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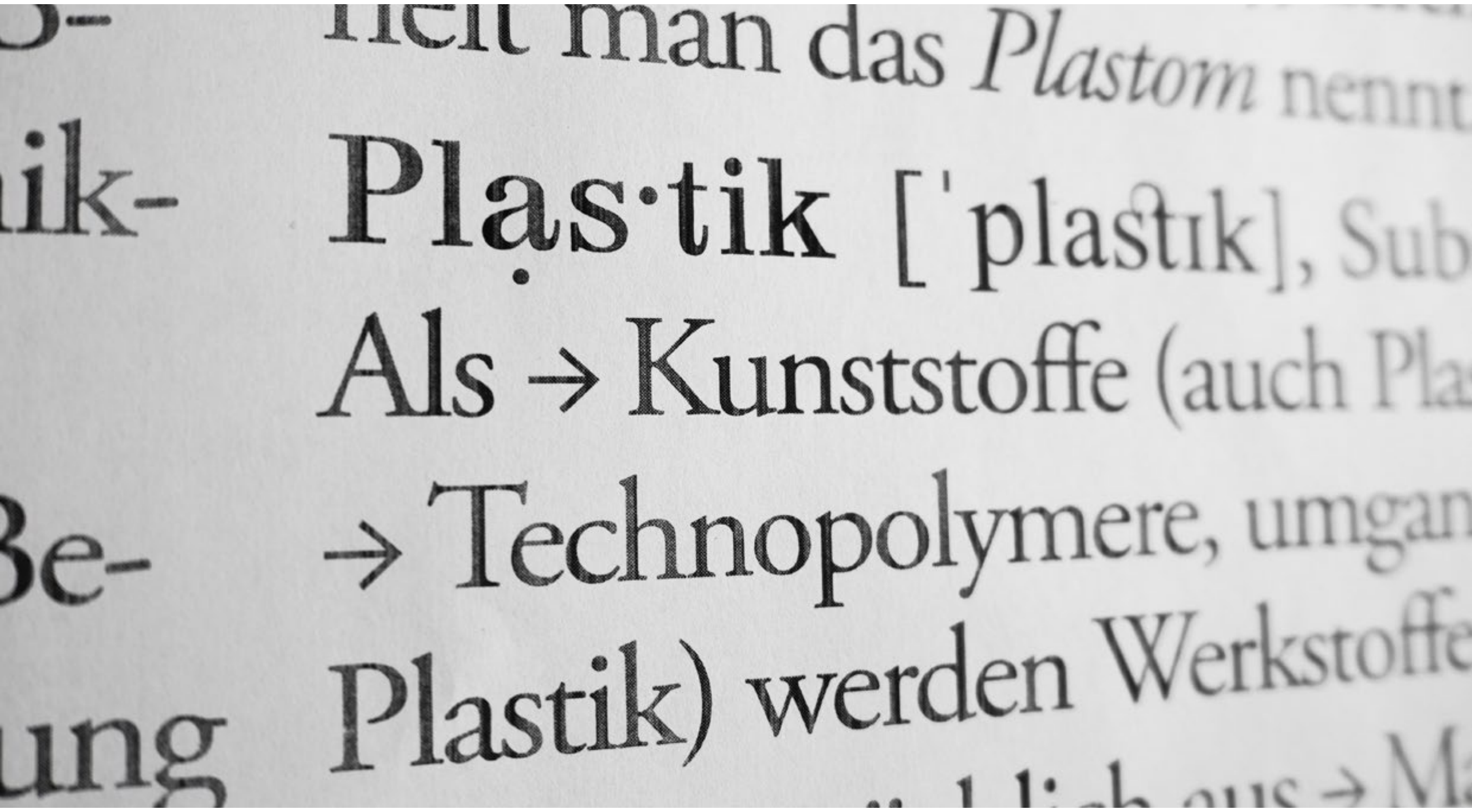
Plastics in the Environment
sources • sinks • solutions

BMBF research focus „Plastics in the Environment – Sources • Sinks • Solutions“

Compendium on Plastics in the Environment



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Contact persons for the BMBF research focus „Plastics in the Environment – Sources • Sinks • Solutions":

BMBF:
Thomas Bartelt
German Federal Ministry of Education and Research (BMBF)
Department 726 - Resources, Circular Economy; Geosciences
D – 53170 Bonn
Phone: +49 (0)228 99 57-3890
Fax: +49 (0)228 99 57-83890
E-mail: Thomas.Bartelt@bmbf.bund.de

Project Management Agency:
Dr.-Ing. Saskia Ziemann
Project Management Resources, Circular Economy; Geosciences
Project Management Agency Karlsruhe, Karlsruhe Institute of Technology
Hermann-von-Helmholtz-Platz 1
D – 76344 Eggenstein-Leopoldshafen
Phone: +49 (0)721 608-24935
Fax: +49 (0)721 608-923235
E-mail: saskia.ziemann@kit.edu

Editor
Scientific accompanying research project (PlastikNet) of the BMBF research focus „Plastics in the Environment – Sources • Sinks • Solutions".
Doris Knoblauch and Dr. Ulf Stein
Ecologic Institute
E-mail: plastiknet@ecologic.eu
Phone: +49 (30) 86880-0
Fax: +49 (30) 86880-100

Website: www.bmbf-plastik.de/en Twitter: @plastik_umwelt

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*Corresponding author

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AbwV	German Waste Water Ordinance (Abwasserverordnung)
BBodSchG	German Federal Soil Protection Act (Bundes-Bodenschutzgesetz)
BImSchV	German Ordinance on the Implementation of the Federal Immission Control Act (Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes)
Bio-PE	Bio-based PE
Bio-PET	Bio-based PET
BMBF	German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung)
BR	Butadiene rubber
CFRP	Carbon fiber reinforced plastic
CR	Chloroprene rubber
DfE	Design-for-Environment
DfR	Design-for-Recycling
DNA	Deoxyribonucleic acid
ECHA	European Chemicals Agency
EP	Epoxy resin
EPS	Expanded polystyrene
EPDM	Ethylene propylene diene rubber
ESSM	Energy and material flow management
GFK	Fiberglass reinforced plastic
IIR	Isobutene-isoprene rubber
IR	Isoprene rubber
KrWG	German Circular Economy Act (Kreislaufwirtschaftsgesetz)
LCA	Life Cycle Assessment
LD50	Dose with a lethal effect on 50% of the population under consideration

MF	Melamine-formaldehyde resins
NBR	Acrylonitrile-butadiene rubber
NIR	Near Infrared
PA	Polyamide
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane resins
PVC	Polyvinyl chloride
RAC	ECHA Risk Assessment Committee
REACH-VO	REACH Regulation
SAN	Styrene-acrylonitrile copolymer
SEAC	ECHA Socio-economic Impact Committee
SBR	Styrene butadiene rubber
TBS	Tracer-Based-Sorting
WHG	German Federal Water Act (Wasserhaushaltsgesetz)

Introduction

The topic of "plastics in the environment" is multi-faceted and complex. Scientific work in this field is therefore highly inter- and transdisciplinary and requires the cooperation of experts from many scientific-technical and socio-economic disciplines.

