lack of sufficient data.

Road markings

Road markings, e.g. yellow and white stripes on roads, consist of ca. 1 – 5 % polymers such as acryl-monomers, styrene-isoprene-styrene, etylene-vinylacetat, and polyamide (Sundt et al., 2014). According to Boucher and Friot (2017), about 588 tonnes of plastics is used per year for road marking. The lifetime varies highly depending on road use and weather conditions, but road markings may be completely removed after 1 year (Sundt et al., 2014), however, road marking are often repainted before complete removal due to traffic safety reasons. It is assumed that over the road markings lifetime), all of it will be removed through erosion and lost to the environment (Sundt et al., 2014), giving a total loss of 0.59 Mt.

City dust

City dust as plastic losses is a generic term associated with sources in urban environments identified in recent country assessments (e.g. Boucher and Friot, 2017). In the current mapping, city dust includes weathering of exterior paints, indoor dust, abrasion of protective coatings, road wear, and abrasion of shoe soles. The plastic types lost as part of city dust were assumed proportional to the global production, excluding production of marine coatings, road marking coatings, and elastomers for tyres which were quantified separately. Information on emissions of microplastics related to general wear and dust generation are scarce. National assessments performed by Lassen et al. (2015), Magnusson et al. (2016), and Sundt et al. (2014) were retrieved and used to scale the losses from national to global scale based on population data. This gave a total loss of 0.65 Mt of microplastics to the environment from city dust –see Table 13 for detailed overview by sources.

Table 13. Plastics losses characterized under the general category "city dust" and the amount of plastics lost to the environment

Source	Amount lost to environment [million tonnes]	Reference for national to global level estimate
Exterior paints	0.12	Sundt et al. (2014)
Household dust	0.01	Magnusson et al. (2016)
Protective coatings	0.05	Magnusson et al. (2016)
Road wear	0.01	Magnusson et al. (2016)
Shoe sole abrasion	0.47	Lassen et al. (2015)
Total	0.65	

It is also likely that the majority of the microplastics from city dust will run-off to the sewage system. If a combined sewage system is used, then the particles will likely be captured in the WWTP, if separate sewage system is used, then the particles will likely be emitted to freshwater or marine waters. However, this aspect could not be adequately quantified due to lack of sufficient data.

Loss through weathering of marine coatings

About 10% of the plastics used in marine coatings for ships and marine infrastructures is assumed to be lost to marine environment over the coatings lifetime (Boucher and Friot, 2017). With a global use of 0.45 Mt of plastics for marine coatings, this gives a loss of 0.05 Mt of plastics ending up directly to the marine environment.

6.3. End-of-life

Information on the loss of both macro- and microplastics during EoL treatment for the different plastics applications is generally lacking. Only Jambeck et al. (2015) estimated amounts of plastics lost as a result of mismanaged (municipal solid) waste which is dealt with in Section 6.3.1.1. Table 14 provides a qualitative overview of the risks of plastics losses to the marine environment when handling solid waste from different plastic applications. Information on losses of microplastics from solid waste treatment is lacking and the EoL stage of the different applications is generally not considered an important source of macro- or microplastics loss. Nevertheless, losses of both macroplastics and microplastics can occur during waste treatment either during handling of the waste or as a result of mismanaged waste treatment where plastics are lost as the solid waste is weathered in the environment.

Table 14. Qualitative overview of the risks of micro- and macroplastic losses to the marine environment when handling solid waste from different plastic applications.

Application	Risk of marine debris
Transportation – Other	End-of-life vehicles (ELV) are generally not considered a source of macro or microplastics. ELVs that are mismanaged via dumping will remain relatively inert and the plastic being part of the vehicle will not be released to oceans. However, there may be some losses due to weathering of the ELVs in the environment, e.g. from wind, precipitation, and photodegradation. Moreover, there can be losses of plastics during dismantling of the ELVs as part of preparation for recycling or during shredding as part of preparation for landfilling.
Transportation – Tyres	Tyres are generally not considered problematic in terms of marine debris during waste treatment. Even during mismanaged treatment such as dumping, the elastomer in the tyre is embedded within the tyre and is not likely to be lost. After dumping, however, some losses to the environment will occur due to weathering of the tyres in the environment, e.g. from wind, precipitation, and photodegradation
Packaging	Packaging is subject to losses of macroplastic during waste handling and treatment either as a clean plastics fraction for recycling or as part of mixed MSW. Losses of mismanaged packaging waste are likely as plastic packaging (such as plastic bags or light bottles) as susceptible to wind drift and other removal pathways such as flooding during overflows.
Building and Construction	Plastic that is part of building and construction waste is not likely to be released to the oceans. If recycled, the plastic is likely to be collected and recycled. If landfilled or dumped, the plastic is likely to remain embedded as part of the inert C&D waste.
Electrical/Electronic	The main risk for this plastic to be released to oceans is if the WEEE is treated as part of residual MSW where the waste is inadequately treated. According to (Bigum et al., 2013)11. kg of batteries, 2.2. kg of toners and 16. kg of cables had been wrongfully discarded. This corresponds to a Danish household discarding 29. g of WEEE (7 items per year, about 16% of WEEE is discarded as part of residual MSW
Consumer & Institutional Products	Consumer & institutional products are subject to losses of macroplastic during waste handling and treatment either as a clean plastics fraction for recycling or as part of mixed MSW.
Industrial/Machinery	As for ELVs, Industrial/Machinery is generally not considered a source of macro or microplastics. Machinery, which is mismanaged via dumping, will remain relatively inert and the plastics contained can be assumed not to be released to oceans. However, in the same way as ELVs, plastics might be lost from Industrial/Machinery due to weathering of the machinery in the environment, and during dismantling or shredding as part of disposal operations.
Other	Unknown
Textile sector – clothing	Clothing which is mixed with other MSW fractions can be lost as part of inadequate waste treatment. However, losses are likely limited as textiles are less subsequent to common removals from open dumps such as wind drift.
Textile sector – Others	Textiles which are mixed with other MSW fractions can be lost as part of inadequate waste treatment. However, losses are likely limited as textiles are less subsequent to common removals from open dumps such as wind drift.

Mismanaged municipal solid waste treatment

The plastics end-of-life phase is generally considered to be the phase where most losses occur (Jambeck et al., 2015) and plastic in the MSW shows the largest risk of being lost to the environment, while other types of waste, such as ELVs or C&D waste, are considered not to be important sources of plastic losses to the environment (see Table 14). The following plastic waste fractions were assumed to be part of the overall MSW: packaging, electrical/electronic, consumer & institutional products, and textiles (both clothing and others).

Using the same assumptions as in Jambeck et al. (2015), it was assumed that all waste dumping as well as waste landfilling in countries, classified by the World Bank as low income countries, was associated with mismanaged waste. Based on data from Hoornweg and Bhada-Tata (2012) on MSW composition and treatment, we estimated the share of plastic MSW going to landfill or open dumps. Aggregation from national to regional level was done by population-weighted averaging. Data on China and India were not part of the dataset by Hoornweg and Bhada-Tata (2012). Therefore, alternative sources were used. The percentage share of mismanaged MSW in India was found to be approx. 90% (Kumar et al., 2009) and the share of mismanaged MSW in China was retrieved to be ca. 32% (Mian et al., 2017).

Jambeck et al. (2015) estimated that between 15% and 40 % of mismanaged plastic waste is lost to the environment. Although, it may be realistic for direct littering, this value was judged to be overestimated for low technology landfills and open dumps. Indeed, it is assumed that crude measures for reducing waste losses (e.g. such as fences for reducing loss due to wind drift) will be present in low-tech landfills while the rather constant addition of new waste will, at least to some extent, compress and capture previously disposed waste. Hence, a 10% loss of mismanaged plastic waste was preferably assumed. The total resulting loss of plastic waste to the environment was estimated to approximate 3.9 Mt –see Table 15.

Table 15. Share of mismanaged waste for each region, the total amounts of plastic MSW, and amount of plastic waste lost to the environment.

Regions	Mismanaged share of MSW	Mismanaged plastic MSW [million tonnes/yr]	Amount lost to the environment [million tonnes/yr]
NAFTA (incl. rest of North America)	No mismanaged waste		
Western Europe	No mismanaged waste		
Japan	No mismanaged waste		
Central Europe & CIS	1%	0.12	0.01
Asia (excl. Japan, India, and China)	17%	5.09	0.51
Africa	93%	9.47	0.95
Latin America & Caribbean	31%	8.86	0.89
Oceania	No mismanaged waste		
India	90%	3.87	0.39
China	32%	3.75	0.37
Middle East	53%	7.53	0.75
Total		38.70	3.87

To estimate the types of plastic lost as part of mismanaged MSW the regional distribution in the plastic applications found in MSW was used, i.e. for packaging, electrical/electronic, consumer & institutional products, and textiles (both clothing and others). To estimate the types of plastic lost as part of mismanaged MSW the regional distribution of applications was used. It was assumed that the distribution of each application in consumption as reported in Table 4 was equal to the distribution in the MSW. The regional distribution in applications using plastic as given from Table 4 was combined with the share of plastic types included for each application as given from Table A3 in Appendix 2.

6.4. Total losses

An overview of the total losses from all sources for macroplastics and microplastics is provided in Table 16 while Figure 6 provides an overview of the plastics lost and the environment compartment (or compartments) the plastics are lost to. The total plastic losses to the environment amount to 8.28 Mt of each year, with a distribution of 64% and 36% for macro- and microplastics, respectively. The largest source of macroplastics to the environment is mismanaged waste which account for 73.4% of the total macroplastics loss. For microplastics, the largest source is abrasion of tyres which account for almost half of the microplastics lost to the environment. City dust and abrasion of road markings are also important contributors with 21.7% and 19.6% of the total microplastics, respectively. This indicates that most losses are related to indirect losses generated from use and weathering of plastics. On the other hand, losses related to products using microplastics, such as cosmetics and personal care products only have little contribution to the total microplastic loss. Direct losses of microplastics from plastics production is also very low compared to other microplastic losses. This finding is in line with measurements for the Baltic Sea where it was found that microplastics concentrations have remained stable for the last three decades although production has increased (Beer et al., 2017). This was likely a result of microplastics losses being population specific, because although plastics production in Europe had increased by about a factor three since 1985, the population in that period had remained relatively stable around the Baltic Sea (Beer et al., 2017).

The estimated losses of plastics to the environment from littering and mismanaged waste treatment, i.e. 4.67 Mt, are comparable to other studies. Jambeck et al. (2015) estimates that between 4.8 and 12.7 Mt of plastic waste generated within 50 km of the coast are released to the ocean as a result of mismanaged waste. However, the loss estimated in this mapping was a global value of loss to the environment while Jambeck et al. (2015) was restricted to coastal areas and losses to the ocean. For this reason, the estimate in this mapping appears to be lower than the estimate by Jambeck et al. (2015). The difference can be attributed to differences in methodology where we assume that only 10 % of mismanaged waste is lost to the environment while Jambeck et al. (2015) assume 15% to arrive at the estimated 4.8 Mt. Moreover, we used updated values for deriving the MSW generation and the share of plastic in the MSW, in addition to deriving a model for estimating MSW generation, thus making a substantial difference. For instance, for China, which is the largest emitter of marine plastics (Jambeck et al., 2015), Jambeck et al. (2015) apply a waste generation rate based on the urban Chinese population (i.e. 1.1 kg/cap/day from Hoornweg et al., 2005). In contrast, we determined MSW generation as a function of GDP per capita for the total Chinese population, thus resulting in a rate of 0.31 kg/cap/day (3 times lower). When upscaling at the country level, this leads to important discrepancies.

For microplastics, only the study by Boucher and Friot (2017) could be found relevant for comparison with the current assessment. They find that 1.8 to 5 Mt of microplastics are lost to the environment. Our study estimated a loss of approximately 3 Mt of microplastics, thereby, positioning itself near the median of the range estimated by Boucher and Friot (2017). This relative alignment could be expected as the data sources for the calculations of microplastic losses are similar between the two studies.

