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Plastics — Environmental aspects — State of knowledge and methodologies

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 14, *Environmental aspects*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 249, *Plastics*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Plastics materials are highly flexible and universally applicable. They can be found in a diversity of product areas and application sectors. In order to achieve a sustainable management and exploitation of products, safe and efficient manufacturing processes are compulsory within the value chain. In addition, an environmentally friendly use and handling across diverse applications is necessary during consumption, reuse and disposal. This ensures that an effective and qualified management at the product's end-of-life is addressed through proper performed procedures and evaluations.

If mismanagement happens at any of the above described life cycle stages, the use of plastics and plastics-containing products can create adverse effects to the environment. It has been proven, not least by the United Nations Environment Programme, that discarded products as well as microplastics are found in the environment around the globe, be it on land or water bodies including the sea. There are diverse causes for this such as inappropriate or inefficient waste management infrastructures, improper management of plastics products and their waste reuse or disposal, inefficient wastewater management, etc. Therefore, various types of entries into the environment and diverse constitutions and compositions of the microplastic particles in the environment are to be considered. Littered articles as well as microplastics consists of different kinds of products and come from different waste, e.g. bottles, films, fishing nets, tyres, cosmetics, clothing fibres, etc.

Over extended time in the environment, plastics products and their waste will breakdown into smaller items and finally disintegrate to microparticles. Microplastics also enter the environment directly through its intentional use in some product applications. Microparticles, be it via primary product use or via secondary fragmentation of macro articles, should be considered with special care since they can give rise to adverse environmental impact especially in the aquatic environment and its biota.

This document with its primary focus on plastics, rather than all the other materials, in the environment intends to provide a survey on the international situation of plastics and plastics in the environment with special attention to microplastics in the marine environment, its detection and determination. For this purpose, the document describes the state-of-the art testing methods as well as assessment approaches.

Although this document gives a representative overview of the current knowledge (up to early 2017) and activities about plastics and microplastics around the world, information is predominately generated from the Northern Hemisphere and activities in Europe and North America.

In this way, the document can be recognized as a contribution towards harmonized procedures and measures in order to provide a sound basis for a reliable and verifiable evaluation of the impact of plastics and microplastic in the environment. The document covers the following key items of interest.

— Status of plastics products and plastics in the environment: Facts about plastics use and proven findings about the occurrence of plastics and microplastics in the environmental matrix, be it on land and water bodies including the sea.

— Terminology: The terms "plastic particles", "plastic microparticles", "microplastics", "plastic nanoparticles" or "solid microparticle" are currently not defined in a consistent way and are, especially in an international context, being used differently. This document makes an attempt towards a globally harmonized terminology.

— Test methods: Methods for the detection, analysis and assessment of plastic particles present in the environment, such as aquatic litter, are neither harmonized nor standardized. Simple visual tests, in particular, have proved to be insufficient. This document will describe the sampling, its preparation of samples and further analytics, especially in waters as the main task of this document, since reproducible and verifiable procedures are indispensable to derive valid data for the environmental assessment and on this basis concluding appropriate measures to improve the environmental situation.

Not only has the plastics economy recognized the importance of this topic and started diverse action programmes, which are, for example, compiled through the Global Plastics Declaration Initiative, also political groups (e.g. G 7 and G 20), international organisations such as OECD, administrations of regions and individual countries are increasingly taking care about the serious issue of littered plastic waste and microparticles in the environment. In addition, numerous research activities have also been initiated. All these key stakeholders will highly benefit from a globally harmonized procedure.

This document includes references to studies and investigations in relation with plastics in the environmental matrix and biota, including microplastics. Important is the chapter terms and definitions. It presents the basis for future work in ISO. The description of the size classes is particularly relevant. Reference is made to other classifications of other organizations, for example in the area of Nanoparticles (see also OECD). The references selected within this document reflect the current knowledge without claiming to be complete or fully up-to-date. The content and conclusions of the different studies referenced in the bibliography are under the responsibility of their authors.

NOTE The document was developed under the scope of ISO/TC 61 *Plastics* and follows resulting requirements. Independent from these, terms are used in the text, which are in the scope of other ISO/TCs, such as:

— ISO/TC 38, *Textiles;*

— ISO/TC 45, *Rubber and rubber products;*

— ISO/TC 217, *Cosmetics*

Plastics — Environmental aspects — State of knowledge and methodologies

1 Scope

This document summarizes current scientific literature on the occurrence of macroplastics and microplastics, in the environment and biota. It gives an overview of testing methods, including sampling from various environmental matrix, sample preparation and analysis. Further, chemical and physical testing methods for the identification and quantification of plastics are described.

This document gives recommendations for three steps necessary for the standardization of methods towards harmonized procedures for sampling, sample preparation and analysis.

This document does not apply indoor and health related aspects.

NOTE The collection of plastics or microplastics in the environment by citizen social monitoring projects is not in the scope of this document. Although such projects can help sensitize the society to environmental problems and can even reduce the entry and presence of plastics in the environment, this monitoring concept is not considered suitable for a robustly representative and scientific analysis of microplastics in the environment via standardization.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
polymer
chemical compound or mixture of compounds consisting of repeating structural units created through polymerization

Note 1 to entry: In practice above 10 000 Dalton.

Note 2 to entry: Polymers comprise both plastics and elastomers. The latter is excluded from the scope of ISO/TC 61.

3.2
plastic
material which contains as an essential ingredient a high *polymer* (3.1) and which, at some stage in its processing into finished products, can be shaped by flow

Note 1 to entry: Plastics consists mainly polymers and minor contents of *additives* (3.7).

Note 2 to entry: Supplementary to the term “plastic”, “plastic product” is also used. According to ISO 472, a plastic product represents “any material or combination of materials, semi-finished or finished product that is within the scope of ISO/TC 61, Plastics”.

Note 3 to entry: Plastics comprise both *thermoplastic* (3.3) and *thermoset* (3.4) materials.

[SOURCE: ISO 472:2013, 2.702, modified — Notes to entry have been replaced.]

3.3
thermoplastic
plastic (3.1) that has thermoplastic properties

[SOURCE: ISO 472:2013, 2.1178]

3.4
thermoset
plastic (3.1) which, when cured by heat or other means, changes into a substantially infusible and insoluble product

[SOURCE: ISO 472:2013, 2.1181]

3.5
elastomer
macromolecular material which returns rapidly to its initial dimensions and shape after substantial deformation by a weak stress and release of the stress

Note 1 to entry: The definition applies under room temperature test conditions.

[SOURCE: ISO 472:2013, 2.327]

3.6
composite
solid product consisting of two or more layers (often in a symmetrical assembly) of, for instance, plastic film or sheet, normal or syntactic cellular plastic, metal, wood or a composite with or without adhesive interlayers

[SOURCE: ISO 472:2013, 2.182.2, modified — The example has been omitted.]

3.7
additives
chemicals added to *polymers* (3.1) to improve/change the individual properties of the specific plastic material

Note 1 to entry: Important additives such as fillers/reinforced materials, softeners and flame retardants are referenced according to ISO 1043-2 to ISO 1043-4.

3.8
macroplastic
any solid plastic particle or object insoluble in water with any dimension above 5 mm

Note 1 to entry: Typically, a macroplastic object represents an article consisting of plastic or a part of an end-user product or a fragment of the respective article, such as cups, cup covers.

Note 2 to entry: The defined dimension is related to the longest distance of the particle.

3.9
microplastic
any solid plastic particle insoluble in water with any dimension between 1 µm and 1 000 µm (=1 mm)

Note 1 to entry: This term relates to plastic materials within the scope of ISO/TC 61. Rubber, fibres, cosmetic means, etc. are not within the scope.

Note 2 to entry: Typically, a microplastic object represents a particle intentionally added to end-user products, such as cosmetic means, coatings, paints, etc. A microplastic object can also result as a fragment of the respective article.

Note 3 to entry: Microplastics may show various shapes.

Note 4 to entry: The defined dimension is related to the longest distance of the particle.

3.10
large microplastic
any solid plastic particle insoluble in water with any dimension between 1 mm and 5 mm

Note 1 to entry: *Microplastics* (3.9) may show various shapes.

Note 2 to entry: Typically, a large microplastic object represents an article consisting of plastic or a part of an end-user product or a fragment of the respective article.

Note 3 to entry: Microplastics in this size range are, for example, plastic pellets as intermediates for further down-stream processing such as moulding, extrusion, etc. resulting to semi-finished products which are not final end-user products.

3.11
microparticle
solid particle insoluble in water in the dimension between 1 µm and 1 000 µm (=1 mm)

Note 1 to entry: There is currently no specific distinction between nanoparticles and microparticles.

3.12
macroparticle
solid particle not soluble in water in the dimension above 5 mm

3.13
nanoplastic
plastic particles smaller than 1 µm

Note 1 to entry: According to OECD nanoparticles are up to 100 nm.

3.14
litter
solid object disposed of or abandoned in the *environment* (3.17)

3.15
marine litter
litter (3.14) found in the marine or coastal *environment* (3.17)

3.16
waste
any material or object which the holder discards, or intends to discard, or is required to discard

[SOURCE: ISO 15270, 3.34]

3.17
environment
conditions and surroundings that might influence the behaviour of an item or biotic life

Note 1 to entry: Environmental matrices are: water, air and soil.

Note 2 to entry: The relation to the environment within this document does not refer to environmental aspects such as resource efficiency, energy consumption, climate protection, etc. rather this document focuses on the relevance with respect to potential releases into the environment on land or sea.

[SOURCE: ISO 472:2013, 2.1310, modified — The definition has been edited to specify biotic life and Notes to entry have been added.]

3.18
ageing
entirety of all irreversible chemical and physical processes occurring in a material in the course of time

Note 1 to entry: For testing purposes, ageing is often applied artificially.