Where different disciplines come together, a certain inconsistency also exists in the way in which things are labelled: Terms and definitions in the technical and regulatory field are very closely linked to specific areas of application. This is why there are sometimes different levels of meaning to a term. The objective of this handbook is to contribute to a common understanding of the numerous relevant terms. It will not always be possible to find one term or one definition for all purposes. In order to limit this problem as much as possible, the authors first identify the area of application of the terms and definitions and base further explanations on that.

This compendium thus aims to sharpen relevant terms and thereby aims to contribute to the better understanding in the heterogenous community on „plastics in the environment". In addition, the brochure is intended to help ensure that communication with and by non-scientific actors on the topic is based on a terminologically correct foundation, especially in emotionally charged debates. After all, these debates are often highly relevant in shaping our future, and it seems important that the necessary political, social and economic decisions should be taken on the basis of knowledge and factual information.

The research focus „Plastics in the Environment"

The German Federal Ministry of Education and Research (BMBF) is funding a total of 20 joint research projects and an accompanying scientific project within the framework of the research focus „Plastics in the Environment – Sources • Sinks • Solutions" (www.bmbf-plastik.de/en) with around 40 million euros over the period of 2017–2022.

The aim of the research is to scientifically record problems in connection with plastic waste in their entirety for the first time and to close existing knowledge gaps. More than 100 institutions from the fields of science, industry and practice are involved in what is currently the world's largest research focus on the effects of plastics on the environment. The research projects are divided into five different subject areas, which are oriented along the entire life cycle of plastics:

- **Green Economy: Material flows, value chains, technologies**
- **Consumption, consumer behavior, trade and production, governance**
- **Recycling technologies**
- **Entry pathways, transport, decomposition and retention in the limnic systems**
- **Seas and oceans as sinks and accumulation areas**

The interdisciplinary character of the research focus is intended to enable a better understanding of the environmental effects of undesirable plastic waste inputs, starting from the soil and river basins and extending into the oceans. In addition, approaches to reducing and avoiding plastic inputs are to be identified and implemented. The range of topics extends from the improvement of certain plastic materials with regard to their environmentally compatible degradability, to the investigation of entry pathways into soils and waters and the analysis of possible toxic effects on aquatic organisms, to the strengthening of environmental awareness among consumers. As key practitioners and implementers of innovations, companies were involved in the development and realization of the research projects since the beginning.

About this compendium

The compendium at hand was compiled within the framework of the cross-cutting topic 3 „Terms and definitions" of the BMBF research focus „Plastics in the environment". It is limited to the definition of essential terms relevant to the research focus and aims at a consistent use of language both within the research focus and in external communication.

The compendium works mainly with existing definitions (including DIN/CEN/ISO standards or legal definitions from German federal legislation); own definition work is done to a very limited extent. The compendium also clarifies how specific terms are used correctly and which terms should not be used.

Scientists from the following joint research projects of the research focus participated in the compendium via workshops and feedback loops: ENSURE, EmiStop, Innoredux, InRePlast, MaReK, MicBin, MicroCatch_Balt, MikroPlaTaS, PlastikBudget, PLASTRAT, RAU, ResolVe, RUSEKU, revolPET, SubμTrack, TextileMission.

01 Environmental Compartments

Air (atmosphere) ...

... and soil (pedosphere) are environmental compartments and are also referred to as environmental media.

Reservoirs are often a starting point for sedimentation.

In order to describe the occurrence and distribution of plastics in the environment, we use **environmental compartments** defined as distinct areas of the earth. These environmental compartments – within the context considered here: **water (hydrosphere)**, **soil (pedosphere)** and **air (atmosphere)** – are also referred to as **environmental media** within environmental law. Even more differentiated distinctions are possible between environmental media according to their sub-compartments.

Essentially, the German Federal Water Act (Wasserhaushaltsgesetz – WHG)[1] makes a distinction between surface waters, coastal waters and groundwater. **Above-ground waters** are defined as the water that flows continuously or intermittently into river beds, stands still or runs down freely from springs (§ 3 No. 1 WHG)[2]. **Groundwater**, on the other hand, is the **underground water** in the saturation zone which is in direct contact with the ground or the subsoil (§ 3 No. 3 WHG).

In order to manage water bodies sustainably, more or less homogeneous units with largely similar characteristics are grouped together. Consequently, according to § 3 No. 6 German Federal Water Act (WHG), uniform and significant sections of an above-ground water body or coastal water body are addressed as **surface water bodies**. Similarly, delimited groundwater volumes within an aquifer or several aquifers are referred to as **groundwater bodies**.

According to § 3 No. 2a German Federal Water Act (WHG), **marine waters** include the coastal waters as well as the waters in the area of the German Exclusive Economic Zone and the continental shelf, in each case including the seabed and the subsoil below the seabed.

1 Federal Water Act (Wasserhaushaltsgesetz – WHG) of July 31, 2009 (BGBl. I p. 2585), last amended by the Act of December 4, 2018 (BGBl. I p. 2254), the German version is available at https://www.gesetze-im-internet.de/whg_2009/index.html#BJNR258510009BJNE000403118.

2 Federal Water Act (Wasserhaushaltsgesetz – WHG) of July 31, 2009 (BGBl. I p. 2585), last amended by the Act of December 4, 2018 (BGBl. I p. 2254), the German version is available at https://www.gesetze-im-internet.de/whg_2009/__3.html.

Coastal waters are defined as the sea areas between the coastline during mean high tide and the German territorial boundary (12 nautical miles limit) (see § 3 No. 2 WHG).