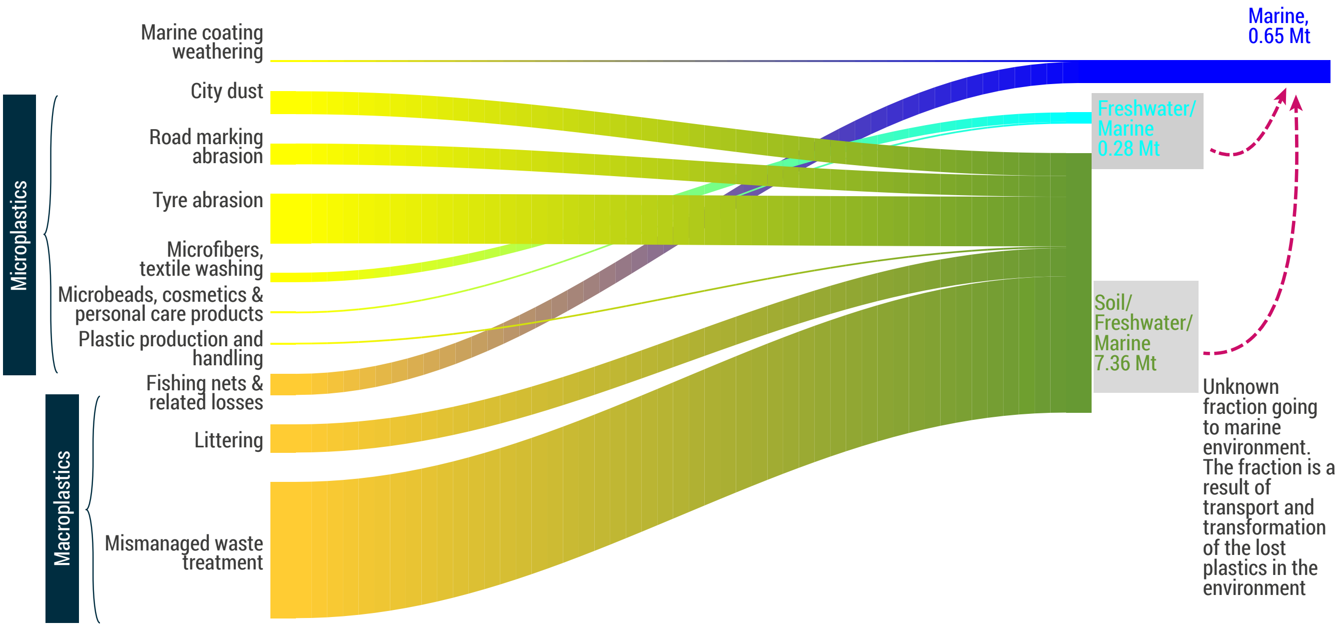


Figure 6. Sources of plastic losses and the environmental compartments to which the plastics are lost

Table 16. Total annual amounts of microplastics and macroplastics lost to the environment

Loss source	Amount [million tonnes]	Distribution (%)
Total Macroplastic loss to environment	5.27	64%
Loss of plastic to environment from mismanaged waste treatment	3.87	46.7%
Loss of plastic from littering	0.80	9.7%
Fishing nets and other losses of fibers related to fishing	0.60	7.2%
Total Microplastic loss to environment	3.01	36%
Microbeads lost to environment from use of cosmetics and personal care products	0.01	0.2%
Loss of rubber from tyre abrasion	1.41	17.1%
Loss through weathering of marine coatings	0.05	0.5%
Loss via washing of textiles – clothing	0.26	3.2%
Road markings	0.59	7.1%
City dust	0.65	7.9%
Loss of plastic during upstream plastic production (Virgin plastic pellets)	0.03	0.4%
Total plastic loss	8.28	100%

Plastics losses distributed between polymer types and regions

The amounts of losses from different types of plastics was determined by combining (i) the information on plastic types used for different applications (Table A3 in Appendix 2), (ii) the calculated total losses (Table 16), and (iii) the plastic applications related to these losses as given from the description of each loss type. The distributions of macroplastics and microplastics types lost to the environment are given in Table 17.

The amounts of losses from different sources of plastic losses distributed into regions are shown in Table 18. The regional distribution was determined using the regional data that have been applied throughout the mapping of the plastic value chain. Overall, for macroplastics, the regions contributing most to total losses to the environment were Africa, Latin America and the Caribbean, and the Middle East which all have a high level of plastic consumption and a large fraction of improperly managed MSW. For microplastics, the most contributing regions were NAFTA (incl. rest of North America), China, Asia (excluding Japan, India, and China), and Western Europe which account for 16%, 20%, 14%, and 11% of the total microplastic losses, respectively. The losses of microplastics are mainly driven by large population and per-capita plastic consumption in the regions.

6.5. Losses not accounted for

A number of known losses of plastic to the environment have not been quantified because adequate knowledge about these losses is missing (Table 19). The losses not accounted for a based on the previously conducted national assessments (Essel et al., 2015; Lassen et al., 2015; Magnusson et al., 2016; Sundt et al., 2014). Together with the losses accounted for in this study, we consider to be comprehensively covering the main sources of potential losses of microplastic and macroplastic to the environment.

Table 17. Mass distribution of macro- and microplastic types lost to the environment per year in Mt and the share of total macroplastics lost, total microplastics lost, total plastics lost, and amount produced per year.

Plastic type	Amount of microplastics lost [million tonnes]	Amount of macroplastics lost [million tonnes]	Total amount lost [million tonnes]	Share of total microplastic loss [%]	Share of total macroplastic loss [%]	Share of total loss [%]	Share of total produced amount lost [%]
PP	0.111	1.061	1.173	4%	20%	14%	2%
LDPE, LLDPE	0.082	0.869	0.951	3%	16%	11%	2%
PVC	0.077	0.157	0.234	3%	3%	3%	1%
HDPE	0.085	0.623	0.708	3%	12%	9%	2%
PET	0.034	0.423	0.457	1%	8%	6%	2%
PS, EPS	0.034	0.262	0.296	1%	5%	4%	2%
PUR	0.029	0.069	0.098	1%	1%	1%	1%
Other Thermopl.	0.019	0.034	0.053	1%	1%	1%	0.5%
ABS, ASA, SAN	0.014	0.130	0.145	0.5%	2%	2%	2%
PC	0.005	0.009	0.013	0.2%	0.2%	0.2%	0.5%
PA	0.005	0.009	0.014	0.2%	0.2%	0.2%	1%
Elastomers (other than tyres)	0.014	0.025	0.039	0.5%	0.5%	0.5%	0.5%
Thermosets	0.061	0.107	0.168	2%	2%	2%	0.5%
Adhesives	0.017	0.030	0.047	1%	1%	1%	0.5%
Sealants	0.003	0.006	0.009	0.1%	0.1%	0.1%	0.5%
Coatings	0.005	0.009	0.014	0.2%	0.2%	0.2%	0.5%
Marine coatings	0.045	0.000	0.045	2%	0%	1%	10%
Road marking coatings	0.588	0.000	0.588	20%	0%	7%	100%
PP fibers	0.203	0.461	0.664	7%	9%	8%	2%
PET fibers	0.127	0.288	0.416	4%	5%	5%	2%
PA fibers	0.030	0.668	0.698	1%	13%	8%	16%
Elastomers (tyres)	1.414	0.000	1.414	47%	0%	17%	20%
Bioplastics	0.004	0.036	0.039	0.1%	1%	0.5%	2%
Total	3.014	5.274	8.288	100%	100%	100%	2%

Table 18. Source of losses of macro- and microplastics to the environment distributed into geographical regions.

Micro- or macroplastic	Source of loss	Share of total loss [%]											Total loss [Mt]
		NAFTA (incl. rest of North America)	Western Europe	Japan	Central Europe & CIS	Asia (excl. Japan, India, and China)	Africa	Latin America & Caribbean	Oceania	India	China	Middle East	
Macroplastics	Loss of plastic to environment from mismanaged waste treatment	0%	0%	0%	0%	13%	24%	23%	0%	10%	10%	19%	3.87
	Loss of plastic from littering	11%	17%	3%	7%	18%	6%	18%	1%	3%	7%	9%	0.80
	Fishing nets and other losses of fibers related to fishing	Global estimate, no information about the regions where losses occur											0.60
	Total macroplastics	2%	3%	1%	1%	14%	21%	22%	0%	9%	9%	18%	5.27
Microplastics	Microbeads lost to environment from use of cosmetics and personal care products	10%	3%	1%	6%	17%	16%	8%	1%	9%	22%	6%	0.01
	Loss of rubber from tyre abrasion	20%	13%	2%	12%	14%	3%	6%	1%	6%	18%	5%	1.41
	Loss through weathering of marine coatings	22%	18%	4%	4%	6%	6%	10%	0%	4%	19%	5%	0.05
	Loss via washing of textiles – clothing	13%	3%	1%	8%	20%	3%	5%	1%	12%	27%	6%	0.26
	Road markings	22%	18%	4%	4%	6%	6%	10%	0%	4%	19%	5%	0.59
	City dust	3%	1%	0%	5%	21%	22%	8%	0%	14%	20%	6%	0.65
	Loss of plastic during upstream plastic production (Virgin plastic pellets)	17%	15%	4%	2%	9%	6%	5%	0%	11%	28%	2%	0.03
	Total macroplastics	16%	11%	2%	9%	14%	8%	7%	1%	8%	20%	5%	3.01

Table 19. List of known sources of plastic loss where estimates of plastic loss to environment could not be made