3.19
biota
living organisms in the *environment* (3.17)

4 End-use applications of plastic materials and its relevance to the environment

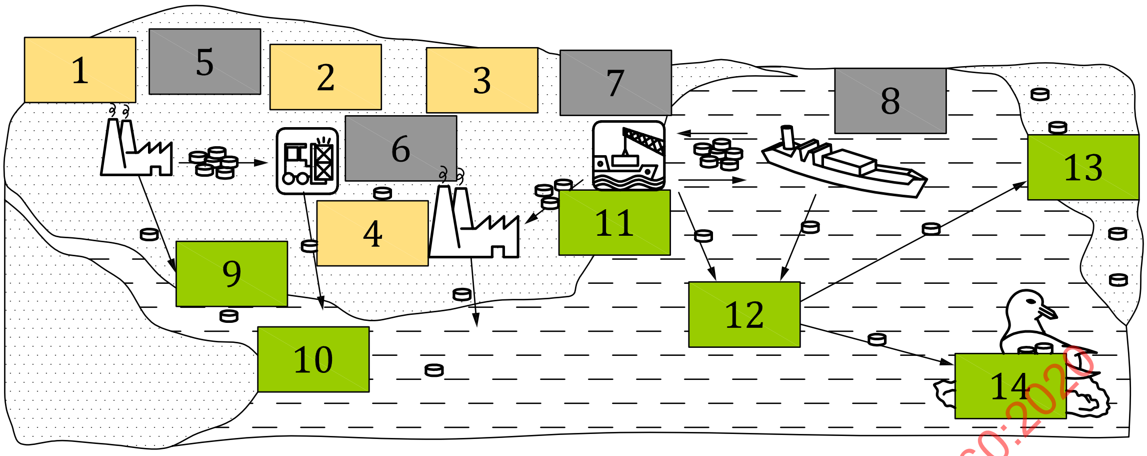
4.1 General

Plastics are important materials in today's modern life and play an integral role in both households and industries. Over recent years, the consumption of plastic materials has significantly increased and today they find diverse fields of areas of application such as packaging, building and construction, automotive, electrical and electronic equipment, etc. Depending on the performance requirements of the final end application, an article can contain plastics and/or composites.

The production of plastic materials is strictly regulated by legislative rules that translate into permit requirements for materials production by the chemical and plastics industry according to the Industry Emission Directive in Europe. In this way, emissions into air, water and soil can be well managed by applying the best available technologies for polymer production according to legislative rules and technical guidance.

The plastics value chain can be described as follows. Plastic materials are mostly manufactured from fossil raw materials like oil or gas and are mainly produced in the form of powders, flakes and pellets (a preformed moulding material). This material may further be compounded before its use in moulding and extrusion processes for its subsequent conversion into intermediate semi-finished products like sheets, profiles, films, etc. These will be shaped into a variety of final articles in the household, buildings, mobility sectors, etc. For the market relevant plastic materials used by the diverse application sectors, see 4.2 to 4.5, the term "plastics" comprises thermoplastic materials and thermosets.

Figure 1 shows how in the industrial value chain the various steps of production, logistics and distributions as well as entry pathways of plastics are distinguished.



Key

Yellow boxes: steps of the value chain
Grey boxes: logistics, distribution, trade, transfer
Green boxes: entry pathways
1 raw material producer
2 compounder/converter
3 OEM
4 supplier/tier
5 logistics on land
6 distribution/trade
7 transfer/shipment
8 logistics on sea
9 drain from municipality
10 river
11 port
12 ocean
13 beach/coast
14 biota

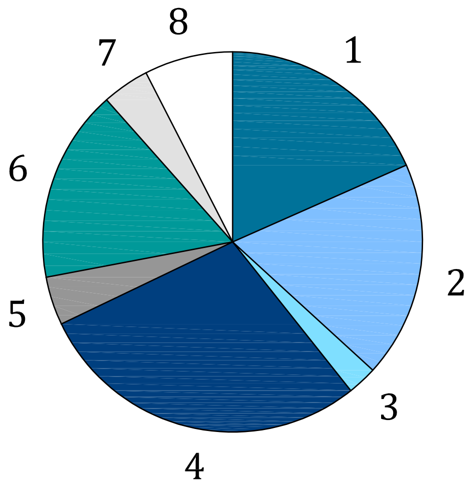
NOTE This figure is based on a graph of International Pellet Watch: www.tuat.ac.jp/-gaia/ipw/en/what.html

Figure 1 — Schematic illustration of the plastics value chain in the context within the environment after a graph of international pellet watch

NOTE Figure 1 represents a highly simplified illustration of the industrial value chain, the logistics and distribution as well as possible entry pathways into the environment. The reality is much more complex, thereby, with further interim steps, interlinkages, dependences or possible further aspects.

Both legislation as well as standardization, especially quality and environmental management like ISO 9000 group of standards and ISO 14000 group of standards, are in place and may be in principle considered as appropriate means to minimize eventual losses for each production step as well as logistics and distribution.

According to the European Market and Research Group of the European plastics manufacturers[2], the total global production of plastic materials amounted to approx. 280 Mio tons in 2016 without other plastics i.e. thermosets, elastomers, adhesives, coatings, sealants and fibres. Asia accounts for about 50 % of the world-wide production with China leading with 29 % of global production. European production is less with 19 % and similar to NAFTA states (Canada, Mexico and the US) who have a share of 18 %. It is assumed that the strong growth in Asia will also continue over the next years reinforcing their leading role in worldwide plastics production.



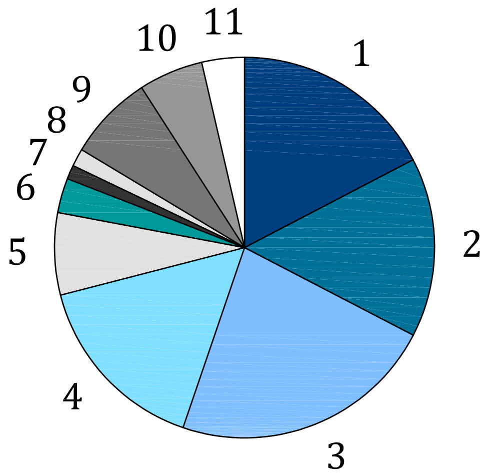
Key

1 NAFTA 18 %
2 Europe (WE +CEE) 19 %
3 CIS 2 %
4 China 29 %
5 Japan 4 %
6 Rest of Asia 17 %
7 Latin America 4 %
8 Middle East, Africa 7 %

NOTE Graph according to Plastics Europe[2].

Figure 2 — World Plastics Material Production in 2016 by country/region

Globally, the most important types of plastic materials are standard plastics. More than three quarters of the global plastics production consist of polyethylene, polypropylene, polyvinylchloride and polystyrene including expanded polystyrene, see Figure 3. Less than 10 % are considered as engineering plastics.



Key

1 LDPE, LLDPE, 17 %
2 HDPE 15 %
3 PP 23 %
4 PVC 16 %
5 PS, EPS 7 %
6 ABS, ASA, SAN 3 %
7 PA 1 %
8 PC 1 %
9 PET 7 %
10 PUR 6 %
11 other thermopl. 4 %

NOTE Graph according to Plastics Europe[2].

Figure 3 — World Plastics Material Production in 2016 by type of polymer

When an article that contains plastic materials is placed on the market, it is used by a variety of end-users such as the industrial/commercial sector as well as the private and household sector. Finally, after an article has fulfilled its valuable intended purpose to the end-user, it comes to its end-of-life stage and, thus, it becomes waste. It is important at this stage that such a discarded product should enter a well-managed waste collection system, operated by either municipalities or by privately organized enterprises for the further waste treatment, so that the embedded material or energy resources will be recovered effectively and efficiently.

However, such effective waste management schemes are not available in all countries of the world which may result in significant amounts of wasted products, including those made of plastics, being improperly treated or thoughtlessly discarded into the environment, on land or at sea. Leakage of plastics into the environment is caused mainly through uncontrolled or improper handling of goods and waste and it is important that measures are taken to prevent this.

The subsequent Clause 5 gives an overview of reports and studies on the occurrence of plastics and plastics containing waste in the environment. Nevertheless, no validated data exist until today in order to accurately report the amount of waste entering the environment. Also, the mechanism on the sources and sinks are not yet sufficiently analysed and understood. Therefore, internationally standardised procedures are a prerequisite in order to set-up facts and derive appropriate measures.

Though environmental, product and waste management legislation (including logistics, shipment and treatment of waste, waste water and sewage), is well-established in several countries, the release of plastic products and other waste materials into the environment by littering through improper management is expected to increase in countries with little or no waste and service infrastructure. A mismanagement of waste is further induced due to insufficient education and information for citizen's on used articles at end-of-life stage and their impacts of the littering.

An indicator for well-established and well-working waste management is a country's waste statistics, which gives information about recovered vs. landfilled waste, especially organic-rich waste fractions which also include plastics waste. If a country recovers most of its material through either recycling or energy-from-waste with little being landfilled, then the established waste infrastructure can be recognized as working rather well. In contrast, there are other countries with a not satisfying waste infrastructure where it is observed that waste is predominantly dumped to landfills, which may or may not be responsibly managed. Also, it is known that unofficial waste disposal and wild dumping exist and here, often leakage into the environment occurs. For instance, according to the statistics of managing plastics end-user waste in Europe (28 EU-member states plus Norway and Switzerland) there are only 9 countries performing very well with recovery rates above 95 %[1]. However, on average the majority of countries in Europe (21 countries) still landfill more than half of their plastic containing waste today. Though recognizing that also proper landfilling does not contribute to uncontrolled leakage into the environment, this survey shows that only few countries in Europe have a good performing environmental status. It is assumed that other regions, be it on the American continent or in Asia, show a similar heterogeneous situation.

Any waste that is improperly managed subsequently leaks into the environment and ultimately into the ocean is unacceptable. Therefore, the priority is to stop waste of any kind, including plastic waste, from being littered on land and sea. For this purpose, it is important to:

— ensure the effective implementation and execution of existing legislative rules and development of such legislation in countries if this does not exist within a country, the producer responsibility schemes — as they are globally in place in some G20 States — should be expanded to further countries and regions;

— develop and practice efficient and effective waste management systems and infrastructures for collection, treatment and recovery;

— promote wise consumer behaviour to increase their appreciation of the value of goods and articles and the opportunities to optimally recover their embedded resources after they have performed their function and become waste;

— mindfully design products while taking resource efficiency and litter prevention into consideration.

In the following sub-sections, key application areas are described from a variety of sectors where plastic products may come into contact with the environment during or after its use.

4.2 Packaging

The packaging sector has the largest share of plastics consumption of all sectors where plastics are used. For packaging, typically polyolefins and bottle grade PET types are used for products such as films, bags, sacks, bottles and containers, cans, pallets, caps and enclosures, etc., all of which have a rather short service life.

Packaging materials quickly reach the end of their life after performing a valuable function in protecting and preserving the goods they contain. It is important that after fulfilling this valuable function they are properly managed at the end of their use-phase. Hence, the waste management of used packaging is today one of the most developed schemes, be it within the frame of producer responsibility via private waste economies or via municipal waste infrastructures. Nevertheless, packaging related items are found in the environment, see Clause 5.

Basically, such schemes require the efficient implementation and execution of waste legislation alongside a practical, effective and workable waste infrastructure for the collection and treatment of packaging waste. This needs sufficient awareness of end-users and consumers about how to discard and manage their packaging waste. Unless such a combination is realized in all countries, we will not achieve that same level of effectiveness in managing the recovery of packaging waste at its end of life and littered packaging will continue to be observed in the environment. Packaging waste is also prone to escape from landfills, if the depositing sites are insufficiently managed. Assessments of littered articles on land and at sea indicate that packaging is the most visible product when not properly managed.