Plastics can enter the natural water cycle at various points. In the course of surface waters, surface runoff increases continuously, starting at the sources, streams, rivers and **transitional waters** such as estuaries. The transport of the plastic particles occurs either floating in the water column or floating on the surface. This can lead to intermediate or final sedimentation and deposition in the sediment. As a result, a transport with debris – the solids transported by a body of water at its bottom – can also occur. Sediments consist of accumulations of various organic and/or mineral loose materials, which usually accumulate at the bottom of a water body as well as on its banks. The starting point for sedimentation in flowing waters is often a reduction of the flow velocity, as it can be observed especially ahead of **reservoirs**, for example at weirs or dams as well as in transitional or coastal waters.

Plastic particles do not only occur in wastewater but are also found in **surface waters**. The key terms relating to this are explained in Chapter 7.

Plastic particles are also found in the soil. The German Federal Soil Protection Act Bodenschutzgesetz – BbodSchG)[3] defines **soil** as the upper layer of the earth's crust, provided that it is the carrier of certain soil functions. This also includes the liquid (**soil solution**) and gaseous components (soil air) of the soil, but not groundwater and water body beds (§ 2 para. 1 BBodSchG). The soil functions are described in § 2 section 2 of the German Federal Soil Protection Act.

Plastics in the air in concentrations relevant for environmental or health protection are mainly present in the form of tire abrasion. The 39th Ordinance for the Implementation of the German Federal Immission Control Act (Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes – BimSchV)[4] defines **air** as the outside air in the troposphere (excluding workplaces to which the public usually does not have access). The troposphere is the lowermost layer of the atmosphere, 8 to 16 km thick. The **atmosphere** is defined internationally as the envelope of gases surrounding the Earth[5] .

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German Federal Soil Protection Act (Bundes-Bodenschutzgesetz – BbodSchG) of 17 March 1998 (BGBl. I p. 502), last amended by the law of 27 September 2017 (BGBl. I p. 3465), the German version is available at https://www.gesetze-im-internet.de/bbodschg/.

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3 German Federal Soil Protection Act (Bundes-Bodenschutzgesetz – BbodSchG) of 17 March 1998 (BGBl. I p. 502), last amended by the ordinance of 27 September 2017 (BGBl. I p. 3465), the German version is available at https://www.gesetze-im-internet.de/bbodschg/.

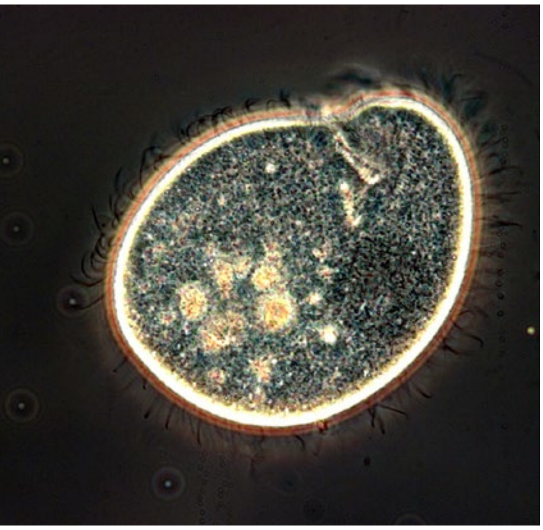
4 Thirty-ninth Ordinance for the Implementation of the German Federal Immission Control Act (Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes – BimSchV) of 02.08.2010 (BGBl. I p. 1065), last amended by Article 2 of the Ordinance of 18 July 2018 (BGBl. I p. 1222), the German version is available at https://www.gesetze-im-internet.de/bimschv_1_2010/.

5 United Nations General Assembly (2015): Protection of the atmosphere. International Law Commission. Sixty-seventh session. Geneva. A/CN.4/L.851, https://undocs.org/pdf?symbol=en/A/CN.4/L.851.

02 Biological Systems

Microflora also includes phytoplankton.

Red algae are part of the macroflora.



Ciliate from an oxygen-deficient pond.

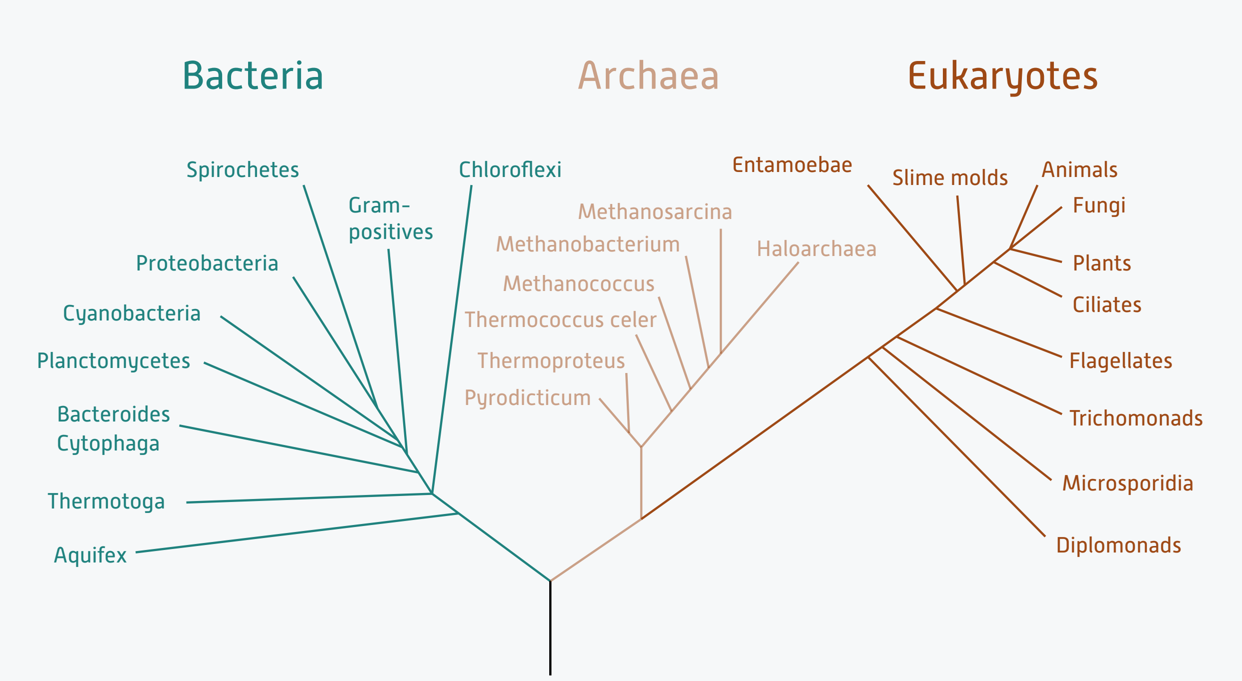
Biological systems are open systems that are delimited from their environment by arbitrarily defined boundaries and are in continuous interaction with their environment. In order to demarcate different biological systems from each other, they are ordered according to their degree of kinship and lineage and classified into hierarchically structured categories. The totality of all living things in the environment can be divided into different **biota**. Primarily, a distinction is made between naturally occurring animals (**fauna**) and plants (**flora**). Within these two categories, size-dependent distinctions can be made. Soil-dwelling animals between 0.2 mm and 2 mm are classified as **meiofauna** or **mesofauna**, for example, while larger animals are classified as **macrofauna** (2-20 mm) and smaller ones as **microfauna** (< 0.2 mm). Within the flora a distinction can be made between **microflora** (usually microalgae of phytoplankton) and **macroflora** (macroalgae and vascular plants).