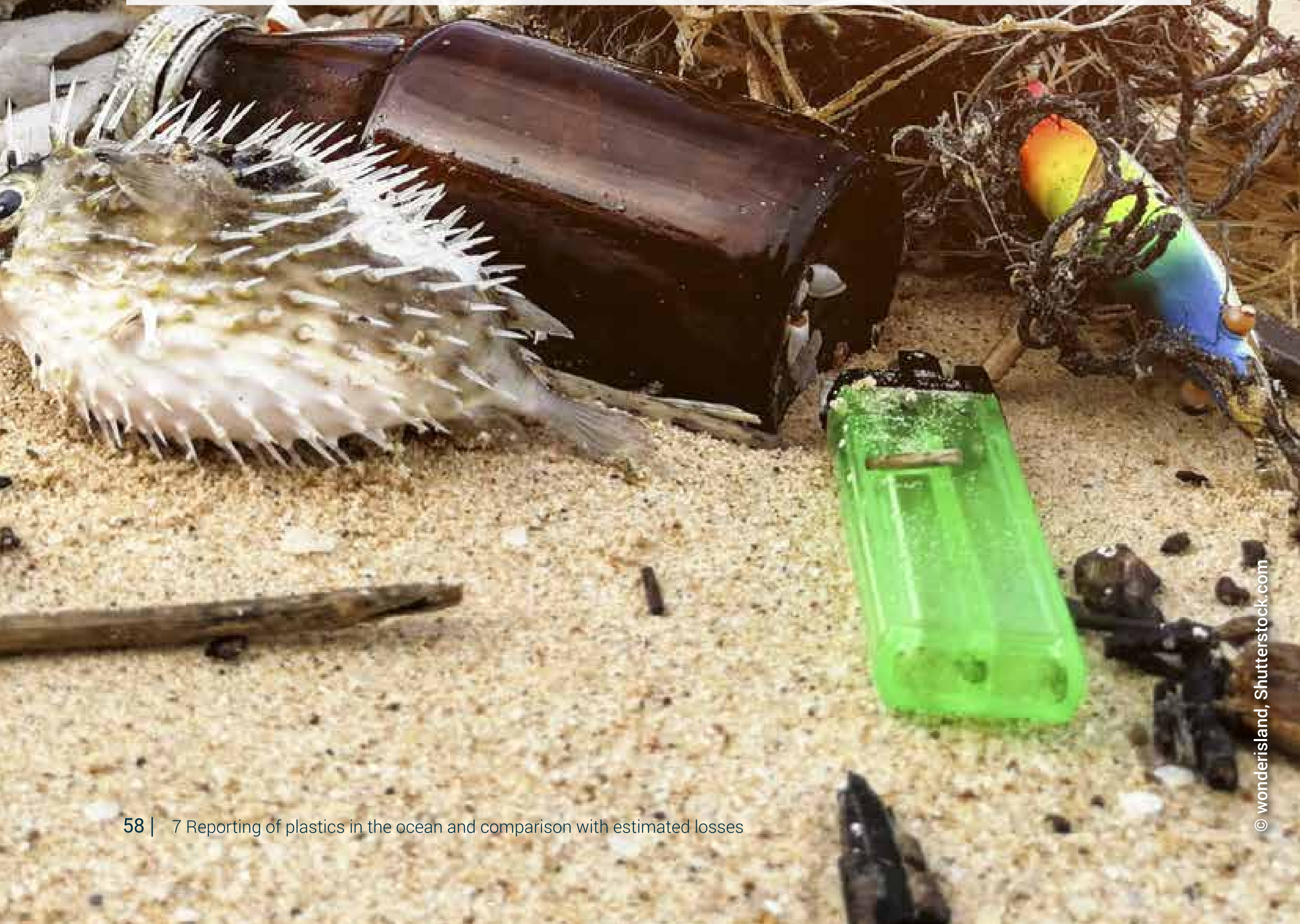
Source of plastic loss	Description	Types of plastic	Micro/Macro plastic	Qualitative evaluation of relevance
Floats and other similar losses from marinas and aquaculture	Floats are common in marinas and aquaculture, as they are sturdy and have very good floating abilities. They can be used as buoys or to support floating jetties (Magnusson et al., 2016)	Primarily polystyrene	May both be emitted as microplastic as a result of weathering of the floats or as macroplastic where larger part of even entire float is lost.	High importance as losses are directly to the marine environment
Abrasive blasting	Plastic granules are used to remove tenacious contaminants e.g. paint, plastics, rubber and adhesive from plastic tools and dies etc. (Magnusson et al., 2016)	The material of the granules varies depending on the wanted features; they may consist of poly(methyl metacrylic) polymer, melamine, urea formaldehyde, urea amino polymers or poly amino nylon type (Magnusson et al., 2016)	Microplastics as the size of the plastic granules used ranges from 0.15-2.5 mm (Magnusson et al., 2016)	Low importance as loss of plastic particles is often reported to be collected (Magnusson et al., 2016). If not collected the particles will likely be washed down the drain (Magnusson et al., 2016) and the majority will be removed in the WWTP.
Pharmaceuticals	Microplastics are used as microspheres in medicines to administrate drugs to organs of humans and farmed animals (Magnusson et al., 2016)	Biodegradable plastics are often used (e.g. PMMA, PLA, PGA), but can also be made of polycarbonate or polystyrene which is not biodegradable (Magnusson et al., 2016)	Microplastic	Low importance as most microplastics are biodegradable. However, part of the non-biodegradable plastics may be excreted by animals and subsequent go to freshwater and from there to the ocean.
Activities on board ships	Garbage, wash water (water used for cleaning of deck and external surfaces) and wastewater discharged from ships (Magnusson et al., 2016)	Not known	Both microplastic and macroplastic have potential for being lost	Medium importance. Loss is likely limited, especially given that Disposal of plastics into the sea is prohibited (Magnusson et al., 2016). However, any losses are directly to oceans, thus, being of greater importance.
Agricultural plastics	Plastic are used in agricultural plastic as big bags containing fertilizer or seeds, silage film, foil, net, spools and drums (Magnusson et al., 2016).	Different types of plastic, but often polyethylene foils (Lassen et al., 2015)	Primarily macroplastics through losses of bigger plastic pieces. However, weathering during use may lead to release of microplastics (Lassen et al., 2015; Magnusson et al., 2016).	Medium importance. Both microplastic and macroplastic is likely to be lost either to soil or freshwater. Is lost to soil the plastic may be transported to freshwater via runoff or wind drift. The plastic in the freshwater may be transport to oceans.
Organic waste treatment	Plastic impurities form a small part of compost and biogas digestate generated by treatment of organic waste (Lassen et al., 2015)	The plastics differ and are likely similar to the plastic type composition in MSW	Microplastic, larger plastic types are removed as part of the organic treatment (Magnusson et al., 2016)	Medium importance. Although, only a small fraction is likely to be found in compost and biogas digestate the compost and digestate will likely be applied to soil where the microplastic is subject to transport from soil via runoff to freshwater, from which it can be transported to the ocean
Artificial turfs	For Sweden it is estimated that between 2300-3900 tonnes are lost per year (Magnusson et al., 2016). For Denmark an annual loss between 450-1580 tonnes was estimated with 1-20 t/yr going to surface water (Lassen et al., 2015).	SBR, TPE, EPDM	Microplastic	Low importance. If extrapolating the Danish estimate of loss to surface water using a per capita approach. The global microplastic loss from artificial turfs is between 0.001 - 0.026 Mt per year. Given that artificial turfs are likely more common in a northern country such as Denmark relative to rest of the World the importance of this source is considered little.
Industrial and construction waste	Dumping of construction and process waste, such as insulation, plastic cables from dynamite, fibers for concrete (Sundt et al., 2014)	Primarily PVC (Lassen et al., 2015), but also, PE, PS (EPS), and PUR (Lassen et al., 2015; Magnusson et al., 2016). Other plastic types are also be used.	Both microplastic and macroplastic. Microplastics during wear and tear of the plastic while large plastic parts may also be lost during handling or from wind drift	Medium importance. The amount of plastic is likely low as formal or informal recycling is likely to undergo. Moreover, the plastic is part of other construction waste and likely to remain as part of the waste. However, as the plastic primarily consists of PVC the potential release of toxic additives in the plastic could be problematic.
Flooding and other extreme nature events	Flooding or other extreme nature events are likely to carry a large mass of plastic from inland to the ocean	All types	Both microplastic and macroplastic	Medium importance, it was not possible to quantify the amounts lost from extreme events. However, given that such events occur rarely we assume this to be a minor problem. However, as extreme event are expected to occur more frequent, e.g. as a results of climate change, we expect this to be a more important source of plastic losses in the future
Plastic recycling facilities	Plastic can be lost due to wind drift and overloaded containers and bins during handling of plastic waste collected for recycling	All types	Primarily macroplastic which is collected for recycling, but microplastic can also be lost	Medium importance. The exact quantity is not known but the fraction lost is likely similar to the fraction lost during handling of virgin plastic pellets (i.e. 0.005% of the recycled plastic)
Printer toner	laser printer toner to a large extent consists of microscopic thermoplastic powder (Lassen et al., 2015)	Usually the powder is a styrene acrylate copolymer (Lassen et al., 2015)	The polymer diameter of the plastic particles is about 2- 10 μm and thus falls within the definition of microplastics (Lassen et al., 2015)	Not known

7

Reporting of plastics in the ocean and comparison with estimated losses

Chapter highlights

- Findings of PP, LDPE, HDPE, and PET coincide well with the theory that the majority of microplastics stem from weathering of macroplastic from littering and mismanaged solid waste
- Findings of PP, PP-fibers, and PET-fibers correspond well with losses from city dust, usage of cosmetics and personal care products, and textile washing.
- Findings of PP, nylon and PS as microplastics are likely also a result of losses of fishing nets, fishing gears, floats, and other equipment related to maritime activities. Here losses may be as direct microplastics or from degraded macroplastics
- The majority of plastic related findings can be attributed to general consumer goods for recreational activities and fishing and maritime related activities that have either been lost either through littering or inadequate waste management. The reported macroplastics types correspond well with the major macroplastic types lost, i.e. PP, LDPE, HDPE, PET, and PA fibers
- Elastomers from tyre abrasion were found to be the largest loss of microplastics. Yet, the elastomers are not reported in ocean monitoring.



To get an idea about the plastic types lost to the environment which actually reach the marine environment, the estimated losses to the environment (see Ch. 6) were compared with retrieved information about the primary plastic types found in marine environment. Table 19 documents a mini-review of microplastics identified in marine debris, which is used for comparative purposes in the following.

This comparison between the estimated losses and reporting of plastics in the ocean was done because it was not possible to estimate the share of the plastics lost to the environment that are eventually lost to the marine environment. Such estimates require modelling of the fate (i.e. transport and transformation) of the plastics in the environment, where only a fraction of the lost plastics will go to the oceans. For instance, if plastic waste is dumped in an area located far from marine- or freshwater the fraction of the plastic going to the ocean will be close to or zero. Assessments on the plastic loss to oceans from different sources have been made (e.g. Boucher and Friot (2017)), but these assessments are based on global release factors which do not fully reflect the potentially large spatiotemporal variabilities that exist. Hence, such estimates are not necessarily representative of the actual situation in terms of losses to the marine environment.

For instance, in order to estimate the mass of microplastics released from a WWTP which end up in the ocean, one should first know the share of the treated wastewater effluent that is released to freshwater and marine water, respectively. For the share of wastewater released to freshwater, the share of the released microplastics that is transferred to the oceans needs to be estimated. This release will depend on the release location along the river and on river characteristics (e.g. monthly river runoff which can vary by more than ten orders of magnitude between rivers (Lebreton et al., 2017)). Such spatial difference is not well captured by global release factors and need further investigation. Ideally assessments of plastics losses to marine environment must be based on spatially and temporally differentiated models (that in turn are based on measurements), where the location of the plastic loss as well as the surrounding natural and anthropogenic conditions are known as the fraction actually being emitted to the marine environment will depend on site specific factors. Such detailed spatiotemporal modelling was not feasible within the scope of this project.

Moreover, the comparison is purely qualitative in terms of comparing the plastic and plastic polymer types lost from the plastic value chain (given in Ch. 6) with the plastic and plastic polymer types found in the marine environment. A quantitative comparison between amounts and lost and amounts in the marine environment was not feasible as this required a better understanding of the development over time. This is required to understand both the temporal development in plastic production and associated losses as well as the temporal development in number and concentration of plastics in the marine environment. Based on a recent study by Beer and colleagues (2017), it appears that a direct relationship between increase in plastic production (and associated losses) and plastics (in this case microplastics concentration) in the oceans do not exist and that other factors are influencing the marine concentration.

With all that in mind, the origins of microplastics in the marine environment might be attributed to two main sources: (a) direct introduction of microplastics through different transport mechanisms and (b) via weathering of macroplastics either in the ocean or during transport of the macroplastics to the ocean (Andrady, 2011). Indeed, the likely mechanism for generation of the majority of microplastics is via weathering of macroplastics (Andrady, 2011).

Indeed, the findings of PP, LDPE, HDPE, and PET correspond very well with the typical macroplastics losses (Table 17) and corroborate the theory that most microplastics might stem from degraded macroplastics, such as packaging and other plastic waste lost as a result of littering and mismanaged solid waste. However, findings of PP, PP-fibers, and PET-fibers also match with estimates of microplastics lost to the environment. These are primarily lost as part of city dust, usage of cosmetics and personal care products, and textile washing (Table 19). Findings of PP, nylon and PS are likely to also be a result of direct losses to oceans of fishing nets, fishing gears, floats, and other equipment related to maritime activities which have been weathered down to microplastics.

Tyre abrasion was, in this mapping, found to be the largest source of microplastics lost to the environment with annual loss of 1.4 Mt. With a specific gravity of 0.94 for tyre elastomers, such as SBR (Mishra and Shimpi, 2005), this would be expected to be substantially present in ocean microplastic samples. However, tyre elastomers are generally not part of the microplastics found in oceans (Table 19). Suggested reasons for this could be that (i) the elastomers behave different than what is expected. For instance vulcanised SBR used in tyres has a specific gravity of ca. 1.13 (Pal et al., 2009), thus, it is likely to sink to the bottom. (ii) A review study on occurrence of tyre particles in the environment indicated that SBR (used as marker for tyre participles) was being measured near roads and as dust in air (Wik and Dave, 2009). Thus, microplastics from tyre abrasion might be present, but the size of the abraded microplastics might be below the detection limit in sampling of marine microplastics. (iii) Finally, there is the possibility that microplastics from tyres are being captured before reaching the oceans, e.g. in soil or freshwater compartments or in the sludge of sewage treatment plants.

To get an idea about the quantities of microplastic participles from tyres that would be expected to reach the oceans, we made a simple back-of-the-envelope calculation of the fraction of tyre elastomers actually reaching the ocean. The calculation was based on our loss estimates and using global fate estimates.