4.3 Building and construction

The building and construction sector is the second important application sector for plastic materials in many countries and dominated by polyolefins, PVC, expanded polystyrene and other plastic insulation materials. Specific take back and waste recovery schemes have been developed by the plastics industry such as for used window profiles, pipes, cables, floorings, etc. Some products if not properly managed on construction worksites may escape into the environment, for example through insulating material, so good site management is essential.

4.4 Mobility and transportation, electrical and electronics

Unlike the aerospace sector which is seeing massive growth in the use of composite materials, the share of plastics in road vehicles is relatively low, ranging between 5 % and 15 % in European countries. This means that in the automotive sector, other materials like metals, ceramics, rubber, etc. are more important. Nevertheless, there is a wide variety of different types of plastics used for cars due to robust performance requirements such as durability, strength, lightweight, temperature and moisture as well as corrosion resistance. Therefore, both standard plastics and engineering plastics as well as composites are used in mobility and transport.

Similar to vehicles, engineering plastics are also used for the electrical and electronics sector, which again represent a minor proportion of plastics within the final end product. It is estimated that on average about one fifth of the materials in electrical goods consist of plastics.

Both the mobility and transport sector as well as the electrical and electronics equipment sector typically require products with a relative long life time. Adequate control requirements for appropriate waste management and global shipments are necessary for such goods at the end of their life to prevent their possible unregulated illegal disposal or treatment.

NOTE Tyres seem to be the most important entry of microparticles due to ageing effects which result from abrasion and partial fragmentation of rubber particles from tyres.

4.5 Agriculture

Growing use of plastics in agriculture has been reported[40]. It is assumed that global consumption of plastics in the agricultural sector is still growing. There are different application areas for plastics such as farming, agricultural and mulch films, textiles, irrigation, home gardening, etc. Plastics in the agricultural sector are further used in transplant and bedding plant production, as irrigation tape, trays and pots, tunnels, hay bale wraps, and in greenhouse construction. The extent to which agricultural soils are mulched with plastic film on a global scale is uncertain. Nonetheless, some information can be found: in China, in 2011, nearly 20 million hectares were reported to be mulched, with use projected to grow 7,1 % or more annually[42]. There are also management procedures where distinct intentional applications in agriculture can result to the release of plastics, such as fertilisers, including secondary raw material fertilisers (e.g. sewage sludge, compost or digestate), as well as livestock manure.

In some countries like Germany, France or Spain, specific take back schemes have been established such as the recycling of mulch films made of polyolefins. Specific utilization of agricultural films with specifically biodegradable plastic applications is growing in some countries or is under development. Specific standards, be it for the recycling of polyolefins or the biodegradation of agricultural applicances, have been developed or are under development at ISO/TC 61 and CEN/TC 249. Regardless of the system used, it is principally important that plastics used in the agricultural sector are managed properly to prevent leakage of such products, materials or residues into the environment.

5 Occurrence of plastics in environmental matrix and biota

5.1 General

There are numerous publications on the occurrence of plastics and microplastics in the environment and the number being published has rapidly increased in the recent years. Results show that plastics can be found in every studied environment.

The majority of research on plastics in the environment focuses on microplastics. Also, the occurrence of smaller particles (nanoplastics) cannot be excluded. Moreover, most of the studies about microplastic focus on the marine environment. From this research, it becomes obvious that field studies are not easily conducted and a large variety of approaches on sampling and analytical techniques exist for the identification and quantification of plastics.

This results in the fact that plastics are presented in a wide variety of units such as: microplastics per litre, spheres per litre, beads per litre, particles per square metre, particles per litre, particles per kilogram, pieces per kilogram, items per kilogram, kilogram per kilogram, kilogram per litre (litres can refer to water or sediment and kilogram can refer to dry or wet weight). Also, units are converted and adapted between publications for specific purposes, and it is not always clear which choices are made in these conversions. In addition, plastics are classified by shape (fragments, pellets, cosmetic beads, lines, fibres, films, foams) and type of polymer (polypropylene, polyethylene, polystyrene, etc.). While the latter is often well determined, the criteria that are used for characterization by shape are not always obvious.

Hence, there is no uniformity in the collection, processing and analysis of samples and data and there is a wide variety of categorizing plastics by shape and polymer type and/or composition. This makes a direct comparison between studies very difficult, and even leads to ambiguity between results. This not only hinders a good understanding of the dynamics and impacts of plastics and microplastics but also hinders stakeholders in taking effective measures to address and (if necessary) mitigate the problem.

There exists a large amount of data on plastics and micro plastics in various environmental matrix and biota. Although these data are not directly comparable, they have led to a broad consensus on possible sources and sinks as well as possible environmental impacts.

This document mainly focuses on microplastics however, reference is also made to macroplastics and to studies from which it is not always clear how the distinction is made between the different size fractions of plastics. This document follows the identification given by the original paper, resulting in sometimes confusing terminology (plastics vs. microplastics). It gives a brief overview of the current knowledge (mainly based on literature published in 2016 and early 2017) on microplastics in different environmental compartments: water (aquatic systems), sediments, sludge and soil (solid systems), air and biota. Although some concentrations are presented, these are merely examples from the literature and should not be interpreted as representative for the whole environmental compartment from which results are derived. Most references are made to English language scientific studies that have included quantitative measurements of (micro)plastics. The results that are presented in this document follows the quantification of the original source.

NOTE This document does not provide a quality statement of the presented data or the referred literature.

5.2 Water systems

5.2.1 Marine waters

Plastics have been found in the oceans worldwide, including remote regions such as Antarctica and the deep sea. The distribution of plastics in the oceans is very heterogeneous. High concentrations have been found close to industrial centres and metropolitan areas, in enclosed or semi-enclosed seas such as the Caribbean and the Mediterranean Sea and in gyres.

In coastal systems, harbours and bays can contain high amounts of plastics. South African coastal harbours contained up to 1 200 particles m^{-3}[3], and concentrations up to 27 909 microplastic particles per 100 m^3 were detected in the Hong Kong Victoria Harbour[4]. However, the latter number is derived from a study that confirmed the large spatial and temporal variation in the abundance of microplastics as also found in other studies.

With increasing amounts of microplastics in the environment, it is inevitable that coastal systems form a source of marine debris for outlying coastal regions and the ocean. Their transport through the coastal systems into the ocean is not only determined by the concentration difference but also by other processes such as tidal effects. Riverine transport of floating plastic debris into European waters has been shown to depend on tidal regimes with more fragments of larger sizes observed during spring tides as compared to neap tides[5].

Once introduced into a water system, plastic litter finally accumulates in the surface water and sediments of the world's oceans. High concentrations of floating plastic debris have been reported in central areas of the North Atlantic[6] and Pacific Oceans[7]. Oceanic circulation models suggest possible accumulation regions in all five subtropical ocean gyres[8]. The models predict that these large-scale vortices act as conveyor belts, collecting the floating plastic debris released from the continents and accumulating it into central convergence zones. Indeed, on the basis of samples collected on a circumnavigation cruise and additional cruises it is shown that plastics and microplastics are found throughout the oceans with plastic concentrations up to 2 500 $g \cdot km^{-2}$ in accumulation zones[9].

Local studies show that microplastics find their way to more pristine marine ecosystems where microplastics have been found in the Southeast Bering Sea, Alaska. Concentrations of plastics in the Bering Sea (fragments were primarily less than 2,5 mm in size) varied between 0,017 and 0,072 number of particles m^{-3} (averages of different cruises[10]). Microplastics have also been found in surface and subsurface waters in the Barends Sea (South of Svalbard) in maximum abundances of 1 and 15 microplastics m^{-3}, respectively[11]. In addition, small-sized plastics increased in abundance North of Svalbart between 2002 and 2014, which indicates fragmentation of plastic litter, and raises concerns about contamination by microplastics in the Arctic region[12]. Finally, microplastics and macroplastics are also found in Antarctic surface waters, on beaches and in sediments south of the Polar Front[13].

5.2.2 Fresh waters

Microplastics are found in all studied fresh water environments, including the water columns of lakes and rivers of Africa[14], Asia[15],[16], Europe[17] to [19], the North American continent[20],[21] and the South American continent[22].

Concentration ranges amongst these studies vary widely. Also, studies conducted in one water body show considerable variations in the distribution of microplastics over the water surface. For example, microplastics in surface water were sampled at 11 locations along the river Rhine between Basel (Switzerland) to Rotterdam (the Netherlands). The highest level of 3,9 million particles km^{-2} was found at Rees in Germany. Downstream the concentrations declined quickly, probably because the sedimentation rate of microplastics increased due to the lower slope and slower water flow rate[23].

Studies show that different lakes across a country are differently contaminated with microplastics. For instance, an average microplastic density of 20 264 particles km^{-2} was found in the Mongolian mountain lake Hovsgol which was more polluted with microplastics than the Lakes Huron and Superior[37],[55].

In addition to the heterogeneous distribution within or across water systems, the occurrence of different forms of microplastics has shown that types of microplastic are not equally found in the environment: fragments and films were the most abundant microplastic types in the study of[37] where no plastic microbeads and few pellets were observed.

5.3 Sediments

5.3.1 Marine sediments

Plastics and microplastics enter the marine environment mostly from land-based sources, often via estuaries. Results from studies show that these systems are potential microplastics hotspots. A study in the Netherlands[24] showed this coastal gradient where they found sediments with the highest number of microplastics (3 305 particles kg^{-1} dry weight) in the Rhine estuary and the second highest in the Wadden Sea Estuary (770 particles kg^{-1} dry weight) as compared to the coastal area sediments in the North Sea (averaged 440 particles kg^{-1} dry weight) and with the lowest number of particles further off shore. The coastal gradient demonstrates the difficulty of evaluating of such findings due to the complexity and heterogeneity of conditions. A similar spatial distribution was found in the Yangtze Estuary with an abundance of microplastics in sediments of 20 to 340 items kg^{-1} dry weight[25] and highest concentrations near the coast. The results indicated that the Yangtze Estuary was polluted by microplastics, both in sediments and in surface water[26].

Land is an important source of plastics debris and microplastics to the ocean, plastics are not only released through direct human activities but also natural processes such as weather cycles play an important role in their introduction into the environment. From a study on South Korean beaches it was recorded that high microplastic levels of 27 606 items m^{-2} occur after the rain season as compared to mean values of 8 205 items m^{-2} before the rain season[27].