However, the term microflora is not only used in the strict sense – i.e. in relation to plant microorganisms – but also in general for the **microorganisms** that colonize a certain habitat (for example, the intestinal tract of an animal). These include **bacteria** and **archaea**, which measure from 0.5 µm to a few µm in size and are also called **prokaryotes** because they lack a defined cell nucleus. Even though they are hardly distinguishable microscopically, they are today assigned to two different domains of life forms due to their biochemical differences (see Figure 2.1; the length of the branches indicates the degree of relationship; the longer, the more distant).

Prokaryotes have multiple metabolic pathways, and the ability to live and grow without oxygen (**anaerobic**) is common among them. Eukaryotic **microorganisms**, i.e. those with a real cell nucleus, include microscopic fungi and slime moulds, ciliates and flagellates (see Figure 2.1). All these microorganisms can multiply by cell division. Some can also act as pathogens. When the community of these organisms actively attaches itself to a surface (for example, intestinal epithelium or materials exposed to natural water), it is referred to as a **biofilm**. Apart from the cells (mostly bacteria), it contains so-called extracellular polymeric substances. They bind the biofilm together, protect the cells and, due to their often slimy consistency, ensure that

Figure 2.1

Phylogenetic tree with the three domains



Source: Illustration based on Carl Woese, et al. using the sequences of the rRNA.

external substances can also adhere to the biofilm surface.

The totality of all living organisms (including plants and fungi) found in the soil can be called edaphon, all those in the soil zone of a body of water (benthic) can be called benthos. This term can also be combined with size classes and affiliation to the designation of the subgroups macrozoobenthos (zoo = animals), macrophytobenthos (phyto = plants), meiobenthos, microzoobenthos and microphytobenthos.

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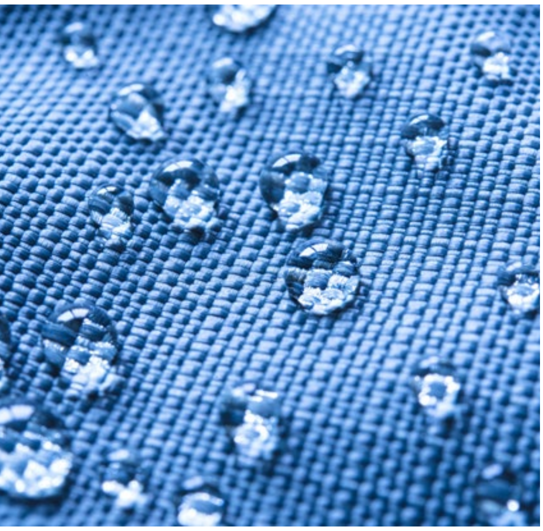
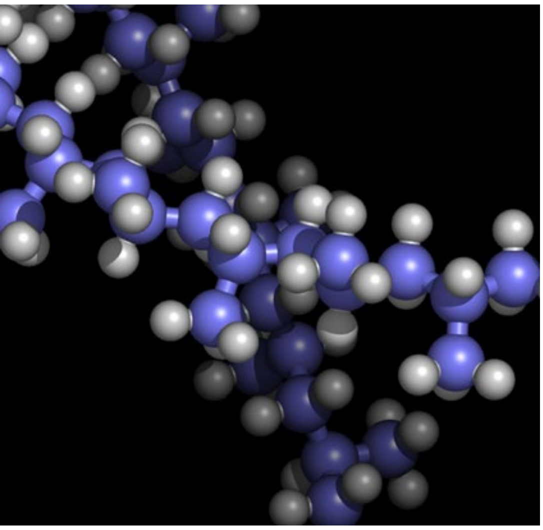
Woese, Carl R.; Kandler, Otto; Wheelis, Mark L. (1990): Towards a natural system of organisms: Proposal for the domains Archaea, Bacteria, and Eucarya. In: Proceedings of the National Academy of Sciences USA. Band 87, 1990, S. 4576–4579.

03 Polymer Materials



Additives can increase the water-repellent properties of polymer materials.

Polymer materials exhibit various properties, e.g. the elasticity of a rubber band.



Ball-and-stick model of a polypropylene

Plastics are materials that consist predominantly of **macromolecules**. In practice, we speak of macromolecules when a molar mass greater than 10,000 g/mol is present. Synthetic polymers are macromolecules consisting of structural, chemical repeating units. These structural repeating units are known as **monomers**.

A small, unspecific number of chemically linked monomers is called **oligomer**. If two different monomer units are combined in one polymer, it is known as a copolymer. It must be pointed out that this practical use of the term is not identical with the regulatory definition in the REACH Regulation[6] – here, much smaller molecules are already assigned to polymers and the molar mass distribution in particular is taken into account.

A plastic material consists of a polymeric skeleton as well as additives, fillers and / or reinforcing materials. **Additives** such as lubricants or release agents can improve the processing properties of a plastic material. Further additives are antioxidants, which protect the polymer during processing, especially against oxidation, and are effective as stabilizers against UV degradation and oxidation in the application. Additives can also have the function of optimizing specific properties of a polymer or adapting them for a specific use. These include dyes, softeners, flame retardants, cross-linking agents or nucleating agents, antistatic agents, anti-fogging agents or antimicrobial additives. The proportion of additives in plastics is generally low (< 1 percent). Exceptions are, for example, softeners in polyvinyl chloride or partially halogen-free flame retardant formulations, in which additives may well be present in the double-digit percentage range.