For rural areas the tyre elastomers are likely removed via road runoff to a ditch and remain in soil, while a fraction leaches out to rivers. Lassen et al. (2015) estimates that between 2-5% of elastomers lost on rural roads end up in rivers. From the river to the ocean, a conservative estimate using the method of Lebreton et al. (2017) indicated that about 0.1 % of the microplastics released to river will reach the oceans. For urban areas, where half of the world population lives (World Bank, 2016b), the tyre elastomers are likely to go the sewage system which can either be released directly to aquatic environment (freshwater or marine) or go to a WWTP. We assume 50% going to WWTP as in Boucher and Friot (2017) and the rest being released to water. 50% of sewage outflows, including from WWTP, is assumed to go to freshwater and 50% to the ocean. We estimated the loss of microplastic elastomers from tyres, using the regional removal rates and overflow assumptions as described in Section 5.2 on wastewater treatment. The resulting total loss of tyre elastomers to the oceans was estimated to be 0.23 Mt, hence, 16% of the estimated loss to the environment. This value is comparable to the value derived by Boucher and Friot (2017), i.e. 0.36 Mt, and would still contribute substantially to the total microplastic loss, as reported in Table 17.

The fate of road marking microplastics is likely similar to tyre elastomer where about 85% of the plastic is being captured before it reaches the oceans. Nevertheless, it is remarkable that this relatively large amount of microplastics entering the oceans are not picked up in samplings of microplastics in the ocean. This indicate that measurements are either not designed in a way that picks up tyre elastomer particles, or it may suggest that tyre elastomers are being subject to environmental processes that either capture the microplastics or remove these from the oceans (e.g. via sedimentation or fast degradation).

Table 20. Commonly observed microplastics in marine debris

Microplastic type	Specific gravity	Typical products/ product categories	Reference
LDPE LLDPE	0.91 – 0.93	Plastic bags, six-pack rings, bottles, netting, drinking straws	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
HDPE	0.94	Milk and juice jugs	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PP	0.83 – 0.85	Rope, bottle caps, netting	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PS	1.05	Plastic utensils, food containers, Floats, bait boxes, foam cups	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PA (fibres)	1.13–1.35	Netting and traps	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PET	1.37–1.45	Plastic beverage bottles	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PET (polyester fibres)	1.37–1.45	Textiles	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PVC	1.38	Plastic film, bottles, cups	(Andrady, 2011; Hidalgo-Ruz et al., 2013)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
CA (cellulose acetat)		Cigarette filters	(Andrady, 2011)yielding microparticles that are carried into water by wind or wave action. Unlike inorganic fines present in sea water, microplastics concentrate persistent organic pollutants (POPs
PAN (polyacrylonitrile)	1.09–1.20	Acrylic fibers e.g. for textiles	(Hidalgo-Ruz et al., 2013)
POM (polyoximethylene)	1.41–1.61	Children's toys, loudspeaker grills, medical technology	(Hidalgo-Ruz et al., 2013)
PVAc (polyvinyl acetat)	1.19–1.31	Paper coatings, CO_2 barrier in bottles	(Hidalgo-Ruz et al., 2013)
PMA (poly methylacrylate)	1.17–1.20	Copolymer for HEMA production and leather finishing and textiles	(Hidalgo-Ruz et al., 2013)
AKD (alkyd)	1.24–2.10	used in paints and in moulds for casting	(Hidalgo-Ruz et al., 2013)
PUR (polyurethane)	1.2	Construction and building, hard plastic parts, bedding, footwear furniture, automotive interiors, carpet underlay, packaging, insulation	(Hidalgo-Ruz et al., 2013)

For macroplastics, findings from 25 years of beach litter sampling from coastal clean-ups (Ocean Conservancy, 2011) show that the majority of plastic related findings can be attributed to general consumer goods for recreational activities and fishing and maritime related activities that have either been lost either through littering or inadequate waste management (Table 20). The number of items does not reveal much about the actual amount, but it clearly illustrates the trend that marine macroplastics to a large degree stem from ocean/maritime activities and short-lived consumer goods. The reported macroplastics types correspond very well with the major macroplastic types lost, i.e. PP, LDPE, HDPE, PET, and PA fibers (Table 17). It thus appears that littering, mismanaged solid waste, and marine activities (from e.g. fishing, aquaculture and sailing activities.) are the dominant sources of marine macroplastics.

Table 21. Commonly observed macroplastics in marine debris based on beach litter sampling by Ocean Conservancy (2011)

Macroplastic type	Number of items found
Food wrappers/containers	14,766,533
Caps and lids	13,585,425
Beverage bottle	9,549,156
Plastic bags	7,825,319
Straws, stirrers	6,263,453
Rope (only fraction is plastic)	3,251,948
Clothing and shoes	2,715,113
Toys	1,459,601
Fishing line	1,340,114
Plastic sheeting/tarps	1,298,171
Balloons	1,248,892
Fishing nets	1,050,825
Bleach/cleaner bottles	967,491
6-pack holders	957,975
Oil/lube bottles	912,419
Buoys/floats	823,522
Strapping bands	801,886
Condoms	632,412
Bait containers/packaging	382,811
Crab/lobster/fish traps	314,322
Crates	313,997

8

Effects of micro- and macroplastics in the oceans

Chapter highlights

- The primary problem posed by macroplastics are animals either ingesting or being entangled in the plastics. Potential effects of macroplastics depend on physical characteristics, such as colour and shape
- Lost fishing equipment and packaging are the most problematic types of macroplastics in the marine environment
- Problem with microplastics relate to physical impacts such as obstruction of feeding organs, reduction in the feeding activity/rate/capacity, particle toxicity, and as carrier of invasive species.
- Microplastics can contain hazardous substances such as additives or residual monomers, leading to toxicity effects in marine organisms. Microplastics can also be a carrier of hazardous chemicals adsorbing to the plastic particles. If the microplastics are taken in by the organism, these chemicals might be leached to the organism's internal system and cause toxic effects.

To cite Paracelsus "*All things are poison, and nothing is without poison, the dosage alone makes it so a thing is not a poison*". Indeed, all plastics released to the marine environment may be harmful; however, the potency of the different plastics may vary greatly depending on their quantities and types. Hence, mass (e.g. in Mt) of macro- and microplastics ending up in the oceans is not a sufficient indicator of impacts, as it does not reflect the actual damages to the natural environment or potential impacts on human health (GESAMP, 2016). It would thus be misleading to only rely on mass when evaluating effects of plastics on the marine environment. For instance, the potential impacts related to the release of 1 kg of LDPE differs substantially depending on whether the LDPE is released as a solid 1 kg block or as 50 plastic bags, or if it is 1 kg of macroplastics (e.g. a plastic container) vs. 1 kg of microplastics. A necessity when aiming to identify hotspots and make sound decisions is therefore to better understand the impacts of different plastic types on the marine environment.

8.1. Macroplastics impacts

Macroplastics in the oceans are primarily problematic because their physical characteristics lead to entanglement in the plastics or to its ingestion, thus potentially leading to suffocation or intestinal blockage (UNEP, 2014). Moreover, macroplastics can be degraded into microplastics in the oceans and, thereby, cause impacts as microplastics –see Section 8.2.

Macroplastics affect all types of marine animals such as invertebrates, fish, reptiles, birds, mammals, and amphibians (UNEP, 2009). Most animals killed by marine plastics are undiscovered as the animals either sink to the bottom (e.g. fish) or are eaten by other animals making it near-impossible to observe and monitor the extent of the impacts, especially when considering the large ocean area over which the affected animals may spread (Laist, 1997; UNEP, 2014). A review of studies reporting impacts of marine debris on different species (Table 21) provide an overview of the different species which have been affected by marine debris either through entanglement or through ingestion of marine debris (CBD & STAP - GET, 2012; Laist, 1997). The review showed that marine debris have been known to affect individuals of 200 and 197 species for entanglement and ingestion-related impacts, respectively (CBD & STAP - GET, 2012). A closer look at the review by Laist (1997) showed that across all groups of animals, 90 species were only found to be affected by entanglement, 132 species were only found to be affected by ingestion, and 45 species were found to be affected by both entanglement and ingestion. This indicates that species are likely to be vulnerable to either entanglement or ingestion but less frequently to both (Laist, 1997). For instance, albatrosses or toothed whales are primarily affected by ingestion while crustaceans due to their feeding mechanism are only affected by entanglement (Table 21).

In addition to monitoring issues, a difficulty in estimating impacts of marine plastics on marine animals is the lack of knowledge of the physical characteristics of plastics when encountered by the marine species as the impacts on particular species will be dependent on the characteristics of the marine debris. The physical appearance of the plastics, e.g. specific colour or shape, can be problematic to certain organisms because the plastics resemble the animal's food. For instance, transparent plastic bags are problematic to sea turtles because they appear similar to jellyfish which is one of the sea turtles feeding sources (Gregory, 2009). In addition to the original appearance of the plastics when lost to the general environment or to the ocean, knowledge about changes to the plastics appearance once in environment are also needed. Here, it is important to know if certain plastics that are thought to be relatively harmless are in fact problematic because their appearance is changed in the environment (e.g. shape).

Table 22. Numbers and percentage of species worldwide with documented entanglement and ingestion records as presented in review (CBD & STAP - GET, 2012)

Species Group	Total number of species worldwide	Number and percentage of species with entanglement records	Number and percentage of species with ingestion records
Sea Turtles[1]	7	7 (100 %)	6 (86 %)
Seabirds[1]	312	67 (21 %)	119 (38 %)
Marine Mammals[1]	115	52 (45 %)	30 (26 %)
Fish[1]	16754	66 (0.39 %)	41 (0.24 %)
Crustaceans[2]	Not indicated	8	0
Squid[2]	Not indicated	0	1
Species Total	-	200	197

[1] Based on CBD & STAP - GET (2012),
[2] Based on Laist (1997)

In the Ocean Conservancy's 25 anniversary International Coastal Cleanup Report (Ocean Conservancy, 2011), a non-exhaustive overview of the number of identified cases of animals affected by marine debris over the last 25 years was presented (Table 22). Out of 4073 identified cases, the majority of the affected animals were found to be impacted by fishing lines (1636 cases) and fishing nets (672 cases). Rope and plastic bags were also found to be problematic with 426 and 404 cases, respectively. This indicates that with regard to impacts of macroplastics, lost fishing equipment and packaging are the most problematic types of plastics and releases of these plastics to oceans should therefore be minimized.

Table 23. Number of identified cases of animals affected by marine debris over the last 25 years (Ocean Conservancy, 2011)

Thrash type	Amphibians	Birds	Corals/ sponges	Fish	Invertebrates	Mammals	Reptiles	Total
Beverage bottles	3	8	0	27	47	13	2	100
Beverage cans	1	2	0	15	17	1	0	36
Crab/lobster/fish traps	1	11	1	48	106	3	3	173
Fishing hooks	2	76	0	54	10	3	6	151
Fishing line	9	722	14	553	237	46	55	1,636
Fishing nets	3	153	1	249	207	29	30	672
Bags (plastic)	13	102	0	142	91	33	23	404
Ribbon/string	0	91	0	37	29	7	2	166
Rope	4	160	0	114	53	71	24	426
6-pack holders	2	63	0	52	21	3	5	146
Plastic straps	2	30	0	34	12	5	5	88
Wire	1	31	1	16	13	7	6	75
Total	41	1449	17	1341	843	221	161	4073

8.2. Microplastics impacts

Knowledge about the types of impacts of microplastics on marine organism and the severity of the different types of impacts is still very limited and research attempting to shed light on this topic is ongoing. In the following sections, we provide some information on the different types of impacts to marine organism that can potentially arise from the presence of microplastics in the oceans. However, for more in-depth information, we refer to the comprehensive studies conducted by the GESAMP group (GESAMP, 2016, 2015) on the impacts of microplastics on the marine environment.