It is not just estuaries but other coastal ecosystem such as mangroves can also contain high concentrations of microplastics. Singapore's coastal mangrove ecosystems contained between 3 and 16 particles per 250 g of dry sediment with highest concentrations near harbours or areas with fishing activities[28]. However, microplastics are also found in remote mangrove area's that are less exposed to human activities such as the mangrove forest of Malaysia where microplastics were found up to 117 particles per 7 500 cm^3 sediment[29].

A portion of the oceanic microplastics ends up on the sea floor, simply as they sink due to density effects or as they are pulled down by coverage with organisms. Some studies have shown the occurrence of microplastics in deep sea sediments at 1 100 m to 5 000 m with an average abundance of up to 1 particle 25 cm^{-3}[30]. In the Kuril–Kamchatka Trench area (NW pacific) microplastics were ubiquitous in box corer samples from depths between 4 869 m and 5 766 m with lowest number of plastic at 60 pieces m^{-2} and highest numbers of more than 2 000 pieces m^{-2}[31].

5.3.2 Fresh water sediments

The density of the plastic in particular will be important for determining its environmental fate. For example, density will influence how particles partition in the aquatic environment including whether they float on water surfaces or settle to sediment. However, even when properties are known, it can be difficult to predict the fate of plastics. For example, it has been observed that supposedly buoyant particles such as polyethylene and polypropylene can be retained within sediments[32]. This could be due to biofouling or agglomeration with organic materials.

Natural processes influence the transport of plastics: results on Lake Garda sediments amount to 108 and 1 108 particles m^{-2} at the southern and northern shoreline, respectively. This pattern is mainly a result of wind and lake morphology and the prevailing currents[33].

The distribution of plastics encountered in sediments is also determined by human activities in the area. In St. Lawrence River in Canada, an average concentration of microplastics (<2,16 mm) in 10 sampling sites was approximately 13 800 particles m^{-2}[34]. In this study, small microplastics were found in regions receiving industrial and municipal effluent, while larger microplastics were found in non-effluent areas. Quantitative and compositional results have been reported of microplastics sampled from shoreline and lake-bottom sediments of Lake Ontario, Canada[21]. Among the particles, polyethylene was the most common type followed by polypropylene. In this study no microplastics were found in the lake bottom sediment deeper than 8 cm, showing that the vertical distribution becomes also important when designing a sampling strategy.

5.4 Sludge

In particular, microplastics are suspected to find their way into the environment via industrial and domestic wastewater. Although, results from recent studies do suggest that waste water treatment plants can effectively remove microplastics, the effluent may still contain significant amounts of microplastics[35]. However, while waste water treatment may effectively remove most plastic and microplastic particles from the water, many of the particles will be retained in the sludge. As it is common practice to use waste water sludge as fertilizer and to dispose waste water sludge to land, treatment plants form a pathway through which plastics enter the terrestrial environment[36] and the aquatic environment[37].

5.5 Soils

5.5.1 Terrestrial systems

The occurrence of plastics in fresh water and marine environments has extensively been studied and they also recognize terrestrial environments and soil as an important source of plastics via different routes of entry such as inappropriately managed landfill sites, loss during waste collection, fragmentation of agricultural plastics, and vehicle and road derived debris. However, the distribution and importance of plastics for soil has, to date, received relatively little attention.

Clearly, plastic litter is widely distributed on land surfaces, in and around urban areas via casual littering, in the vicinity of landfill sites and in agricultural areas. Where casual littering around urban areas seems an obvious pathway for plastics into the environment, some landfills may become important sources of municipal waste, including plastics to the environment in coming years as the amount of plastics in waste has steeply increased to approximately 10 % (by weight of the waste buried) in the last decades[38] and is increasing still[39].

There are accounts of inadvertent contamination of soils with small plastic fragments as a consequence of spreading sewage sludge[40], and contamination via compost that is prepared from municipal solid waste[41]. For instance, 1 000 to more than 4 000 particles of microplastics per kilogram of dry mass sludge were found in agricultural sites and restored landfills in Europe, where the first 10 cm of soil has been found to contain 670 plastic fibres per kilogram soil. As discussed in 4.5 of this document there is increasing concern in the growing use of plastics in agriculture, through which plastics may become incorporated into soils.

Also, road networks are recognized as corridors of plastic and rubber deposition, partly through surface deposition of discarded material, where plastics are likely to degrade or be dispersed relatively quickly and thus do not accumulate as substantial deposits. Hence, these are likely to be zones of microparticle occurrence through degradation and fragmentation.

Although microplastics may remain in soil for years[39], eventually microplastics are likely to be mobilized and distributed by wind, or be transported with surface run-off to aquatic environments.

5.5.2 Beaches

Studies on the occurrence of plastics in the marine environment seldom include the coastal dunes and backshores. However, studies that do include these areas show that high amounts of plastics can occur in these areas. Transects across the shore from coastal dunes and backshores of Brazil show that dunes accumulate larger amounts of microplastic pellets than backshores with ± 135 pellets m^{-2} in dunes and < 20 pellets m^{-2} in backshores[43].

Occurrence of microplastics on beaches in China was counted at 200 to 600 number of items per 50 g dry sediment[44], here the authors clearly state that all sampling sites were close to centres of human activity. This might influence the numbers of plastics found in this study. Inevitably this influence is also mentioned in other studies: the abundance of plastic debris on the continental coast in a study by[45] could be associated with coastal urban centres and their economic activities, where these authors found an average of 27 plastic pieces per m^2 for the continental coast of Chile. In the same study, it was found over 800 items/m^2 at Easter Island, where transport of plastic debris via the surface currents in the South Pacific Subtropical Gyre, could result in the accumulation of small plastic debris on the beaches of the island[45].

Plastic debris and microplastics along the beaches of the Strait of Hormuz, Persian Gulf showed a similar distribution with the order of microplastic abundance generally reflecting the level of anthropogenic activity in the area with the highest abundance of 1 258 particles per kilogram near industrialized areas and few microplastics in protected areas and mangroves[46].

In samples taken from the North Sea Island Norderney along drift lines and in a dune valley 1 to 4 small potential microplastics per kilogram dry sediments were found[47]. Further investigations have been performed at the East Frisian Islands and the Kachelotplate. However, these findings could not be verified by other scientific considerations. This shows the importance of robust and verifiable measurements.

5.6 Air

Wind is a common vector for dispersal of any kind of small particles including plastics, indeed atmospheric transport and deposition might be a direct and significant pathway of microplastics from consumer products to the environment[48]. Moreover, microplastics were recently found in concentrations between 1,0 and 60,0 fibres m^{-3} in indoor environments (apartments and office), elevated as compared to outdoor concentrations that are found between 0,3 and 1,5 fibres m^{-3}[49].

In spite of the above studies, the knowledge gap of the contribution of microplastic to air contamination or air quality remains significant.

5.7 Terrestrial fresh water and marine biota

The occurrence of plastic fragments is of particular concern not only because they are difficult to remove from the environment but also because they have the potential to be ingested by a wide range of organisms either by direct feeding or via trophic transfer where microplastics particles can potentially enter the foodchain at the lowest trophic level by being adsorbed to algae and ingestion by aquatic grazers[50].

Upon ingestion, it is possible that these small fragments may present a physical risk in a similar way to larger items of debris by clogging feeding appendages or the digestive system. Moreover, microscopic fragments are also known to be taken up from the gut into other body tissues[51],[52]. It is noteworthy to mention that these results are from experimental studies, carried out with high exposure concentrations. It is necessary to distinguish between the theoretical transport path way and a real effect in the targeted organism. Valid investigations are missing at the moment. Uniform examination procedures are also necessary for this purpose.

Possible impacts arising from land-applied microplastics begin in the terrestrial ecosystem with implications for terrestrial species. However, studies on the impacts of microplastics on terrestrial organisms are remarkably scarce. In a study on 17 birds in Shanghai researchers counted 364 plastic items (in size from 0,5 mm to 8,5 mm), interestingly no relationship between plastic load and body condition was found in this study[53]. Plastic debris was also found in fresh water birds as geese and ducks in Canada[54].

In freshwater environments, microplastics have been found in the crustacean *Daphnia magna*[55] and freshwater fish[22] (and references therein).

In past decades it has been noticed that marine biota such as mammals, turtles and numerous other organisms ingest large plastic items including bags and bottles[56]. A study done in the North Pacific[57] found plastic particles in the stomachs of 8 of the 11 seabird species caught as bycatch. Moreover, examination of the gut content of thousands of marine birds in two separate studies revealed that the ingestion of plastics by seabirds had significantly increased during the 10 to 15-year interval between studies[58].

There are a number of examples of marine organisms of other trophic levels that ingest microplastics. Grazing microzooplankton has been noticed to ingest 1,7 µm to 30,6 µm polystyrene beads[59]. Ingestion of microplastics by decapods has been observed[51], where 83 % of the animals sampled contained plastics (predominately filaments) in their stomachs. Ingestion of microplastics in the range of 20 µm to 2 000 µm by the amphipod *Orchestia gammarellus* and the polychaete *A. marina* has been reported[60]. Deposit- and suspension-feeding sea cucumbers are also found to ingest plastic fragments, of a size fraction of 0,25 mm to 15 mm[61]. Also, the suspension-feeding common mussel *Mytilus edulis* has been shown to capture and ingest large microplastic particles ranging from 2 mm to 16 mm in size[51][57].

Microplastics were found in 36,5 % of fish belonging to 10 species sampled from the English Channel[62][63] with An average of (1,9 ± 0,1) particles recovered from those which contained plastic. These findings were comparable to those from the North Pacific Central Gyre[64]; small plastic fragments (predominantly of the size class 1 mm to 2,79 mm) were found in approximately one third of all fish caught.

These smaller organisms are preyed upon and thus form a route of entry to various compartments of the marine food web. Higher trophic level organisms have been found to ingest microplastics transported by prey items where microplastics of approximately 1 mm in diameter were recorded in the scat of fur seals and sea lions[65][66].

6 Testing methods

6.1 General

A systematic comprehensive overview for chemo-physical and biological testing methods about different techniques for sampling, sample preparation and identification is complex. Therefore, the goal of this document is not an overview of all the methodologies described in existing literature, but to provide a first insight about different methods and techniques depending on different samples of environmental matrix. No results due to plastic particles appearance are presented. No comment/assessment on the monitoring strategies or sampling design of different geographic sampling locations is given.

This document focuses on the analysis of microplastics and large microplastics. It is based on peer-reviewed studies with original data published before early 2017, while avoiding meta-analyses. A few review articles are also available (see References [67] to [71]).

6.2 Sampling

6.2.1 General

The sampling process is the first step in an investigation of plastic particles in environmental matrix. Particles are not homogenously distributed within the environment, they are perceived as local pollutants. A representative environmental aliquot is often not defined. The sampling procedure is often controlled by the limitation of sampling techniques, not by the representativeness of the environmental sample aliquot or location. Recommendations due to the preferred use of different sampling strategies, such as random sampling, collective or pooled sampling are still not existing.