Fillers are usually present in plastics as inert components. They are used to stretch and economize the polymer matrix, but can also have a significant influence on the functionality of the material, especially its mechanical and thermal properties. Fillers, especially short glass fibers, are often used in the double-digit percentage range.

6 Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

When synthetic polymers are mixed with gas-releasing additives or propellants during processing, they produce **foams** which are characterized in particular by low density, low thermal conductivity and low mechanical stability. Depending on the polymer starting material used and the processing method, very variable degrees of hardness can be produced.

Materials that consist of two or more different classes of materials are called **composites**. By combining their material properties, their geometric arrangement and dimensioning, they can achieve different material properties than the individual components. Typical uses for composite materials such as carbon fiber reinforced plastics (CFRP, carbon) or glass fiber reinforced plastics (GRP) are, for example, lightweight construction in the automotive sector or the rotor blades of wind turbines.

Plastics are classified according to the type of chain linkage and the resulting formability. **Thermoplastics** feature isolated chains, **thermosets** are polymerchains held together by relatively strong **intermolecular bonds**, and **elastomers** (colloquially known as **rubber**) are held together by relatively weak **intermolecular bonds**. This categorization also classifies the respective processing and functional properties. For each material class there are very typical representatives, which will be described in detail below. However, through suitable selection of the polymer building blocks and processing conditions, it is possible to produce materials which represent a transition of the functional properties, e.g. thermoplastic elastomers or duromer soft foams.

Thermoplastics can be melted repeatedly and shaped with great variability. The molecular chains in thermoplastics may be **amorphous** (disordered) or **semi-crystalline** (in partially ordered structures). Amorphous and semi-crystalline materials exhibit a characteristically varying mechanical property profile depending on the temperature. The property of partial crystallinity can be influenced by process control and additives during processing. Typical examples of semi-crystalline plastics are polyethylene (PE), polypropylene (PP), polyamide (PA) and polyethylene terephthalate (PET). Known amorphous plastics include polymethyl methacrylate (PMMA), polycarbonate (PC), polystyrene (PS) or expanded polystyrene (EPS), and polyvinyl chloride (PVC). A mixture of two or more polymers is called a **blend**.

Elastomers and thermosets are permanently shaped by **crosslinking** during their processing and cannot be remelted. The relatively weak **intermolecular bonds** of the polymer chains in elastomers allows a very high flexibility, which is usually also noticeable in the macroscopic properties at ambient temperature (high extensibility with low deformation). Examples of synthetic elastomers are ethylene-propylene--diene rubber (EPDM), styrene-butadiene rubber (SBR) or silicone rubber. In contrast, the mobility of the polymer chains with the relatively strong intermolecular bonds in thermosets is very limited, so that they generally exhibit stiff and brittle behavior at ambient temperature. Typical examples of thermosets are epoxy resins (EP), melamine-formaldehyde resins (MF) or rigid polyurethane foams (PUR). Elastomers and thermoset polymer chains are not ordered, they are amorphous.

Finally, it is worth highlighting the terms **adhesives** and **coatings** (synonymous with paints, varnishes), which are generally based on a wide variety of thermoplastic and duromer polymers which will not be explained further at this point.

The temperature at which the amorphous polymer chains switch from their frozen, rigid state to the flexible, elastic state is called the **glass transition temperature**. It represents an important physico-chemical property of the respective polymers.

Table 3.1

Overview of terms used for synthetic polymers

Synthetic polymers	Plastic materials, fibers, elastomers, other (thermosets, adhesives, coatings)
Plastics	Plastic materials, other (thermosets, adhesives, coatings)
Plastic materials	Standard plastics, engineering plastics, PUR
Standard plastics	PE, PP, PVC, PS, EPS, PET (bottle grade)
Engineering plastics	PA, PC, PMMA, Styrol, Copolymers (ABS, SAN), Blends, other high-performance plastics
Thermoplastics	Standard plastics, engineering plastics
Thermosets	EP, MF
Elastomers	SBR, IR, IIR, BR, NBR, CR

Source: PlasticsEurope Deutschland

In case of amorphous thermoplastics, this is the beginning of the softening range, which gradually undergoes a change into the flow range. In case of semi-crystalline thermoplastics, the amorphous regions soften and a transition from the brittle to the flexible state begins. When the temperature is raised further up to the **melting temperature**, the semi-crystalline materials transition to the free-flowing state. If polymers are heated further, the molecular structure decomposes into smaller, gaseous fragments. This process begins at the **decomposition temperature**. The frequently used term **degradation temperature** is less specific and can in some cases only be hardly distinguished from the **maximum operating temperature**.

Plastic materials can additionally be classified according to other criteria. A possible classification is the differentiation based on the origin of their monomeric components and on degradability (see Table 3.1).