Exposure of marine organisms to microplastics

Marine organisms are exposed to microplastics via feeding (including filtration, active grazing and deposit feeding) and transport across the gills (ventilation) (GESAMP, 2016). Whether different species are prone to exposure to microplastics depends on a number of factors. Size, type, and shape of the microplastics are important characteristics with regard to types of exposure, and contribute determining which marine animals are most likely to be exposed. Plastic density is an important factor as plastics with lower density than seawater will float while heavier plastics will sink to the sediments (or stay in the water column). Floating plastics are more likely to be ingested by zooplankton and fish while sedimented plastics are more likely to be ingested by organisms living in the sediment, such as crabs, worms and mussels (Wright et al., 2013). Low-density plastics may also be sedimented due to biofouling, i.e. when a biofilm develops on the plastic, thereby increasing overall density (Wright et al., 2013). Colouring is also an influencing factor as microplastics whose colours resemble prey are more likely to be ingested (Wright et al., 2013).

Globally, marine organisms across many trophic levels interact with microplastics via a number of pathways. As a consequence, there are many mechanisms by which an organism can take up this material. Microplastics can adhere to the body (i.e. attached to external appendages) and/or be absorbed (i.e. taken up by the organisms into the body through cell membranes). Alternatively, microplastics can be taken up across the gills through ventilation, or enter the organisms via direct or indirect exposure routes. Organisms can thus ingest microplastics as food, unintentionally capturing it while feeding or intentionally choosing it and/or mistaking it for prey. Organisms may also indirectly ingest plastic while ingesting prey containing microplastics, leading to a so-called trophic transfer (GESAMP, 2015).

Physical effects of microplastics

Microplastics may also pose physical threats to biota. The effects may be obstruction of feeding organs, reduction in the feeding activity/rate/capacity due to ingestion of microplastics. Moreover, microplastics may adsorb onto the organism surface. For instance, a study showed that adsorption of nano-sized plastic particles to algae hindered photosynthesis and appeared to induce oxidative stress (GESAMP, 2015). Research showing and validating the impact and severity of physical effects is still ongoing, in particular in demonstrating observations of these effects outside of the laboratory (GESAMP, 2015). Moreover, transport of small microplastics (essentially nano-sized) from the intestinal system to tissue, cells, or body fluids of organisms have been shown in both field and laboratory studies. Indeed, the microplastics taken up in organs and tissues can lead to particle toxicity with associated inflammation and fibrosis. (GESAMP, 2015).

Carriers of invasive species

Microplastic debris may provide a substrate for organisms which may drift long distances and pose an ecological impact via transport of non-native species. The transport of marine organisms from microbes to invertebrates using floating substrate (e.g. wood) has always occurred. However, the increase in marine debris has substantially increased the available substratum for transport of invasive species in ocean regions. Moreover, the longevity of plastics relative to most of the natural substrata allows for increased transport distances which allows for mature during transport (GESAMP, 2016).

Carriers of hazardous chemicals

Plastics, with a structure derived from long chains of monomers, are considered to be biochemically inert due to their large molecular size (Rochman, 2015; Teuten et al., 2009). However, plastic debris present in the marine environment carry chemicals of smaller molecular size (molecular weight < 1000 g/mol). These chemicals can penetrate into cells, chemically interact with biologically important molecules and disrupt the endocrine system (Teuten et al., 2009). Such chemicals are categorized into two groups: (i) hydrophobic chemicals and metals sorbed from the surrounding environment (i.e. seawater) owing to affinity of the chemicals for the hydrophobic surface of the plastics, and (ii) additives, monomers and oligomers of the component molecules of the plastics (GESAMP, 2015; Lassen et al., 2015; Teuten et al., 2009; UNEP, 2014). Once taken in by the marine organisms, the hazardous chemicals may leach from the microplastics and potentially be transferred from the gastrointestinal tract to the tissues of the marine organism (Browne et al., 2013; GESAMP, 2015). Indeed, according to Nerland et al. (2014), if there is a concentration gradient between the exposed organisms and the plastics taken up by the marine organism, the gut fluids have the potential to facilitate the transport of chemicals from the plastics to the organism. The exposure of the organisms to the hazardous chemicals would however also depend on the release rate of the chemicals (i.e. the rate of leaching from the microplastics), the plastic retention time in the organism, and the uptake rate of the toxic chemicals (Koelmans et al., 2014).

Plastics can be associated with a number of potentially hazardous chemicals either originating from the plastic itself (as monomers and additives) (Andrady, 2011; Browne et al., 2007; Lithner et al., 2011) or chemicals sorbed to the plastics (GESAMP, 2015). However, the risk to marine organisms in terms of exposure to the hazardous chemicals is very uncertain. More research is needed on the chemicals which can potentially be available for uptake by marine organism and that can potentially cause impacts on marine organisms. At present, the relative importance of contaminant exposure mediated by microplastics compared to other exposure pathways remains unknown (GESAMP, 2015). Thus, further research is needed to understand the extent to which plastic debris is an important source of chemicals to the marine environment and any ecological hazards associated with it (GESAMP, 2016).

Chemicals adsorbed from surrounding seawater

The transport and fate of hydrophobic chemicals, such as persistent organic pollutants (POPs), which may be present in the marine environment, can be altered by the presence of microplastics. Nerland et al. (2014) described the processes and factors that affect the transfer of organic contaminants to and from the microplastic particles. Affecting factors are for instance:

- concentration gradient, sorption process (e.g. polymer-water partition coefficient);
- polymer type (e.g. glassy versus rubbery polymer);
- contaminant's physico-chemical characteristics;
- microplastic particle's physical characteristics (e.g. surface to volume ratio), and;
- environment characteristics, incl. water turbulence, temperature, and salinity (Nerland et al., 2014).

In particular, the affinity of chemicals to sorb to plastics rather than remain diluted in water (as determined by the polymer-water partition coefficient (KP/W;L/kg)) is important for determining whether the pollutant will sorb to plastics (Andrady, 2011). KP/W values above 10^3 L/kg have been determined for a number of plastics including PP, PE, PS, and PVC (Lee et al., 2014; Smedes et al., 2009; Teuten et al., 2007), indicating that POPs and other hydrophobic chemicals found in seawater are likely to sorb to microplastics.

However, clear evidence that microplastics will increase the net-uptake of hydrophobic chemicals, such as POPs, relative to other existing uptake pathways is lacking. On the contrary, some studies have shown that when considering all POPs exposure mechanisms simultaneously, addition of POPs-free microplastics if anything decreases bioaccumulation of POPs in deposit feeding organisms (GESAMP, 2015). This is because addition of "clean" microplastics to the environment will change the existing equilibrium in the marine water. As a consequence, a fraction of the POPs will be adsorbed to the plastic particles and, thereby, not be available for exposure of marine organisms (GESAMP, 2015). However, due to the long lifetime of plastics in sediments, it is likely that this removal mechanism of pollutants from seawater to plastics will only be very short-lived before a new equilibrium between plastics and seawater is reached (Teuten et al., 2007).

Additives

Additives are used in plastic production to give the produced polymers properties required for specific applications (Lithner et al., 2011). These include for example phthalates as plasticizers, brominated and phosphorus organic flame retardants, colorants, stabilizers, curing agents, antioxidants (Lassen et al., 2015; Nerland et al., 2014). Additives can generally be divided into the following 4 categories:

- Functional additives (stabilisers, antistatic agents, flame retardants, plasticizers, lubricants, slip agents, curing agents, foamingagents, biocides, etc.);
- colorants (pigments, soluble azocolorants, etc.);
- fillers (mica, talc, kaolin, clay, calcium carbonate, barium sulphate);
- reinforcements (e.g. glass fibres, carbon fibres) (Hahladakis et al., 2018; Hansen, 2013).

PVC is the plastic type requiring the most additives, accounting for about 73% of the world production of plastic additives by volume. The additives used for PVC are primarily plasticizers and heat stabilizers (Hansen, 2013; PVC, 2018). This is followed by polyolefins (polyethylene and polypropylene) and styrenics, which account for about 10% and 5% by volume, respectively (Lithner et al., 2011).

Additives are usually not covalently bonded to the polymer and therefore they can leach out from the plastics as it degrades and enter the marine environment (Gewert et al., 2015). Migration of additives (such as phthalates and adipates) from PVC, PE and PVA (polyvinyl alcohol)has been measured and documented in literature on food safety (Biedermann et al., 2008; Fankhauser-Noti and Grob, 2006; Fasano et al., 2012; Goulas et al., 2007; Hahladakis et al., 2018; Wei et al., 2009). However, it is not known if the same level of migration actually occurs in the marine environment. A laboratory experiment however demonstrated that stomach oil, acting as organic solvent, facilitates the migration of PBDEs (a brominated flame retardant) from the plastic matrix, thus increasing the risk of organisms being exposed to the chemical (Tanaka et al., 2013). In another study, Lithner et al. (2012) performed toxicological tests on Daphnia magna from leaching of potentially hazardous chemicals from different plastic products and plastic types. It was found that leaching of chemicals from plasticized PVC (containing additives such as plasticizers and heat stabilizers) led to acute toxicity effects on the daphnia.

A number of comprehensive reviews of studies on measurements of plastic related additives in the marine environment and on releases of additives from microplastics have been performed (GESAMP, 2016; Hermabessiere et al., 2017). The reviews show that plastic related additives are found in the marine environment and that it is likely that part of the additives in the marine environment stem from microplastics in the marine environment (GESAMP, 2016; Hermabessiere et al., 2017).

Overall there is a large pool of knowledge about the toxicological effects of plastic related additives, incl. effects on marine organisms (Lithner et al., 2011; Teuten et al., 2009). Therefore, releases of hazardous chemicals such as additives to the environment should be minimized. However, it is currently not possible to determine whether microplastics in the oceans lead to a larger concentration of additives in the marine environment and whether the presence of microplastics increases exposure of marine organisms to the hazardous additives. In general it is recommended to avoid losses of additives to the marine environment. Due to the potential leaching of additives from polymers, particular focus should be on limiting losses of PVC as the majority of additives are used in PVC. Focus should also be on reducing losses of polyolefins (polyethylene and polypropylene) and styrenics which are also large users of additives.

Residual monomers, and oligomers

With regard to potential impacts related to the polymers that make up the plastics, Lithner et al. (2011) made a hazardous ranking of polymers based on the monomers and additives used for producing the polymers. However, a hazard ranking based on monomers is insufficient because the polymers are generally biochemically inert once they are produced. Hence, the potentially hazardous monomers will not be readily available for exposure of the marine organisms. Indeed, such hazard ranking needs to factor in the extent of residual monomer content and the potential leaching due to the degradation of the polymer into oligomers or monomers.

During plastic production, a monomer or a number of co-monomers are polymerized in a chemical reaction to produce a long chained polymers. The polymerization reactions rarely proceed to completion (Araújo et al., 2002) and result in the formation of impurities as residual monomers or oligomers. The residual monomers are unwanted as these reduce the functioning of the polymer while there are also not biochemically inert. The residual monomers and oligomers can, therefore, potentially be leached from the microplastics (Lund and Petersen, 2006) and, if released to the marine environment, pose a risk to marine organisms.

Although plastics are generally considered to be biochemically inert, as plastic ages in the marine environment, it presents a potential chemical hazard that is not only due to the release of POPs from the plastic surface and chemical additives leaching out of the plastic, but also due to releases of chemicals produced by degradation of the plastic polymer itself (Gewert et al., 2015). Polymer degradation can proceed by either abiotic or biotic pathways. Generally abiotic degradation precedes biodegradation, and is initiated thermally, hydrolytically, or by UV-light in the environment (Andrady, 2011; Gewert et al., 2015). Leaching of monomers or oligomers as a result of polymer degradation have been shown, but primarily under non-environmentally relevant conditions (Gewert et al., 2015; Lund and Petersen, 2006). Hence, there is little knowledge about the potential migration of monomers from plastics degraded in the marine environment.