Plastic particles have been described in environmental compartments across the Earth: marine and fresh waters, in sediment, sludge and soil, as well as in air and biota (see Clause 5). Although different techniques are used for sampling, this differentiation is also used for the organization of this clause.

The different density properties of various plastic material types (0,9 kg/L to 1,6 kg/L) result in the accumulation on either the surface of water or on water ground or within the water column. In turbulent water or for particles with densities around 1 kg/L, depending on the salt concentration, the particle distribution might be unpredictable and random. Similarly, for sediment sampling, various particles size classes might result in the concentration of plastic particles in the top layer of sediments. These factors should all be considered when designing a sampling plan.

The use of plastic equipment in sampling procedure (for example PVC or SiR tubes), sample transport and storage (PE or PP containers or bottles), as well in lab equipment (tubes, bags, etc.) is documented. However, no comment is given about a possible contamination effect by such equipment. Furthermore, the protection of samples against contamination from workers clothing (synthetic fibres) and articles of daily use (cosmetic products), as well as contamination from atmospheric fall out is often not considered. Recently published articles document relevant effects. Here, further systematic efforts due to assessment of contamination by sampling and handling should be made or clear guidance should be given, respectively. The documentation of harmonized quality control measurements, including blank measurements, recovery rate experiments as well as comprehensive error bar documentation is an urgent need.

6.2.2 Water (aquatic systems)

The methods for sampling of aquatic systems should include all relevant sources of water cycle, such as marine, fresh and ground water as well as various types of waste water (according to different water purification strategies in different countries).

The majority of reports in literature relate to methods for the sampling of water surfaces[72] to [97], mainly in marine compartments, but also for lakes or rivers the major works use "water surface" sampling methods. These methods are Manta, Plankton or Neuston trawl[1)] with variable mouth openings and mesh size. Such surface sampling nets are pulled behind ships for various times at various speeds. The penetration depth of these nets in water is only sometimes documented, however according to the rare descriptions and the dimension of the nets at least only the upper 0,5 m of the sea surface is sampled. The results of the investigations are expressed in items per area or items per volume. A few works also add information about the absolute weight of particles identified. Due to the fact, that only the water surface is sampled, the expression of “items per area” seems adequate, however for the harmonization of different environmental compartments “items per volume” would be necessary.

Net dimensions, the sampling area and mesh size are the most relevant sampling parameters which are reported in articles. Table 1 summarizes the lowest and highest values of these key parameters. The net mouth opening in the broader dimension varied from 0,4 m to 1,2 m and the sampled area (according to own calculations, using the ship speed and broader mouth dimension) between 120 m^2 and 4 000 m^2. Whereas the majority use mesh sizes of 333 µm, nets with mesh sizes of 150 µm and 1 000 µm are also used. An upper value of particle dimension is given only in some cases. However, it can be assumed, that often also particles with a dimension of more than 5 mm are counted, which strictly speaking do not represent microplastic particles.

Further information about the net length, the depth of immersion, the water flow inside the nets or the wind conditions during sampling is also sometimes available. However, often no principal calculations about water flow through or alongside the net, which can affect sampling conditions is given. This is recommended, since a reduced water flow through net might result in a non-representative sampling.

Table 1 — Overview about the imported key parameters for sampling with nets

	Lowest value	Highest value	Comment
Dimension of the net mouth (larger side)	0,4 m	1,2 m	The depth of penetration is often missing.
Dimension of sampling area	~120 m^2	~4 000 m^2	Calculation according to net dimension mouth width multiplied per speed and time.
Restriction of lower limit of particles size (mesh size)	150 µm	1 000 µm	Major part of works uses 333 µm. The information about the upper limit of particles is often missing.

A small number of microplastics samples taken in deeper or turbulent water (more than 1 m below water surface) used Bongo trawl, where also nets with various geometries, mesh sizes, mouth opening and sampling speed are used (compatible values to Table 1). However, the documentation of sampling depth should be considered with care, because during the casting and catching of nets from a ship the sampling procedure is difficult to control. In a single study (Reisser et al. 2015)[93], sampling was performed with stacked bongo nets down to a water depth of 5 m.

As an alternative method for marine or limnic water sampling, especially deeper water, various pump techniques are described[98] to [103]. They used suction or submerged pumps, which are described as (multistage) centrifugal, impeller or membrane pumps using different volume rates and pressures. The pumped water volumes are stored and filtered afterwards in the lab. Alternatively, the pumped water is filtered directly during the pumping process. For these pump techniques the filtered water amount and the sampling depth are documented. However, no comment is given to possible particle destruction

1) Plankton net for sampling surface and sub-surface fauna.

during pumping process. For studies of particle size distributions, a systematic investigation would be necessary, because aged polymer particles could be very brittle.

Pump methods are described for the sampling of water management systems (waste water plant influent and effluent)[104] to [107]. It is unprejudiced documented that for those sampling locations, the choice of sampling volume and even the mesh size depend on the pollution of water by particles. Due to the high particle loading, especially in waste water inlet, often non-continuous water volumes are taken by use of buckets, containers or special equipment (i.e. Ruttner sampler, Magnusson et al. 2014[108]). The taken water volumes are filtered. Filter materials such as glass fibre (Whatman filter), copper or (stainless) steel sieves as well as nets parts taken from plankton nets (nylon) are used with various mesh sizes. In a single study (see Mintenig et al. 2014[109]) stainless steel filter cartridges were used.

From the most relevant sampling parameters, i.e. the sampling volume and the filter mesh size, strong differences exist for various works dependent from the sampled water source. Table 2 summarizes the lowest and highest values of these key parameters.

Table 2 — Overview about the imported key parameters for sampling with pumps

	Lowest value	Highest value	Comment
Restriction of lower limit of particles size (mesh size)	~10 µm	~300 µm	Only two, non-representative works use glass fibre filters with mesh sizes smaller 1 µm.
Pumped volume (marine/limnic water)	10 L	3 900 L	The chosen volumes are related to the presence all (natural and synthetic) of particles in water sample and the related problems of blockade of filter material.
Pumped volume (clear water, effluent WWP)	50 L	21 000 L	
Pumped volume (waste water, influent WWP)	0,3 L	50 L	

The majority of works use mesh sizes from 10 µm up to 300 µm, with the choice often depending on the source from which the sample is being taken. The sample water volume depends on the sampled water compartments. For clear water the highest volumes are found (50 L up to 21 000 L), followed by marine or limnic volumes (10 L to 3 900 L) and waste water the lowest volume of (0,3 L up to 50 L).

Once the samples are collected using nets and pump methods, the sample can be stored on the filter or removed from the filter. The samples should be transported to the lab for further analysis. Dependent on the focus of the work, the samples may be stored as sampled, i.e. in water, in formalin solution or dried in an oven at moderate temperatures (room temperature up to 110 °C) for various times (few minutes up to 24 h). A single study used a cryo drying process.

Continuously working centrifuges (flow-centrifuges) or hydro-cyclones are a further alternative for water sampling. These techniques are well known for separation of suspended matter or particles from water, however for sampling of microplastics no studies are described in peer reviewed journals.

6.2.3 Sediment, sludge and soil (solid systems)

A large proportion of the studies investigated sediment or sludge at coast lines, beaches and the sea floor or river banks[110][123]. Investigations about microplastics in soil, compost or fertilisers are rare or not present. However apart from the composition of these solid samples the requirements for representative, harmonized sampling in solid systems should be similar.

In literature the sampling of sediments is described (including inter-tidal and subtidal locations with defined distances to high and low water level as well as maximum and minimum tideline) or on shoreline of water. Similar to water sampling the sampling procedure is often controlled by the limitation of adequate sampling techniques, nor by the representativeness of the environmental sample aliquot or location.

For sampling of sediment from bottom water, sampling tools like Eckman (Thompson et al. 2004)[110] or VanVeen grab (Claessens et al. 2011)[116] as well as Box corer (Vianello et al. 2013)[118] are used in some cases. By using those methods, defined volumes can be taken without disturbing the sediment texture. However, the major content of the works use defined samples volumes, taken by hand. For shoreline sampling, descriptions about the distance to high or low water level or to maximum and minimum tideline are given. Perpendicular to those water lines various, random chosen samples are taken. The masses or volumes of these samples are always related to the upper 1 cm to 5 cm layer of sediment. Areas between 0,04 m^2 and 0,3 m^2 are sampled.

Table 3 — Overview about the imported key parameters for sampling of sediments

	Lowest value	Highest value	Comment
Sampled volume	0,5 L	20 L	Not always clear comment about dry or wet weight (For conversion between mass and volume an estimated sediment density of 1,6 kg/L was determined).
Sampled mass	2 kg	70 kg	
Separated sample volume for further preparation	75 g	6 kg	Preceding homogenization process of sample?
Relative content of prepared sample in relation to sampled mass in the field	1 %	40 %	Calculation consider only dry masses

In Table 3, the lowest and highest values of relevant key sampling parameters are summarized. Between 0,5 L to 20 L or 2 kg up to 70 kg sediment samples are taken. The samples are stored and transported to lab. In contrast to the water samples here always a drying process is documented (see chapter about sample preparation). After this often only a representative smaller content of the complete sample is given to the sample preparation and analysis. The sample mass, which is analysed further varies between 75 g and 6 kg. According to the sampled masses in the field this is only 1 % to 40 %.

6.2.4 Air

For sampling of microplastics in the air, only limited references are known[124][125]. In these studies, they pumped defined volumes between 2 m^3 to 5 m^3 through glass fibre filters or dry and wet deposition from atmospheric fallout through stainless steel sieves. In sum relevant amount of especially fibres can be observed. This work is supported by various studies, which demonstrate that the identification of microplastic particles is influenced by sample contamination in the lab.

6.2.5 Biota

The goal of this chapter is not an assessment of the impact the a microplastics particle has on the quality of life of biota and as such all feeding and ingestion experiments were discounted. An overview about the field sampling of microplastic in biota should be separated into different classes of biota because of their different living environment and their different habits and nutrition behaviour in the environment as well as their different dimensions and subsequent uptake of plastic particles. An overview about different biota sampling concepts is given in Table 4[126] to [136].

The sampling procedure of different kind of biota is not connected to systematic, scientific sampling protocols; the sampling is in all cases only documented as an individual sample acquisition. The commercial purchasing, as well as the samples from commercial fishing is on the one hand side pragmatic use of resources, however a guarantee on the representativeness of such samples is not possible.