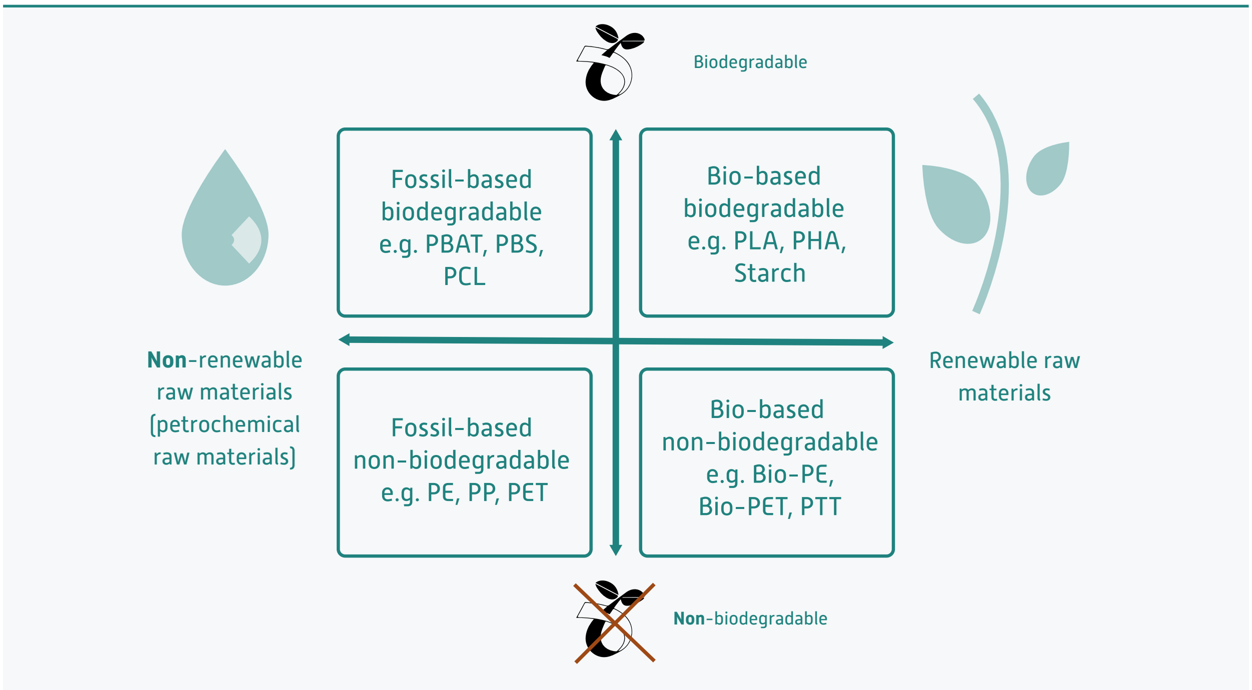
Bio-based plastics (based on renewable raw materials), such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), originate from renewable raw material sources (including cellulose, starch from e.g. wood, corn, sugar cane), in contrast to **fossil-based plastics** (based on non-renewable raw materials), such as PE, PP and PET, which are produced from raw material sources that have been formed over very long periods of time from decomposition products of organic matter. **Biodegradable plastics** such as polybutylene adipate terephthalate (PBAT), polybutylene succinate (PBS) or polycaprolactone (PCL) can be enzymatically converted under certain conditions by biological activity. Inorganic substances (e.g. H_2O, CO_2) are released in the process. There is no correlation between biodegradable and biobased plastics. Both fossil and biobased plastics can be biodegradable, and at the same time there are also biodegradable and fossil plastics that are not biobased. Furthermore, the polymer materials should be divided into **natural polymers** or **synthetic polymers**. Natural polymers that are chemically modified are called **semi-synthetic polymers** (e.g. natural rubber by cross-linking with sulfur).

Further relevant classifications can be made on the basis of the physical and chemical properties of plastics. This concerns, for example, the **solubility** of plastics in water or the absorption capacity of water in plastics. Materials that exhibit these properties are referred to as **water-soluble polymers** (including polyethylene glycols) or **gel-like polymers** (including polyacrylates). Only polymers in their flowable range, i.e. above the melting temperature and without additional solvents, should be referred to as liquid polymers.

In practice, only thermoplastics and thermosets are often interpreted by the term plastics. Elastomers made of synthetic polymers and technical products based predominantly on synthetic polymers (e.g. textile fibers, coatings, tires) are often treated separately. It is therefore recommended for all joint research projects within the scope of the research focus to always specify whether the term "plastic" or "plastics" is used in the narrower or broader sense, e.g. including elastomers, textile fibers, coatings, tires etc. This makes sense insofar as the investigations and their results always

Figure 3.1

Classification of polymers according to the origin of their monomeric constituents (fossil or from renewable raw materials) and their degradability.



Source: own illustration based on „PlasticsEurope" and Endres/Siebert-Raths 2009

refer to the defined project framework, which means the same applies to the statements. On the other hand, the topic of "plastics in the environment" requires different approaches in order to reach at proposed solutions, so these can only ever be developed in relation to the problem specified in each case. This also requires a specification for the use of the terminology for polymers and plastics, respectively, either in a broader or in a specific, narrower sense.

With regard to the material limitation, the word component "plastic" and the term "plastics" are used synonymously in this compendium to describe a broad concept of plastics. Given that the focus of the entire debate lies primarily on environmental aspects, this includes all polymer materials, as described above. Whenever the term "plastic litter" or "marine plastic litter" is used in general, "plastic" is usually understood broadly, i.e. as representative of all possible polymers such as fibers, paints, elastomers, etc., and not in the narrow sense of plastic materials.

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04 The Origin of Emissions from Plastics


In some cases, seeds or fertilizers are encapsulated by plastic (example image).


Plastics emissions include tire abrasion.


The term „beach litter" has become an established term for plastic litter on the beach.

Plastics can enter the environment intentionally or unintentionally during their life cycle. If plastics lead to adverse changes in ecosystems, organisms or material goods in the short or long term outside their intended function, or if such adverse changes are expected, they constitute **pollutants** for the environment, i.e. they can have **harmful effects** on the environment. To demonstrate the damage caused by plastics, however, complex evaluation concepts (including dose-response relationships, causal chains and risk assessments based on them) must be developed. They are also necessary in the regulatory framework.[7]

The input of substances that are harmful or expected to be harmful into the environment as a result of human activity is referred to as **emission** (synonym: **release or environmental input**), their distribution in the environment as **transmission**, and the impact at a specific location or in an environmental compartment as **immission**. The impact on individual organisms or ecosystems is called **exposure**.

As a generic term for all entries of plastics into the environment through human activity[8], the term „**plastic emission**" is recommended. This refers to emissions or inputs of plastics (analogous to particulate matter emissions or exhaust emissions) and not to emissions from plastics (e.g. volatile organic compounds (VOCs)). In the case of plastic emissions or plastic inputs, a distinction can be made between the following trajectories:

a. microplastics (see chapter 5) deliberately (intentionally) added to a product in applications in an open environment or their release through accidents or leakages,
b. fragmentation of plastic objects due to mechanical stress or environmental influences during use,
c. improper/illegal disposal of plastic objects as well as legal retention in the environment including subsequent fragmentation into microplastics.

7 For example, within the framework of a restriction procedure of the European Chemicals Agency (ECHA) in the Committees for Risk Assessment (RAC) and Socioeconomic Effects (SEAC). This also includes the consideration of limit values.

8 The term „human activity" refers to any direct or indirect human activity that causes emissions or inputs into the environment. This includes littering, the release of substances from everyday practices, manual activities, machines and large-scale technical facilities, agriculture, etc.