The hazard ranking of monomers by Lithner et al. (2011) showed that PUR, polyacrylonitrile (PAN; e.g. used as part of acrylic fibers and for production of ABS, SAN and ASA), and PVC plastics were ranked highest due to the hazardousness of the monomers, e.g. propylene oxide, acrylonitrile, bisphenol A, and vinyl chloride which are all considered carcinogenic (Lithner et al., 2011). Toxicity due to leaching of hazardous substances has been shown for both PVC (Lithner et al., 2012) and PUR (Bejgarn et al., 2015), while leaching of potentially hazardous chemicals from acrylonitrile-butadiene-styrene (ABS) does not seem to occur (Lithner et al., 2012). Through application of a precautionary approach, a particular focus should be on reducing residual monomer content when producing these plastics (and in general for all plastics that contain potentially hazardous monomers) and to limit general losses of these plastics to the environment due to the potential risk for leaching of hazardous chemicals. A specific focus should be on PVC which according to (Gewert et al., 2015) is the least stable of the high tonnage polymers (i.e. PE, PP, PVC, PS, PET, PUR) and has the highest sensitivity towards UV radiation and photo-degradation. It is therefore more susceptible to degradation and potential release of hazardous monomers/oligomers or additives (Gewert et al., 2015)

9

Hotspots related to losses and potential impacts on marine environment

Chapter highlights

- For macroplastics, the main hotspots in terms of losses from the plastic value chain and potential impacts on the marine environment are related to the EoL stage through mismanaged plastic waste management and littering, in particular near coastal areas
- Direct losses of plastics from fishing or maritime related activities were also identified as a hotspot since the plastics are lost directly to the oceans
- Marine animals can be adversely affected through ingestion of or entanglement in macroplastics. Moreover, weathering of macroplastics to microplastics can cause impacts related to microplastics
- PP, HDPE, LDPE and LLDPE, PP-fibers, and PET-fibers are important types of microplastics lost to the environment. Their losses can be sourced to the use stage throughout city dust, usage of cosmetics and personal care products, and textile washing. The losses can also be related to degradation of macroplastics into microplastics. These microplastics are potentially a problem due to their ability of causing physical impacts on marine organisms.
- Losses of plastics which can potentially leach hazardous additives or residual monomers should be avoided. This is particularly relevant for wastes from the construction and transportation sectors, where plastics containing potentially hazardous additives or monomers are largely used.

Based on the estimated plastic losses to the environment (Ch. 6), the brief review of findings of plastics in the oceans (Ch. 7), and the review of impacts of different plastics on the marine environment (Ch. 8), this chapter provides an overview of the potential key hotspots in terms of losses to the environment from the plastic value chain and potential impacts on the marine environment. Table 23 provides an overview of the quantified losses to the environment, also indicating the main polymer types, plastic application categories, and potential impacts associated with the losses.

The largest loss of macroplastics stem from mismanaged solid waste treatment and from littering of plastic and plastic containing products. These losses are related to plastics packaging, consumer & institutional products, textiles, and electronics. Overall, for macroplastics, the regions contributing most to total losses to the environment were Africa, Latin America and the Caribbean, and the Middle East which all have a high level of plastic consumption and a large fraction of improperly managed MSW.

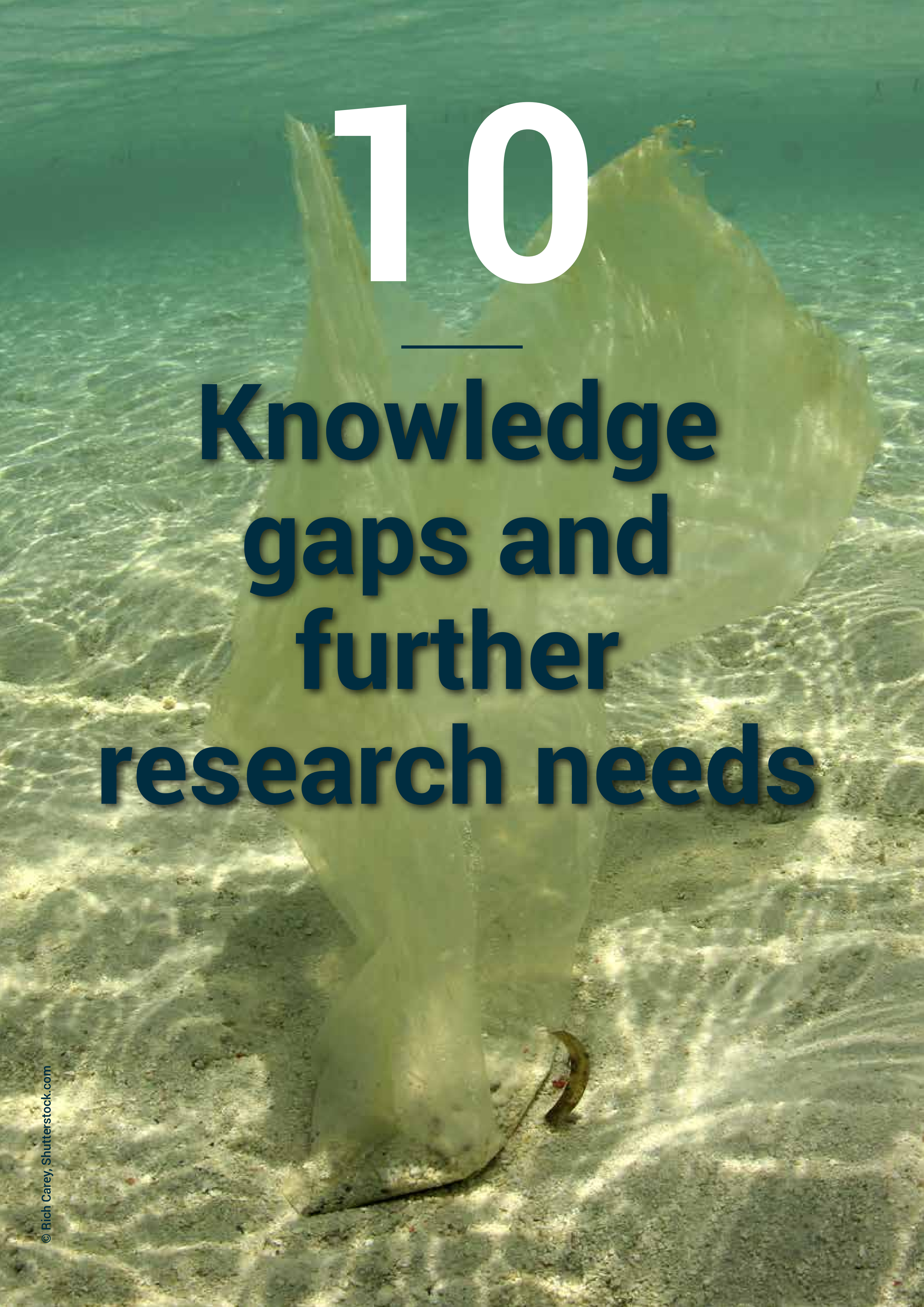
The types of plastics lost fit well with findings of macroplastics in the oceans. Moreover, the findings of microplastics also fit well with these plastic types, corroborating that a large part of microplastics stem from weathering of macroplastics. Another potentially important hotspot is direct losses of macroplastics from marine activities. Although the amounts are relatively low compared to other losses, the plastics are lost directly to the environment, often reported in samples of marine plastics, and pose significant problems in terms of impact on the marine environment because they include types of plastics (e.g. bags, rope, nets, lines, etc.) that are specifically found to cause potential ingestion and entanglement by marine animals. Moreover, losses from marinas and aquaculture, in particular polystyrene floats, appear important. These losses were not quantified due to lack of data, although floats and buoys are reported to be often found as part of marine debris (see Table 20). They are lost directly to the marine environment, particularly through leaching of styrene monomers and oligomers from polystyrene, which has been demonstrated in the literature (e.g. Genualdi et al., 2014; Tawfik and Huyghebaert, 1998), thus posing a potential hazard risk to marine organisms.

With regard to microplastics losses, PP, HDPE, LDPE and LLDPE, PP-fibers, and PET-fibers were important in terms of amounts of microplastics lost to the environment. These microplastics are problematic due to their ability to cause physical impacts, such as reducing activity/rate/capacity, induce particle toxicity, adsorb toxic pollutants, and transporting invasive species (see Section 8.2). The actual source of these microplastics types found in the marine environment is likely a combination of weathering of macroplastics and direct losses of microplastics (i.e. as part of city dust, usage of cosmetics and personal care products, and textile washing). For losses of microplastics, the most contributing regions were NAFTA (incl. rest of North America), China, Asia (excluding Japan, India, and China), and Western Europe which account for 16%, 20%, 14%, and 11% of the total microplastic losses, respectively. The losses of microplastics are mainly driven by large population and per capita plastic consumption in the regions. Losses of these microplastics should, therefore, be minimized. However, we stress that it is important to assess the environmental consequences of the measures aimed at reducing all losses to gauge whether or not they might create other, potentially larger, environmental problems elsewhere. Another, potential hotspot is microplastics from tyre abrasion. Tyre abrasion was found to be the largest source of microplastics to the environment, however, the plastics particles are not sampled in the marine environment, which may be due to the particles being captured elsewhere in the environment or because the size of the plastic particles are below the sampling detection limit. Taking a precautionary approach, there should be focus on limiting losses of plastics particles from tyre abrasion. If the plastic particles go to the marine environment and due to the small size of the plastic particles, these can potentially cause physical impacts on marine organisms, particularly through uptake of the particles which can lead to particle toxicity but also through inhibition of feeding activity/rate/capacity.

Microplastics containing potentially hazardous additives or residual monomers were also identified as a hotspot. PVC, PUR and PAN were found to be the most problematic in terms of containing potentially hazardous residual monomers and additives. Moreover, toxicity from leachates from PVC and PUR has been evidenced in laboratory settings. PVC and PUR are primarily used in building and construction and PUR is additionally largely used in the transportation sector. Unfortunately, it was not possible to make estimates of the losses of plastics from these applications. Hence, more information on the disposal of construction and demolition waste, and disposal of industry and machinery waste is needed. Losses of plastics, such as PVC and PUR, have been identified as posing a hazardous risk to the marine environment.

Table 24. Summary table of sources of plastics losses to the environment and the life-cycle stages related to the loss, indicating the amounts lost to the environment and whether micro- or macroplastics are lost. Moreover, the main polymer types, plastic application categories, and potential impacts associated with the loss are indicated. The table is sorted as after macro- and microplastics lost and, hereafter, sorted in descending order based on amount lost.

Sources of plastic losses to the environment	Related life-cycle stage	Amount lost	Micro- and/or macroplastics lost	Main polymer types associated with loss	Plastic application categories associated with loss	Main potential impacts associated with plastic loss to marine environment
Mismanaged waste treatment	End-of-life stage	3.87 Mt	Macroplastics	PP, LDPE & LLDPE, HDPE, PET, PP fibers	Packaging, Electrical/Electronic, Consumer & Institutional Products, Textile (Clothing and Others)	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from weathering of macroplastics
Loss of plastic from littering	Use stage	0.8 Mt	Macroplastics	PP, LDPE & LLDPE, HDPE, PET, PP fibers	Packaging, Electrical/Electronic, Consumer & Institutional Products, Textile (Clothing and Others)	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from weathering of macroplastics
Fishing nets and other losses of fibers related to fishing	Use stage	0.6 Mt	Macroplastics (0.0003 Mt of microplastics from abrasion of dolly ropes)	Only possible to quantify losses for PA fibers	Marine/maritime related activities	Ingestion of and entanglement in macroplastics. Physical impacts related to microplastics stemming from dolly ropes and weathering of macroplastics
Loss of rubber from tyre abrasion	Use stage	1.41	Microplastics	Tyre elastomers (e.g. SBR)	Transportation - Tyres	Physical impacts related to microplastics. Likely more related to impacts of very small (likely micro and nano-sized) particles
City dust	Use stage	0.65	Microplastics	Losses are likely to occur for all polymer types. Top five polymers lost are believed to be PP, LDPE & LLDPE, PVC, HDPE, and not specified thermosets	Paints and protective coatings for exterior use. Textiles and other dust generating applications. Clothing with relation to shoe ole abrasion. Road use (related to road wear)	Physical impacts related to microplastics
Road markings	Use stage	0.59	Microplastics	Road markings (specific polymer types are unknown)	Road marking application	Physical impacts related to microplastics
Loss via washing of textiles	Use stage	0.26	Microplastics	PP fibers, PET fibers, PA fibers	Clothing and textile application	Physical impacts related to microplastics (synthetic fibers)
Loss through weathering of marine coatings	Use stage	0.05	Microplastics	Marine coatings (specific polymer types are unknown)	Marine coating application	Physical impacts related to microplastics. Potential hazardous impacts for certain coatings, e.g. epoxy coatings (Lithner et al., 2012)
Loss of plastic during upstream plastic production (Virgin plastic pellets)	Production stage	0.03	Microplastics	All polymer types. Top five polymers lost are PP, LDPE & LLDPE, PVC, HDPE, and not specified thermosets	Not relevant. Loss occurs before application	Physical impacts related to microplastics. Potential toxic impacts related to losses of virgin microplastics containing hazardous additives or residual monomers.
Microbeads lost to environment from use of cosmetics and personal care products	Use stage	0.01	Microplastics	PP, PE, HDPE, PA	Cosmetics and personal care products	Physical impacts related to microplastics