Furthermore, depending on the biota's dimension it may be completely prepared for further analysis (for example bivalves, worms, etc.) or only the stomach or gut is considered (fishes, birds, etc.). Despite the problem of the different conditions for chemical or biological preparation and possible loss of microplastic, as well as the problem of visual analysis (see the chapter later), these different concepts results also in different final results. Microplastic assessment in biota is documented for bivalves and worms in numbers or mass of microplastic per mass of biota, whereas for fishes and birds in numbers or mass microplastic per individual.

Although the analysis of different types of microplastic in different kind of fishes (depending on their habits and nutrition behaviour) might give an insight into sinks and the fate of microplastics in the environment, the representativeness of such studies should be careful considered. The sampling of microplastic in biota as a monitoring concept as presented can work as a real quality assessment, but not as harmonized techniques for microplastic detection.

Table 4 — Overview about the imported key parameters for sampling of biota

Classes	Sampling technique	Analysed part	Comments
Bivalves, Polychaeta	Bought from commercial providers, random pick up sampling	Complete digestion in various chemical solutions (next chapter)	Findings in numbers or mass MP per mass of biota, only microplastic particles were considered
Fishes (marine: pelagic, benthic, demersal, freshwater)	Bought from commercial providers, fisheries sampling	Stomach/gut analysis, sometimes with additional digestion in various chemical analysis	Depended on the dimension of the fishes also Particles > 5 mm were considered. Findings in numbers or mass MP per individual
Birds	Died animals from birders, hunters, accidents	Stomach/gut analysis	
Seals	Died animals from disease	Stomach/gut analysis	

6.2.6 Statistical considerations for sampling

Statistical considerations are important in order to determine the optimum procedure and number of samples when analysing the content of plastic and microplastics in a defined environmental matrix. In particular, the diverse and manifold environmental matrix, which may even change over time, will affect the sampling procedure and, thus, the analysis result. Therefore, it is important to use an appropriate method of sampling when the content of plastic particle is highly scattered in the respective environmental medium.

The sampling procedure should not only consider where, when and how samples are taken, but also under which conditions and how many. Principally, sampling should be reproducible within a defined window of informative basis.

6.3 Sample preparation

6.3.1 General

Due to the high loading of natural particles beside the plastic particles, before analysis samples taken from the environment should be enriched or concentrated. The sample preparation depends strongly on the sampled environmental compartment; therefore, different strategies are used to extract the sample from the complex environmental matrix. The structure of this chapter is related to different preparation techniques, not to samples from different environmental compartments. The preparation technique should be chosen depending on the composition of the sample.

Although most works added control experiments with reference materials, the integrity of these materials is only rarely documented. Here an urgent need for systematic studies is necessary, using defined polymers with controlled particle size distributions as well as defined environmental matrix and adequate analysis. This means, not only the material composition should be controlled, but also the integrity of the particles size, applying different treatment conditions.

For the purpose to summarize the various strategies for sample preparation by use of physical, chemical or enzymatic treatment, the following note on a still missing issue is taken. The increasing interest in sampling from waste water plants (influent, effluent) makes the additional disinfection of samples necessary to protect the workers and researcher staff against infections from the municipal water management. This becomes very important, when the samples are dried because under these conditions microbes or viruses can be transported via the air. Various common sampling procedures are sensitive towards disinfection risk and their prevention procedures. In addition, their effects on the microplastic particle can be also highly relevant. For example, the conditions during steam sterilization can lead to the melting of PE particles and so the information about the particle size gets lost. Irradiation sterilization methods (beta or gamma) might attack the molecular weight distribution and so information about the polymer morphology gets lost. While a comprehensive knowledge about these effects can be found in the topic of “medical products", systematic investigations for plastic particles are still missing with this regard.

6.3.2 Physical preparation methods

Physical preparation methods, which are usually concentration procedures, are used especially for sediment samples to reduce the inorganic content in the samples. These methods are often used in combination with chemical pre-treatment and optimized also on the subsequent particle analysis.

Density separation is a promising tool due to the fact that polymer densities are between 0,9 g/ml and 1,6 g/ml whereas sediments' densities are more than 2 g/ml. A major content of work focused on density separation[137] to [148]. For effective density separation, the use of saturated metal salt solutions are necessary. According to the high sample volumes (see Table 3) the metal salt solution should be cost efficient and not poisonous. It should also be guaranteed that the solution will not attack the polymer particles. Here systematic works are still missing, especially for very small particles and different treatment conditions.

Currently sodium chloride (NaCl) solutions are used, which separated due to 1,2 kg/L. Also sodium iodide (NaI) and zinc chloride ($ZnCl_2$) are used, as well as sodium or lithium tungstate salts ($NaWO_3$, $LiWO_3$). Table 5 summarizes the important parameters for NaCl and $ZnCl_2$ separation techniques, which are the most common with separation limits of 1,2 g/ml and 1,6 g/ml, respectively.

The samples (50 g up to 6 kg or 500 ml up to 12 L) are stirred or shaken in these solutions for times between few seconds up to 2 h, then a certain wait time until the sample is settled down (few minutes up to 12 h) and the floating particles can be removed by careful filtering. Whereas the procedure with NaCl is done often with common laboratory equipment (breaker glass, magnet stirrer, etc.) the application of $ZnCl_2$ is demonstrated in specially constructed equipment, the Munich Plastic Sediment Separator (MPSS, Imhof, et al. 2012)[171]. This method is optimized due to the separation of sediments.

Table 5 — Overview about the imported key parameters for density separation

		Lowest value	Highest value
NaCl	Sample mass	50 g[a]	1 000 g[a]
	Solution volume	500 ml	4 000 ml
	Stirring time	30 s	1 h to 2 h
	Settle down time	2 min	6 h
$ZnCl_2$	Sample mass	400 g[a]	6 000 g[a]
	Solution volume	300 ml	12 000 ml to 30 000 ml
	Stirring time	10 min	
	Settle down time	1h	12 h

[a] The sample mass can have been determined from a wet or dry sample.

Further physical techniques are the use of centrifugation[149],[150]. Only a few works describe the use of this technique subsequent to an elutriation method[151] to [154]. A sodium iodide solution was used and, compared to the other physical technique, only a very small volume was centrifuged (40 ml including sample and solution). Studies with higher sample volumes are not known.

6.3.3 Chemical preparation methods

The chemical treatment of samples is often applied for organic rich samples or biota[155] to [169]. It is usually combined with other enrichment techniques. In Table 6, the relevant key parameters are summarized.

Different concepts have been developed. Most common for water or sediment sample is the use of ~30 % hydrogen peroxide (H_2O_2) solution in combination with iron salts (Fe II) as a catalyst or in combination with sulfuric acid (H_2SO_4). Alternatively, especially for samples from biota (mussels, bivalve) concentrated hydroxyl solutions are used (NaOH, KOH) or concentrated oxidizing acid solutions (HNO_3, HNO_3 + $HClO_4$). The temperature and duration of the treatment are documented. They vary from room temperature up to 100 °C. The time of treatment varied from approximately 1 h up to several days.

Table 6 — Overview about the imported key parameters for chemical treatment

Chemical	Concentration	Time	Temperature
H_2O_2	30 to 35 %	12 h to 7 d	RT to 50 °C
H_2O_2 / Fe II salt	30 %	30 min to 48 h	75 °C
H_2O_2 / H_2SO_4	30 to 35 %	12 h to 21 d	RT
KOH	10 %	24 h to 21 d	RT to 60 °C
NaOH	40 %	24 h	60 °C
HNO_3	69 %	1 to 2 h	60 °C to 100 °C
HNO_3 / $HClO_4$	65 %	12 h	RT
RT = room temperature			

The effectiveness of these methods is well documented for the degradation of biogenic matter (relative mass reduction). Furthermore, in many experiments, samples with different reference polymers are prepared. By this, the effect of treatment on the chemical integrity of the polymer should be controlled.

6.3.4 Enzymatic preparation

An enzymatic treatment of the samples has proven to be particularly effective for samples that are to be examined spectroscopically[170]. In most cases, different organisms with specific effects are used.

6.4 Analysis

6.4.1 General

During the first studies, only light microscopy was often used as an identification technique for microplastics in samples. The particles in real samples were identified according to their colour and their shape. For better surface morphology pictures, some of the works also used electron microscopy. This detailed surface characterization is better than light microscope identification, because polymer particles might own characteristic processing structures on their surface. However, this is like light microscopy, not unambiguously. Works during the last 3 years to 5 years showed that by this, a high misinterpretation results up to 70 %, especially for small particles.

The analysis of a plastic includes the overall identification of chemical constituent, that means including the major component analysis of polymer sort, as well as minor component analysis of stabilization additives, fillers, etc. Even if only the plastic material is analysed, the minor component analysis of additives is already challenging. The complete identification of the chemical composition of a small plastic particle beside a large number of natural organic particles in environmental samples is currently not possible. Hence, the detection of microplastics should be restricted to the identification of the major synthetic polymer component(s).

Plastics, especially the most relevant polymer types, are not soluble or are only soluble under hard conditions (not practical/acceptable for environmental analysis), therefore all methods which are typically performed in solution (i.e. H/C-NMR, HPLC, LC-MS) fail. Methods analysing only the atomic composition fail (i.e. RFA, ICP-MS), because both, synthetic and natural polymers consist mainly of carbon, hydrogen, oxygen and nitrogen. Even the additives of plastics are mainly made of these elements. Further elements of polymers which are rarely present, such as chlorine, sulfur or silicon are also present in inorganic components of environment.

This chapter presents spectroscopic, thermal and chemical methods. At the end, a comparison of the different analytical methods is presented (see Table 7 and Table 8), summarizing the methodical requirements and the information, which can be taken from the results. In particular, knowledge of relevant information, which can be drawn from the method, should be considered before choosing a specific analysis tool, because different methods work with different information content and depth. Up to now, different tasks for analysing microplastics are of interest:

— type of polymer;

— number of particles, mass fraction;

— particle size distribution and shape;

— ageing status.

The methods presented behave very differently due to the possibilities to determine this information, but also due the preparation of sample, the analysed amount/mass of sample, the time, necessary for generation of results, as well as established user knowledge and price of measurement tools.

6.4.2 Spectroscopic analysis methods

Most spectroscopic studies using Fourier transform infrared (FTIR) or Raman because they can analyse unambiguous, non-destructive plastic[171] to [195]. Both methods apply for identification the characteristic vibration spectra and compare them with spectra from databases. It should be noted that commercial spectra databases are often focus on synthetic polymers, therefore often cellulose based materials are only present as cellophane or rayon reference spectra.

A macroscale attenuated total reflection (ATR) FTIR tool can be used for particles larger than approximately 500 µm. Often the reflection crystal is covered by diamante layer, so the method is very stable against harms of crystal. The µATR-FTIR tools for particles smaller than 500 µm is, in principle, possible, but need careful sample pre-selection to avoid damage to expensive, mechanical sensitive detection crystals (Germanium) from inorganic particles (for example silicates).