The **deliberate (intentional) use** of plastics in certain products in the form of microplastics occurs primarily because certain functionalities result from the addition. These can include abrasion effects (e.g. microbeads in cosmetics), opacity effects (e.g. light scattering from particles in liquid cosmetics, detergents, cleaning agents and cleansers), viscosity changes (e.g. in paints), the protection or targeted release of substances (e.g. encapsulation of seeds or fertilizers with polymers) or even improved force reduction on artificial turf sports fields (e.g. through an infill of elastomer-based granulates). The addition is ecologically relevant if the usage is in an open environment, i.e. a transition from a spatially limited technical application to an environmental compartment is very likely or is accepted due to foreseeable impacts.
An example is a controlled release pellet used in agriculture and horticulture. However, the decision as to whether an application is an open environment or not is often a difficult one (cf. artificial turf pitches and cosmetic microbeads).

The typical delivery form of plastic materials for the plastics processing industry is plastic pellets of a few millimeters in size (see chapter 6). Even if these are not generally used directly in end applications (such as special packaging solutions for paving stones, for example), they can be released into the environment through accidents, averages or leakage.

Fragmentation is the decay of larger objects into smaller ones as a result of mechanical, physical, chemical or biological fissuring. Fragmentation as a result of natural processes is called **weathering**. Fragmentation can occur on the surface or within the volume. Mechanically induced fragmentation of the surface is also called **wear**. If objects wear as a result of contact with other bodies, it is called **abrasion** or **attrition**. If the wear occurs as a result of mechanical loads, it is called **surface disintegration**.

Carelessly leaving or throwing away individual objects (such as packaging or cigarette butts) while on the way is often referred to as **littering** and is subject to fines by many local authorities. Littering also covers disposal via domestic wastewater (e.g. tampon foils, scraps of fruit nets). In addition, littering also includes forgetting or losing waste. There is also „indirect" littering, for instance, objects blowing away that have not been adequately secured. If the objects are plastic, the term **plastic litter** is established; if the objects are found in the sea, they are called **marine plastic litter**, or **beach litter** if found on the beach. Illegally disposed plastic waste, but also plastic products that remain in the environment legally as macroplastics after the end of use (pipes, geogrids and geotextiles made of plastic), can further fragment due to environmental impacts and thus represent a source of microplastics themselves.

Secondary raw materials such as **composts**, **digestate** and – at least in part – **sewage sludge** (see also Chapter 7) are used as fertilizers in Germany. They often represent **secondary sources** of plastic emissions. The requirements for secondary raw materials are regulated in the German Fertilizer Ordinance. With the use of these secondary raw material fertilizers in agricultural or landscaping recovery, plastics can also enter the environment, especially the soil, as there is sometimes severe contamination with plastic particles in composts and digestate (from separately collected biowaste). This is due, among other things, to the use of plastic (bio)bags that do not degrade quickly enough as bio-waste collection bags, to misdirected waste, to the fermentation of food waste with packaging residues, and to inadequate treatment or processing technology to remove plastic residues from the waste biomass.

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05 Micro- and Macroplastics

Abrasive particles in cosmetic products are called microbeads.

These plastic particles at the beach are considered as large microplastics.

Fibrous microplastics (length < 5 mm) enter the environment unintentionally, e.g. during production, maintenance and use of fabrics/textiles.

Depending on the size of the released objects, plastic emissions are **particles**, **fibers**, films or **shaped solids**. For this, the terms **microplastics** and **macroplastics** have become established. The terms are intended to cover different sizes as well as different material properties. There existis no standard definition until now.

Historically, the boundary between micro- and macroplastics was drawn at 5 mm, as initially many plastic pellets and fragments were found on beaches that were more commonly in the millimeter range than the micrometer range. In terms of size classification, we recommend the classification developed in the cross-cutting topic "Analytics and Reference Materials" of the German Research Focus „Plastics in the Environment" (Braun et al. 2021). Here, plastics emissions are subdivided into the four size categories **nanoplastics**, **microplastics**, **large microplastics** and **macroplastics**, as shown in Table 5.1.

Table 5.1

Size categories for plastics emissions (in accordance with ISO/TR 21960)

Name	Nano-plastics	Micro-plastics	Large Micro-plastics	Macro-plastics
Size range	< 1 µm	1-1.000 µm	1-5 mm	> 5 mm

When using these size classification, the following aspects are especially relevant:

- The size ranges of the classes are selected largely arbitrarily; in some cases they are based on analytical detectability. Neither environmental behavior nor risk can be derived from them.
- Particle collectives (see Chapter 6) usually have a size distribution. It is thus likely that plastics emissions are generated by a specific use, the individual particles of which must be assigned to various size classes.
- Individual particles may exhibit different lengths in the three spatial dimensions[9] .

In accordance with Chapter 4, it is recommended to use the generic term plastics emissions and to use the terms nano-, micro-, large micro-, and macroplastics primarily for detailed discussions. In particular, expressions such

9 Typically, the classification would be made according to the maximum length. At the same time, however, fibers and films are usually classified according to diameter or thickness. Occasionally, the classes for fibers are also defined differently.

as „avoidance/prohibition/reduction of microplastics" suggest that we are dealing with a group of materials that is meaningfully defined from an environmental point of view. However, this is not the case. Therefore it is important to always describe the particle sizes and shapes, the material type, the application context (e.g. as an industrial intermediate or for consumer uses), etc..

Microplastics are divided into **primary microplastics** and **secondary microplastics**. This distinction serves to identify the origin of microplastics. Primary microplastics are those that are deliberately (intentionally) used in particle form in products or are released through freight or operational accidents. Secondary microplastics are those released from disintegration of macroplastics. These can be, for example, littered items or products remaining in the environment after the end of their use phase. The problem of this distinction is that microplastics released during the use phase through abrasion and weathering are not clearly assigned to one of the two types, but are assigned to primary microplastics by some authors and to secondary microplastics by others. With regard to the classification of sources and the derivation of appropriate recommendations for action, this is unsatisfactory and the introduction of a third group is recommended[10]. Although it is hardly possible to assign identified microplastic particles to a specific type in terms of environmental analysis due to the lack of conclusive particle characteristics, a third category would definitely be helpful for source identification and the attribution of responsibility.

For abrasive particles in cosmetic products, the term **microbeads** has become established. This term should be used exclusively for this application.

Fibrous microplastics (length < 5 mm)[11] are objects that unintentionally enter the environment during the production, care and use as well as the disposal of a fabric/textile. The clear distinction from microplastic particles is made by the larger aspect ratio of at least 3:1. Fibrous microplastics have to be distinguished from the term **microfibres**. Microfibres are generally very fine fibres with a cross-section of approx. 3-10 µm.