10

Knowledge gaps and further research needs

Chapter highlights

- A number of potential losses from the plastics value chain could not be quantified. Further investigation of these activities/processes are needed to provide a better estimate of the actual plastic losses
- A link between loss of plastics to the environment and subsequent release to the oceans is so far missing. Measurements or models describing the fate (i.e. transport and transformation) of plastics in the environment and the fraction of the lost plastics ending up in the oceans are needed
- Sound estimates of the effects of both micro- and macroplastics on the marine environment are needed. For microplastics, this could be based on the hazardousness of the substances in the microplastics (e.g. residual monomer content, additive content, ability to transport hazardous substances in surrounding seawater). For macroplastics, such effect modelling could be based on the usage of the plastics and the physical characteristics of the macroplastics (e.g. the plastics types, shapes, colours most likely to lead to cases of entanglement and ingestion)

This report provides a comprehensive overview of the global production and consumption of different polymers. Based on available literature on the losses of plastics throughout the plastic value chain, we were able to estimate the annual mass of microplastics and macroplastics that are being lost to the environment. We compared the estimated amounts lost to environment with findings of microplastics and macroplastics in oceans and coastal areas to evaluate whether the types of plastics lost to environment correspond to those found in the oceans and if some plastic losses are more likely to be found in the marine environment. Based on studies on the potential impacts of microplastics and macroplastics on marine organisms, we can get a rough overview of the plastic types that are most problematic and where focus should be placed to reduce plastics losses to the marine environment.

However, a number of important knowledge gaps still remain, and these need to be abridged to provide a more robust assessment on the impact assessment of plastics in the marine environment. These research needs can be categorised into (i) estimating losses of plastics to the environment, (ii) modelling fate of plastics once released to the environment, in particular gauging the fraction of releases ending up into the marine environment, and (iii) quantifying the impacts of plastics present in marine environment.

10.1 Losses of plastics

During production stage: More specific information on the losses of plastics from different plastic production processes and from handling and transport are needed. This can aid in providing a more representative estimate of the losses associated with production of the different polymer types. Given that losses from production, handling, and transport are generally small relative to other sources of losses, this knowledge gap is of less importance compared to losses from usage (e.g. littering) or end-of-life of plastics applications (see below). However, losses associated with production can be substantial in terms of microplastics concentrations. For instance, measured microplastic concentrations were 2-3 orders of magnitude higher in harbours with plastic production facilities (i.e. 102.000 plastic particles per m^3) compared to microplastic concentrations measured outside the harbour (i.e. 310-560 plastic particles per m^3) (Norén, 2007)

During use stage: Better estimates of littering are needed. Currently only one global estimate of littering is available. However, to get results that better reflect the reality of littering, estimates need to be geographically differentiated and differentiated into different plastic types and/or plastic application. It is plausible that local authorities have estimates on the littering levels in their municipalities. Review and collection of such highly spatially specific information was outside the scope of this study, but could be conceived as a next step for developing more representative estimates on waste littering, incl. littering of plastic wastes. Moreover, further research seeking to better understand the drivers for littering are required to support development of possible tackling measures.

More information about the fate of microplastic particles lost during tyre abrasion and road marking are needed. These are among the largest sources of microplastics losses to the environment, and information about the environmental fate and impact of these plastics are lacking. Information about losses related to city dust are needed as this was found to be the second largest source of microplastic losses. More research on the drivers for city dust generation and the potential losses of plastic particles are needed. Information about the spatial differences in city dust generation and the types of dust generation are also needed (e.g. which plastic types are part of city dust?).

More information about wastewater treatment is needed. This is particular relevant for quantifying losses of microplastics that go to the drain after use (e.g. personal care products) or during fate after being lost (plastic particles from abraded shoe soles carried which are being transported to city sewer system). Here, information about the fate of the wastewater is needed e.g., if any then which wastewater technology is applied and what is the microplastic removal rate? Such information is needed at a spatially differentiated level as there are large geographical variations in treatment of wastewater which can have large influence on estimate about the losses of microplastics to the environment.

During end-of-life: Estimates of the plastics lost during EoL treatment is generally missing. Only estimates on losses from mismanaged MSW treatment have been proposed. There is a need for further research on mismanaged MSW treatment. Firstly, it is important to define what mismanaged waste constitutes and what should be accounted for as mismanaged waste. Secondly, data on the extent of mismanaged MSW treatment and the associated environmental losses from mismanaged MSW treatment are needed. This is particularly important as this is the largest source of macroplastics lost to the environment. For other waste fractions, such as C&D and ELV, there is generally insufficient knowledge about the treatment share at country level. These may be important sources of plastics losses, but cannot be quantified due to insufficient information. The lack of adequate data for both MSW and other waste fractions is most profound for developing countries, where information about predominant treatments may exist for a limited number of countries, but are not sufficient to provide a representative estimate of the treatment shares in e.g. entire Asia or Africa.

Unaccounted sources: Knowledge about the processes for which losses could not be accounted for are also needed (Table 18). This is especially the case for floats and other plastic losses from maritime activities which are known to contribute to marine plastics, particularly as losses are directly released to oceans. Fishing and maritime related information is generally lacking. This is particularly the case for developing countries where sound information on e.g. size of the fishing fleet is lacking and where information on informal fishing or similar activities is also lacking.

10.2 Fate of plastics in the environment

Our assessment of losses from the plastic value chain is restricted to losses to the environment. Further quantification of losses ending into the oceans requires more knowledge about the subsequent fate (i.e. transport and transformation) of the polymers and/or their products or applications once these have been emitted to the environment.

First, more information about the geographical location of the losses are required. For instance, information about proximity of the losses to marine or freshwater systems is needed as water is a key transport route of plastics to the ocean (Cable et al., 2017; Lebreton et al., 2017; Schmidt et al., 2017) while wind drift may also be relevant for lightweight plastics and microfibers. Once the geographical location of the losses is known, information about the transport routes of the plastics from its loss location to the ocean is required. This is needed to determine the fraction of the plastics lost that actually reaches the marine environment, as well as to determine what transformation the plastics may undergo while being transported to the oceans (environmental conditions leading to degradation, etc.).

Let us take the example of microplastics from tyre abrasion, which is a large loss to the environment (see Table 16). In rural areas, these microplastics are likely to be captured in road ditches, where they may become bound to the soil matrix, and thus not move any further. In contrast, in urban areas, the particles are likely to end up in the sewage drain and be removed as part of wastewater treatment. Therefore, a very small fraction of the total loss of microplastics from tyre abrasion to the environment may actually reach marine ecosystems. The consideration and representative modelling of such fate is regarded as a significant and necessary step to quantify the magnitude of the plastic losses actually contributing to marine plastic debris.

Moreover, more information about the fate of marine litter in oceans is required. For instance, to what extent is marine litter accumulating in the oceans and what are potential sinks for marine litter in the oceans (e.g. sedimentation)?

10.3 Impact of plastics on marine environment

An additional important knowledge gap is the impact of different plastics on the marine environment. The mass of plastics lost to the environment is not a sufficient indicator of actual impacts on the environment because different plastics have different physicochemical properties and toxicities. Considerably different impacts may thus be observed for a same mass of plastics released to the environment. Therefore, once the losses of plastics from different sources to the marine environment have been quantified, there is a need for providing quantitative estimates of their impacts on marine organisms and other animals living near or relying on the oceans (e.g. birds) as well as on humans (e.g. via seafood consumption). For microplastics, such estimates may be based on information about the potential toxicity of different additives and residual monomers present in the polymers, although more studies on the absorption, distribution and effects of microplastics in the organisms are required. In general there is a need for understanding the different impacts related to microplastics and their severity, not only across microplastics but also relative to other potential pressures causing impacts on marine organisms (e.g. relative to ocean acidification or marine eutrophication).

With respect to macroplastics, information on the number of animals affected by macroplastics are still inadequate and more comprehensive field studies, assessing a broad range of animals and plastic types, are required to get a better estimate of the magnitude of the problem. Indeed, more information is needed on the specific plastic types causing most impacts. This should take into account the characteristics of the macroplastics, such as their use (e.g. plastic bags, bottles, wrapping, etc.) and physical appearance (e.g. shape, size, weight, colour, etc.), which can be important in terms of the plastics fate in the general environment and ocean, and impacts on marine organisms and which species that are most likely to be affected by specific macroplastic types. In the perspective of a global assessment, information is needed on the produced amounts of typical plastic types such as packaging (e.g. plastic bags, bottles and wrapping) and on their release pathways, in particular via littering and inadequate waste management, which are the two major sources (see Section 6.4).

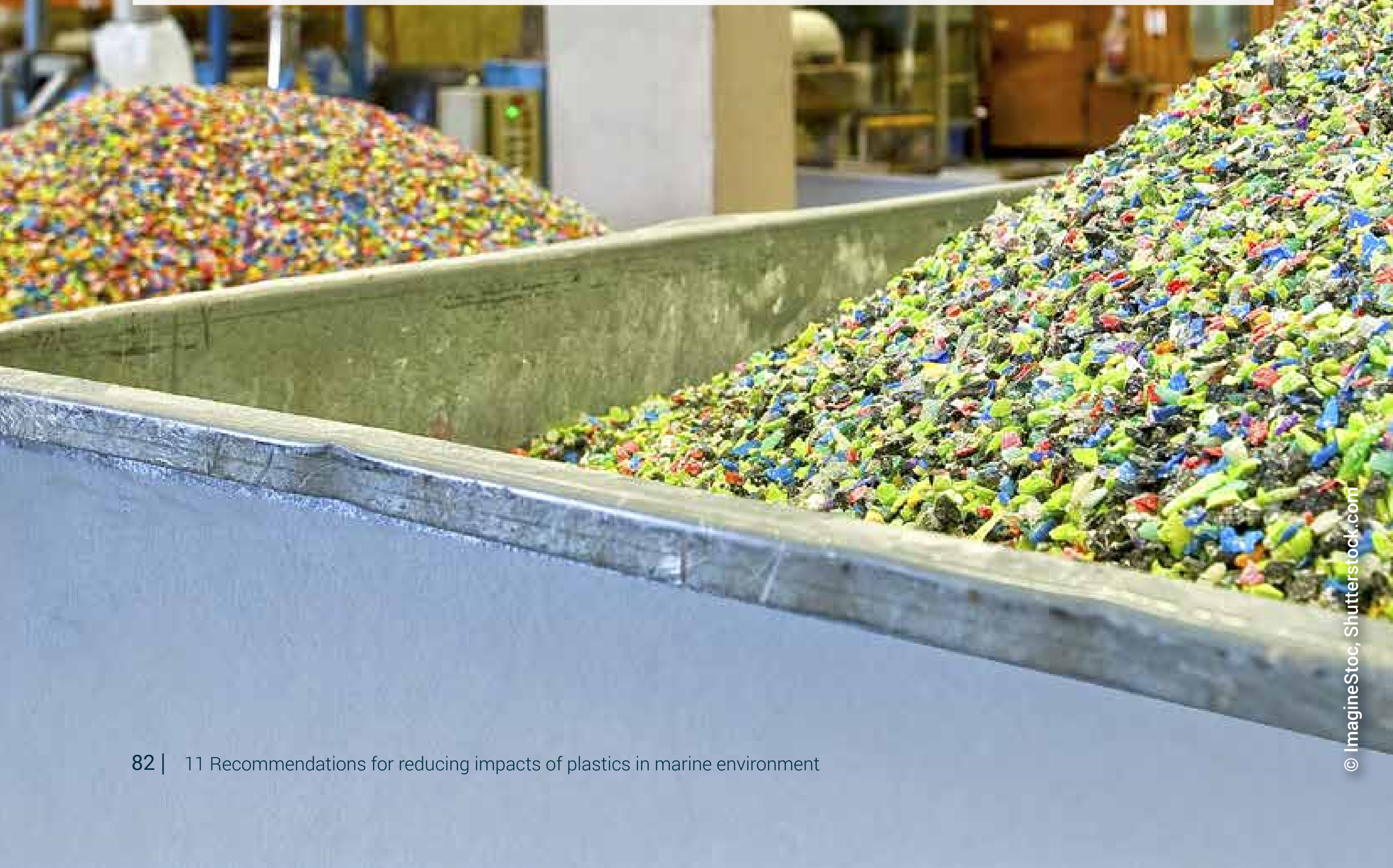
11

Recommendations for reducing impacts of plastics in marine environment

Chapter highlights

To reduce losses and potential impacts on the marine environment, it was recommended to:

- Focus on reducing loss of macroplastics from MSW, in particular plastic packaging. Initiatives should not be limited to the end-of-life stage; instead, measures for reducing potential plastic losses at the end-of-life stage should be implemented along the entire plastic value chain. Particular focus should be on regions whether the largest losses occur, i.e. Africa, Latin America and the Caribbean, and the Middle East
- Focus on reducing microplastics losses from use of consumer-related applications. Initiatives should not be limited to the use stage; instead, measures for reducing potential plastic losses at the use stage should be implemented along the entire plastic value chain. Particular focus on the regions North America, China, Asia (excluding Japan, India, and China), and Western Europe which are responsible for the majority of microplastic losses
- Focus on reducing direct plastic losses from marine activities (e.g. fishing, aquaculture, etc.).
- Generally focus on reducing losses of plastics that can potentially pose a hazardous risk to marine organisms



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Based on the above holistic evaluation of the annual plastics production, losses to the environment, and observations of plastics in the oceans, complemented with a qualitative evaluation of impacts on marine organisms, hotspots were identified, and a preliminary set of recommendations is issued below. It should be noted that these conclusions and recommendations are highly uncertain due to data paucity for the mapping in the current study. These data gaps resulted in the inability to quantify total losses of plastics to the marine environment, and the lack of a quantitative assessment of plastics damages therein (damages to marine ecosystems and human health).

Overall it is recommended to:

i. Focus on implementing measures along the entire plastic value chain to reduce losses of macroplastics, in particular from MSW during the end-of-life stage and in particular plastic packaging. Initiatives should not be limited to the end-of-life stage; instead measures for reducing potential plastic losses at the end-of-life stage should be implemented along the entire plastics value chain. Particular focus should be on regions where the largest losses occur, i.e. Africa, Latin America and the Caribbean, and the Middle East. To reduce losses and potential impacts it is recommended to:

- Take into account the need for recyclability already at the design and production stages of the plastic product.
- Reduce consumption of plastics (either reducing use of packaging or substituting with other materials) to, thereby, reduce the amount of plastic waste being generated, being careful about regrettable substitutions.
- Reducing littering, most importantly near coasts and river banks. Here, it is important to raise public awareness, and provide incentives for behavior changes.
- Develop integrated approaches to waste management where waste policies defined at national government level are enforced at local municipality level, where liability is with regard to collection and handling of waste
- Reduce improper waste management by creating incentives for moving up in the waste hierarchy (i.e. reduce, re-use, recycle the plastic waste). Focus should be on design for recycling, and on increasing circularity of the plastic products.
- To reduce plastic losses, simple solutions such as placing fenced around landfills or open dumps (effective for mitigating plastic losses from wind drift) should be implemented as short-term solutions (keeping in mind that more structural solutions like adapting waste policies are needed as well).

ii. Focus on reducing microplastics losses from use of consumer-related applications. Initiatives should not be limited to the use stage; instead, measures for reducing potential plastic losses in the use stage should be implemented along the entire plastics value chain. Particular focus on the regions NAFTA (incl. rest of North America), China, Asia (excluding Japan, India, and China), and Western Europe which are responsible for the majority of microplastic losses. Measures for reducing losses may include:

- Reduce use of microbeads in cosmetics and personal care products.
- Apply weaving techniques that lead to lower releases of synthetic fibers during textile washing.
- Switch from synthetic textiles to natural fibers. However, environmental impacts related to cotton or wool production may exceed those related to synthetic textiles taken from a life cycle perspective.
- Increase the share of population connected to WWTP, particularly in developing countries. Microplastics emitted from e.g. city dust, road markings, personal care and cosmetics, and textile washing can substantially be reduced in WWTP with at least secondary treatment.

iii. Focus on reducing direct plastic losses from marine activities. Although the amounts are relatively low compared to other losses, the plastics are lost directly to the environment and often reported in samples of marine plastics. Moreover, plastics in fishing nets (e.g. polyacrylonitrile) and polystyrene floats exhibit a hazard risk to marine organisms if the monomers are released. Possible measures for reducing losses from marine activities are:

- Education and raising awareness for persons involved in marine activities. Measures include education of fishermen and other professionals (e.g. involved in aquaculture) on proper handling and disposal of fishing gears and other used plastic equipment to avoid accidental losses and improper disposal of damaged equipment. This may be particularly important in regions where governmental control and monitoring of the marine activities is lacking. Incentives for behaviour change in that context should thus be encouraged.
- Education and information of populations, who use coastal areas such as beaches, marinas, and piers, to sensitise them on consequences of littering to marine life and on correct behaviours to adopt.
- Stimulating policy and technology-driven initiatives to reduce direct losses to oceans from fishing industry, e.g. by banning the use of dolly ropes or by using technologies leading to lower losses of plastics and less abrasion of the nets and other materials.
- Developing a market for reuse/recycling of plastic products (e.g. floats, fishing nets, traps, etc.) to reduce informal disposal at sea. Such implementation of circular economy can incentivise the professionals involved in marine activities to ensure waste plastic products are properly handled. In a context of circular economy, it may also generate added value; for instance, discarded nylon nets could serve as fibers in reinforced concrete (Bertelsen et al., 2016).

iv. Generally focus on reducing losses of plastics that can potentially pose a hazardous risk to marine organisms. Knowledge about potential toxic impacts of some plastics is still limited. However, a number of studies have shown the potential hazardousness of certain plastic types because they contain hazardous additives or residual monomers (e.g. PVC and PUR; see Section 8.2). To reduce losses and potential impacts it is recommended to:

- Investigate the options for reducing residual monomer content and use of additives, and explore options for substituting hazardous additives with less hazardous alternatives (supported by life cycle assessment studies).
- Place a particular focus on reducing losses related to potentially hazardous polymers

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Appendix 1

Global plastics production and consumption distribution

The geographical distribution of plastic production between regions as reported in Table A1 was derived based on information about total plastic production given from the references used in Table A1.

Table A1. Geographical distribution of Global plastics production

Region	Percentage share of global plastics production (2015)	Reference
NAFTA (incl. rest of North America)	18.5 %	(PlasticsEurope, 2016a)
Western Europe	18.5 %	(PlasticsEurope, 2016a)
Japan	4.3 %	(PlasticsEurope, 2016a)
Central Europe & CIS	2.6 %	(PlasticsEurope, 2016a)
Asia (excl. Japan, India, and China)	7.6 %	Overall distribution from (PlasticsEurope, 2016a). Distributed between India and "Asia (excl. Japan, India, and China)" based on population (World Bank, 2017).
Africa	5.3 %	Overall distribution from (PlasticsEurope, 2016a). Distributed between Middle East and Africa based on population (World Bank, 2017).
Latin America & Caribbean	4.4 %	(PlasticsEurope, 2016a)
Oceania	0.3 %	(Commonwealth of Australia, 2016)
India	8.7 %	Overall distribution from (PlasticsEurope, 2016a). Distributed between India and "Asia (excl. Japan, India, and China)" based on population (World Bank, 2017).
China	27.8 %	(PlasticsEurope, 2016a)
Middle East	2.0 %	Overall distribution from (PlasticsEurope, 2016a). Distributed between Middle East and Africa based on population (World Bank, 2017).

The geographical distribution of plastic consumption between regions as reported in Table A2 was derived on the basis of information on the per-capita plastics consumption in the different world regions.

Table A2. Geographical distribution of plastic applications

	Per capita plastics consumption		Population (2015)		Total consumption	
Region	kg per capita	Reference	Capita	Reference	million tonnes	Share of total consumption
NAFTA (incl. rest of North America)	139	(Plastics Insight, 2016a)	482,763,846	(World Bank, 2017)	67	21%
Western Europe	136	(Plastics Insight, 2016a)	427,942,967	(World Bank, 2017)	58	18%
Japan	108	(Plastics Insight, 2016a)	127,141,000	(World Bank, 2017)	14	4%
Central Europe & CIS	48	(Plastics Insight, 2016a)	399,785,149	(World Bank, 2017)	19	6%
Asia (excl. Japan, India, and China)	22	(Plastics Insight, 2016a)	1,147,123,784	(World Bank, 2017)	25	8%
Africa	13	(Panda et al., 2010)	1,100,367,965	(World Bank, 2017)	14	4%
Latin America & Caribbean	56	(Plastics Insight, 2016b), scaled up to full plastic consumption based on information on PE, PP, and PVC resins	506,305,451	(World Bank, 2017)	27	8%
Oceania	84	(FAO/ICAC, 2011; PACIA, 2011)	39,518,729	(World Bank, 2017)	3	1%
India	13	(Plastindia Foundation, 2014)	1,309,053,980	(World Bank, 2017)	17	5%
China	45	(Plastindia Foundation, 2014)	1,402,753,098	(World Bank, 2017)	63	20%
Middle East	38	Estimated based on (Panda et al., 2010; Plastics Insight, 2016a)n	413,690,442	(World Bank, 2017)	16	5%
World average	44		7,356,446,411		323	100%

[1] The total does not add up to the Global plastics production. The difference is attributed to the types of polymer included in per capita consumption number where, often, fiber and rubber polymers are excluded. However, the approximated geographical distribution was used to describe the general distribution of plastic consumption.

Appendix 2

Use share of polymer type for different applications

Table A3 provides an overview of the distribution of different polymers used in the different application included in this mapping.

Table A3. Use share of polymer resin production according to plastic application

Application type/Polymer type	LDPE, LLDPE	HDPE	PP	PS	PVC	PET	PUR	Other	Fibers	Marine coatings	Road marking coatings	Elastomers (tyres)	Bioplastics	ABS, ASA, SAN
Transportation - Other	1%	5%	15%		3%		19%	35%	10%				7%	16%
Transportation - Tyres												100%		
Packaging	68%	57%	49%	30%	8%	100%	2%	2%					58%	
Building and Construction	6%	20%	7%	29%	69%		29%	12%					4%	3%
Electrical/ Electronic	3%	1%	5%	8%	3%		5%	7%					2%	27%
Consumer & Institutional Products	15%	10%	22%	24%	5%		12%	5%					7%	44%
Industrial/ Machinery	1%	1%	1%				4%							
Other	8%	6%		9%	12%		30%	39%	18%				11%	8%
Marine coatings										100%				
Personal care products		0.06%[2]	0.001%[2]											
Road marking											100%			
Textile sector - clothing									46%				11%	
Textile sector - Others									25%					
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Reference	1	1	1	1	1	1	1	1	3	4	5	6	7	8

1 Distribution based on (Geyer et al., 2017).
2 Plastic type distribution for personal care products and cosmetics was based on (Boucher and Friot, 2017).
3 Fiber application distribution based on (Grand View Research, 2017).
4 All marine coating polymers go towards marine coating application.
5 All road marking coating polymers go towards marine coating application.
6 All Elastomers (tyres) goes towards tyre production. [7] Distribution based on (European Bioplastics, 2017).
8 Distribution based on (Grand View Research, 2015b).

Appendix 3

Plastics production flow chart

Flow chart depicting the production flow of the main polymer types produced covering more than 80% of global annual polymer production. The production chains for the following polymers and polymer types were excluded due to lack of information on the specific production: Other Thermoplastics, Thermosets, Adhesives, Sealants, Coatings, Marine coatings, and Road marking coatings.

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