In praxis, for particles smaller than approximately 500 µm microscopic FTIR and Raman techniques are used, both methods can work in automated scanning or imaging mode. For FTIR also the option of using a focal plane array (FPA) detector is described, with simultaneous working multiple detector elements. For all transmission mode FTIR imaging techniques the arrangement of sample on IR transparent substrates is necessary and only thin, spread layer of particles can be analysed (particles with dimension up to 100 µm. 100 µm is the common transmission mode limit in transmission FTIR spectroscopy for polymer films. In FTIR spectroscopy, the substrate for particles should be IR transparent or material with minor characteristic signals. Advantages are therefore the filtering of water samples through IR transparent filter materials, such as alumina, Polytetrafluoroethylene, PTFE or silicon. Various advantages and disadvantages are observed for these different kinds of materials (mechanical stability, overlaying signals). The use of reflection mode on a reflection substrate is not so common nor is the use of diffuse reflection techniques (DRIFTS) which are only rarely described. This is probably because polymers reflect infrared irradiation poorly.

Raman detected the signal in scattering mode, therefore samples can be analysed on surfaces as received. Further advantages of Raman microscopy are the insensitivity to water in the sample and its ability to measure black und reflective samples which are problematic in IR spectroscopy. A main problem of Raman is the intrinsic fluorescence of sample, which can be minimized but not completely eliminated by choosing different processing conditions (laser) and sample preparation.

Both methods, FTIR and Raman can determine the chemical structure of a specific polymer type as well as the particle size. For Raman in real samples lower limit of approximately 5 µm to 10 µm is documented. However, the lower detection limit depends strongly from the detection parameters, such as scanning speed, data acquisition and evaluation as well as the sample preparation. Imaging of large sample areas results in large data volumes which are difficult to handle. Therefore the use of chemometric data analysis is helpful. The identification of individual, separated particles by ATR FTIR and the use of all Raman/FTIR microscopic techniques is very time consuming, therefore often only a small part of the sample is analysed and the result is extrapolated to the complete sample. We found the exact particle identification protocol often incompletely described, at least particles numbers between a few up to 200 or filter areas between 1 % up to 10 %.

The use of NIR or hyperspectral imaging is present in literature, but need further investigations. Furthermore, studies, using solid H-NMR or C-NMR were not found. For both methods possibilities and limitation are still unclear.

6.4.3 Thermo-analytic methods

Thermal analysis techniques are quite common in polymer analysis. In these techniques, the specific decomposition processes and specific decomposition products are used to analyse the occurrence of a polymer in the sample or the composition of the respective polymer.

Pyrolysis - gas chromatography mass spectrometry (Py-GC-MS) uses individual isolated particles[196][197]. This technique offers very specific information about particle composition (polymer type), even additives in these polymer particles in minor concentration can be analysed. In routine analysis, careful cleaning procedure are necessary, because this method is very sensitive to contamination.

The combination of thermogravimetric analysis (TGA) with GC-MS is a new technique for microplastic analysis[198][199]. This analytical combination method, known as thermal extraction desorption-gas chromatography-mass spectroscopy (TED-GC-MS) separates locally the thermal extraction from the analysis process, hence the problem of contamination is minimized. The further possible alternative TGA with evolved gas analysis (EGA), such as FTIR or MS is only rarely described and needs further investigation. Both techniques allow the qualitative and even quantitative determination of microplastic particle.

Using differential scanning calorimetry (DSC) as thermal-analysis method is different, because here the specific melting process in a calorimetric analysis is used for identification[200]. Therefore only semi-crystalline polymers can be detected, such as PE or PP. Amorphous polymers like PVC or PS fail, furthermore the DSC signal can be strongly influenced by ageing process of the particles.

Compared to FTIR or Raman spectroscopy TED-GC-MS, TGA-EGA and DSC works with higher sample weights, so the result could be more representative for an environmental aliquot. All thermo-analytic methods have the advantage of giving clearly faster information about the composition of microplastic particles. The main disadvantage is, that they do not give simultaneously information about the particle size distribution.

6.4.4 Chemical extraction methods

The use of chemical methods for the extraction of “good” soluble polymers (such as PS) and subsequent analysis of the solution (via FTIR) is described in literature and should be considered further[201] to [203]. Advantageous will be here the wide availability of the equipment.

The chemical extraction and subsequent chromatographic analysis is also described, but not established (i.e. GPC, LC, SEC, MALDI-TOF). These methods look promising to gain information about the molecular weight which might be important in characterizing the ageing status of the polymer.

However, here the limitations of methods are caused by the availability of adequate solvents. Furthermore, especially the latter methods are relatively expensive and need a high level of user knowledge.

Table 7 — Overview about the key method parameters for MP analysis, applicable to the majorly produced polymers, such as PE, PP, PS, PET, PA, PVC

		Preparation (after filtering)	Analysed sample mass	Measurement time related to sample mass	Comment
Spectroscopic	Raman (Imaging)	As received	~1 µg	~30 min	Problem of fluorescence
	FTIR (Imaging)	Transmission mode: spread on IR transparent substrate	~1 µg	~30 min	Particles smaller ~100 µm
		Refection mode: as received	~1 µg	~30 min	Worse signal/noise ratio
	FTIR (FPA)	Spread on IR transparent substrate	~1 mg	~5 h to 10 h	Particles smaller ~100 µm, very large data volumes
	ATR-FTIR	Separation of individual particles	> 1 mg	~30 s	Particles smaller > ~500 µm
	µ ATR-FTIR	Separation of individual particles	~1 µg	~30 s	Very sensitive to mechanical destruction on inorganic particles
	NIR	Investigation under progress			
Thermo-analytic	Py-GC-MS	Separation of individual particles	~10 µg to 100 µg	~1 h to 2 h	Sensitive to contamination
	DSC	As received	~2 mg to 5 mg	~1 h to 2 h	Only for semi-crystalline polymers
	TED-GC-MS	As received	~50 mg	~2 h to 3 h	
	TGA-EGA	Investigation under progress			
Chemical	Extraction + identification	As received	> 1 g	~1 h	Only for soluble polymers

NOTE The measurement time is related to a sample with approximately 4 % of particles, all < 125 µm with a moderate resolution and achieved results of Table 8.

Table 8 — Overview about the information from MP analysis (according to PE, PP, PS, PET, PA, PVC)

		Identification	Mass content	Particle size/ number of particles	Comment
Spectroscopic	Raman (Imaging)	Yes	no	yes	Sensitive to particle surface
	FTIR (Imaging, FPA)	Yes	no	yes	
	FTIR (FPA)	Yes	no	yes	
	ATR/µATR - FTIR	Yes	no	yes	Sensitive to particle surface
	NIR	Investigation under progress			

Table 8 *(continued)*

		Identifi-cation	Mass content	Particle size/ number of particles	Comment
Thermo-analytic	Py-GC-MS	yes	no	no	Very sensitive to polymer composition
	DSC	yes/no	yes/no	no	Only for semi-crystalline polymers
	TED-GC-MS	yes	yes	no	Not for PVC
	TGA-EGA	Investigation under progress			
Chemical	Extraction + identification	yes/no	yes	no	Only for soluble polymers

7 Methodology of entry pathways (Monitoring)

Today's investigations and studies about the entries of plastics into the sea are predominantly based on rather rough assumptions and secondary literature research. Primary and validated data with analysis on site, which directly measure the littering in the environment, be it on land or on sea, have not yet been performed in a robust manner. Also, there is no uniform or harmonized procedure to be able to locate waste and particles in the wide and diverse environment.

The German and Austrian plastic industries have recently developed a methodology which is capable of determining the entry pathways of waste and particles quantitatively. This model has been developed for the assessment of land-sources of plastic entries in Germany which finally enter the North Sea (Lindner 2017)[21]. With this model, it may become possible to detect the most relevant entry pathways from land into the sea. Also, the relevant types of waste will become transparent so that appropriate measures for solutions to prevent entries of litter into the environment can be derived.

The methodology takes a systematic approach towards a detailed analysis of different entry pathways. In this way, the origin of entries, its nature as well as assessments of amounts can be evaluated. The model may thus be suitable for investigating entries into the environment from any country into the seas.

Principally, discharges of litter into the sea can be distinguished between land-based sources and sea-based sources, see the Figure 4[21].

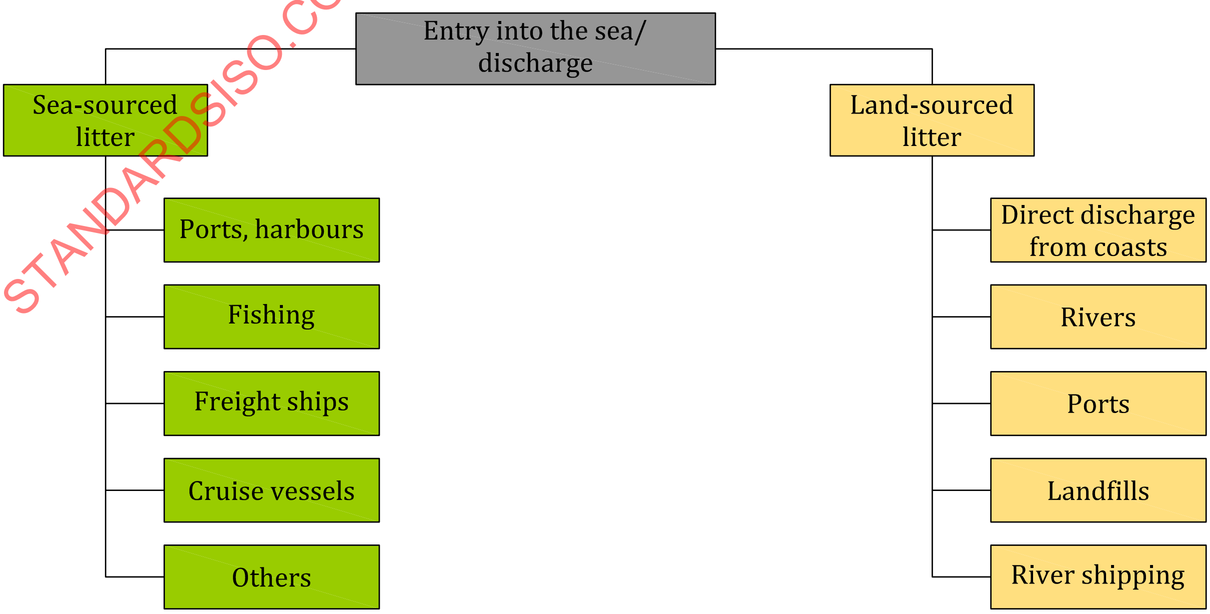


Figure 4 — Schematic illustration of entry pathways of litter into the sea

For the model, the main land-based entry pathways and sources of litter have been identified and are shown in the right side column of Figure 4: direct discharge from coasts, rivers, ports, landfill sites and river shipping are on the left.

Other land-based entries e.g. from treatments of sewage plants, barrages, leachates and also from drifting or flooding are partly considered with individual parameters.

For the development of the model, basic assumptions at best practice approach were made. In this way, entries into the environment have been analysed on the basis of both primary data research i.e. expert interviews with different institutions and stakeholders from industry, waste operators, academia and NGOs as well as secondary data research like monitoring concepts e.g. from Regional Seas, official statistics, scientific studies and further literature. In this way, both macro plastics, i.e. visible plastic articles > 5 mm, which were discarded as waste from different applications like packaging, agriculture etc., as well as micro plastics, i.e. primary plastic particles smaller than 5 mm from industry like fibres, cosmetics and plastics production and conversion as well as plastic fragments within bio-waste and compost, were taken into account. Rubber which occurs in the environment, e.g. from tyre abrasion has not been considered within the scope of the methodology, as rubber does not represent typical end-user waste that contains, among other things, plastics. Furthermore, and according to the Official Statistics, rubber is differently allocated and separated in the data survey from plastic materials.

The main land-based entry pathways and sources, as shown above in Figure 4, have been analysed in detail as follows:

— Rivers:

  Both micro and macro plastics can occur in rivers and thus be transported into the sea. In order to analyse the amounts, which enter into the sea, river basin districts and sea regions were considered on the basis of the European structure of hydrological catchment areas (Vogt 2007)[22]. Transport losses in rivers were assumed as important factors, though with large variances. They were considered on the basis of expert interviews and empirically at a best guess.

— River shipping:

  Ships that enter inland waterways via the sea and may cause litter, predominantly macro plastics, are considered relevant.

— Coastal areas:

  For coastal regions, the European concept of Nomenclature des Unités territoriales statistiques (NUTS) has been applied according to Eurostat (Eurostat 2013). Regions within the NUTS-3 level represent a coastal area where more than half the population lives below 50 km from the sea. In contrast to rivers, the transport losses are significantly smaller into the sea.

— Ports:

  Harbors and ports are considered according to the NUTS-2 level. To allocate macro plastics from ports, the waste should originate within the harbor and not the ship on the sea.

— Landfill sites:

  Landfill sites which are near to the coast can become relevant sources of plastics in the environment, if they are not fully covered or follow the rules of best available technology and performance.

For each of these entry pathways the amounts of entries into the sea can be assessed on the basis of an accumulative model by using individual factors for the different applications, pathways, transport losses due to sedimentation and water flow, density of regional inhabitants, etc. The factors allow to reflect real entries by a methodical sound, verifiable and transparent empirical assumption. First results were summarized (Lindner 2017)[21]. For the example of entries from Germany into the North Sea, the methodology shows that the majority of entries into the sea originate from macro plastics, which were transported via rivers. Microplastics play a minor role. Coastal regions show second priority.

The model is capable to also investigate sea-based entries by the same approach. Sea-based entries like fishing, shipping, cruising, etc. can be analysed similarly. However, the framework conditions and parameters need to be determined and adapted at an individual basis for each sea and each area and country.

8 Basics of environmental assessments

In order to assess certain environmental effects, assessment concepts and methodologies based on a scientific approach are indispensable prerequisites. This is necessary in order to classify and to assess observed environmental effects. For this purpose, occurrences and effects should be dependably and verifiably measurable. Internationally recognized and harmonized investigation methods are absent. In addition, environmental matrix-related assessment concepts are largely lacking for plastics.

The term environmental assessment can refer to a multitude of different concepts and methodologies. In general, it describes the underlying paradigm of regulative or scientific methods which allow a classification of measured results with respect to the environment or health. Generally speaking, two basic categories of assessments can be distinguished: preventive approaches, which consider environmental matrix worth protecting from external intervention, even if the consequences are not entirely known; and second, approaches which take a positive stance towards external intervention depending on the expected environmental effect.

While the approaches differ, they are both used by international agreements whose aim is to protect the environment or human health. Accordingly, the differences are also reflected in the nature of the regulative measures derived from the underlying paradigms. Preventive measures promote early and anticipatory action in order to avert harm to the environment or health. This means an area before any negative effects can be expected. Risk-based approaches, however, foresee action only if harm to the environment or health is likely to arise. In this sense, preventive approaches tend to be broader and farther reaching than risk-based approaches. Correspondingly, measures derived from risk-based approaches are likely to have a more clear defined scope with specific consequences (e.g. pathway specific trigger values).

In order to apply the approaches to a methodical assessment concept, both should be translated and defined into scientifically sound procedures and methods. Depending on the subject matter, these can refer to matrix (waters, soil, air), processes and services (ideally according to standardized procedures), or products (such as qualitative requirements and effects for materials used in the environment). Regulative approaches developed on the principle of prevention tend to follow a matrix-based approach, while risk-based approaches usually focus on products.

In order to operationalize the two approaches, concepts with material requirements should be developed. This includes that the effects of substances or actions on environmental matrix and biota are categorized and assessed at a scientific basis. These can include:

a) Background levels in environmental matrix in order to assess the relevance;

b) Assessment regarding the effects on biota;

c) Assessment regarding specific ecosystem functions;

d) Deduction of current reference condition;

e) Identification of specific indicators for microplastics;

f) Development of a modular system for a first assessment scheme.

In the next step, the values for relevant parameters (precautionary principle vs. risk-based approach) oriented at previously defined levels of protection need to be defined. This requires an effective research methodology and scientific assessment.

In order to maintain a healthy environment and to ensure the usability of waters, air and soil, early approaches focused on limiting direct emissions, e.g. from industrial plants discharging their effluents in rivers. While these have often led to better water quality, approaches solely targeting at facilities have the disadvantage of neglecting cumulative effects of pollution from numerous single sources. In order to take these into account, conducting assessments based on the environmental matrix is indispensable. On this basis, additional requirements can be derived.

It should be noted that the term “risk” is not undisputed, as the definition depends on a number of different factors and assumptions. In general, risk assessment is calculated with the so-called insurance formula:

Risk = amount of damage × probability of occurrence

However, for environmental risk assessment, this formula bears a number of problems, as the amount of damage (comparability of environmental damage/economic evaluation thereof) as well as the probability of occurrence (due to dynamic loads) is hard difficult to calculate. In relation to the eco-toxicological risk term, risk is therefore defined as the result of exposition and threat.

Risk = exposition × threat

For environmental assessments, the determination of the current state is critical. It should be comprehensively assessed as a baseline for the group of substances in order to describe possible prior loads. With a view to local levels of impurities as well as in light of punctual emission sources thereof, the determined values can be compared with the baseline in order to assess the occurrence of substances.

In order to assess inputs in different environmental matrix as well as its relevance in relation to different protected goods, a technical assessment concept is the first step to assess the relevance of the occurrence or the input. The result of this technical concept is the specific determination of a value or values on whose basics measurements can be categorized following a harmonized methodology. The first step is to characterize the environmental medium, which should be analysed based on the relevant substances. In our case, these are either single types of plastics, or the sum of all plastics.

Because of the specific characteristics of plastic particles, especially the potential physical damage of target organisms depending on its shape, size, surface and constitution, microplastics cannot easily be integrated in existing assessment concepts, as these refer to dissolved substances. The relevant parameters are an indispensable pre-requisite for the assessment concept and methodology.

Links between concentration contents and effect are established here as well. But it should be noted that difficulties occur in the test procedure, as respective contents of particles can be calculated. However, maintaining a stable suspension over the test procedure can hardly be verified. Therefore, a defined exposition is not possible either.

There is a close relationship between an assessment concept and the corresponding investigation methodology. The concept should describe which parameters are relevant. The necessary parameters should then be methodically underpinned/underlaid because they depend on the particular area and circumstances, which are considered. For example, a total content of a plastic particle in the respective environmental matrix can provide an initial assessment of a defined situation. Total contents are also suitable for creating material flow balances.

9 Recommendations for the development of standards

In this document, various areas in the context of “Plastics and the Environment” were considered. Particular attention was paid to the need for methods to be harmonized and standardized. Different areas (science, administration, companies) have various requirements for the investigation procedures. It is clear, however, that standardized procedures are necessary to meet the various requirements of the different sectors. It is also clear that it is an international task to develop procedures, since the occurrence of plastics in the environment is a global fact.

This document concludes, that harmonized and standardized investigation procedures are a prerequisite for carrying out studies of the material flows and the basis for the assessment of the contamination of various environmental matrices. Key stakeholders will benefit from a sound-based and robust methodology such as academia, industry, politics and administration.

It should be noted that methods which are currently applied may have a different status and/or a different degree of maturity for the respective methodology in the various sectors. This applies to the environmental matrix (water, soil, air) as well as to the scientific disciplines (chemistry and biology). Investigation results, which were determined solely on a visual basis, no longer correspond to the state of knowledge. Most advanced are chemical investigation methods in the water sector. Many of the methods used in the scientific literature are very specific. The underlying procedural rules are often not suitable to develop an appropriate standard on this basis. Currently, no method seems to be suitable for transferring into the standardization process.

Therefore, it is recommended to create in a first step a general technical basic document, which describes cornerstones of upcoming standardization works. These include the description of the objects to be examined (kinds of plastics, shapes, sizes), the investigation areas (water, soil, air, products, biota), uniform classifications clusters and fields of application of the methods. The report should also contain suggestions for the presentation of results (reference variables). It is to be shown which method seems appropriate for which question or application. Measurement accuracy as well as time for the whole investigation procedure and effort in relation to the necessary equipment are important assessment factors. Topics such as quality assurance for sampling in the field (e.g. sampling strategy), sampling technique, sample preparation and analytical technique should also be dealt with.

In a second step, the development of standards for the chemical characterization of plastic in various environmental matrices should start. It is clear that – at least - different detection methods are needed. The most important aspect seems to be the standardization of a method for the determination of total contents. This allows a first assessment of a possible contamination of various matrices. The relevant bulk plastics (PE, PP, PA, PS, PET, PU) should be reliably determined by the procedure. When developing the method, care should be taken that sample collection, sample preparation and detection are matched. These three areas are interconnected. They should be developed together.

In a third step standards for representative determination of particle numbers in different size classes are needed.

In addition to chemical analysis, methods for determining shape and size of the particles and maybe others (e.g. degradation status) — are also necessary for a complete picture. Furthermore, methods for the effect of plastic particles on biota or their vector function are to be harmonized.

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