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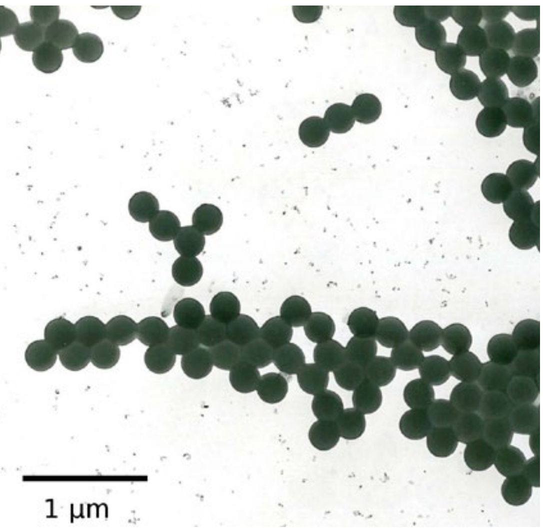
10 The authors will monitor the development of these terms and adjust them in a possible new edition.

11 In ECHA's restriction proposal, a length of 15 mm is proposed for fibrous microplastics and an aspect ratio (ratio of length to diameter) of at least 3 to 1 for the separation of fibres and particles.

06 Characterization of Particles


Granules or pellets are easily pourable particles measuring a few millimeters.


Textile microplastics



Agglomeration of latex particles forming an agglomerate.

Particles are objects that are small compared to the scale of the system under consideration. The properties of particles are usually determined collectively and illustrated by means of statistical evaluations. In this way, they differ from **piece goods** (also known as shaped bodies), which can be described as individual objects.

For particles, a distinction is made as to whether they tend to have a spherical (round), cubic, platelet, cylindrical or acicular **shape**. Only a few particles have ideal shapes (spheres, cubes, tetrahedra, etc.), so for the most part they must be described approximately. The approximation of a particle to a spherical shape is called sphericity.

When describing particles, it is often useful to think of them as a **disperse system**. **Dispersion** generally means a (fine) distribution, spreading or dispersion. A disperse system consists of a **disperse phase** – the particles – and a **continuous phase** – the surrounding medium. If the surrounding medium is liquid, the dispersion is called a **suspension**; if it is gaseous, it is called an **aerosol** or smoke; if it is a liquid/liquid dispersion, it is called an **emulsion**. A loose dispersion on a surface (mostly containing larger particles, such as sand or compost) is a **heap**, **granular** or **bulk material**. An **agglomerate** is a particle formed by the aggregation of several particles; particularly loose agglomerates are also called **flocs**. Figure 6.1 shows coarsely dispersed systems by particle size.

For particles and particle collectives further designations exist, some with clear plastic reference, some without:

» **Pellets** are easily flowable particles in the size of few millimeters. Depending on the production technology, cylindrical, lenticular, but also irregular shapes exist, which are used as starting material in subsequent plastics processing or directly in products.

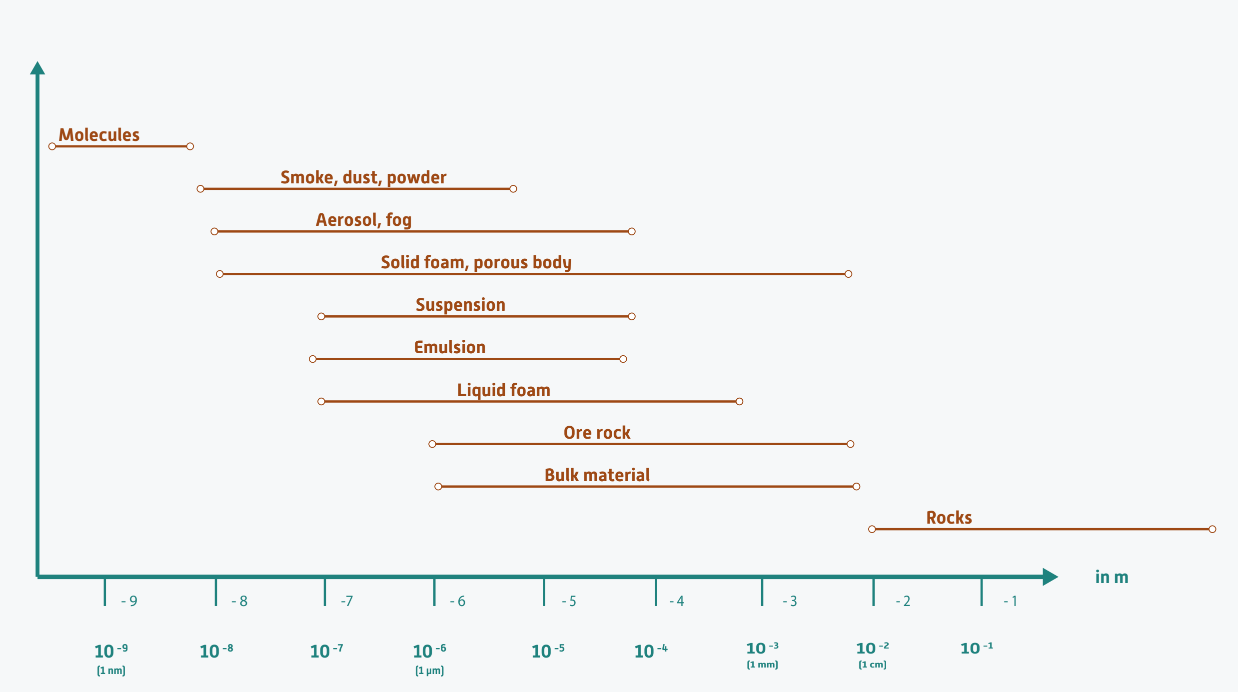
» **Fragments** are particles that result from breakage or disruption of larger objects.

» **Powders** are dry, extremely fine particle collectives. The terms are primarily used for cosmetics or pharmaceutical preparations and should not be used in relation to environmental aspects or outside the industries mentioned.

… and Fibers

Figure 6.1

Coarsely dispersed systems by particle size



Source: own illustration based on Ingenieurkurse.de 2020

The most important characteristic of a particle is its **particle size**. If the particle size of all particles is identical, the collective is called **monodisperse**. In practice, this is rarely the case. As a rule, the particle sizes exhibit a dispersion, i.e. they are of different sizes – the collective is **polydisperse**.

Other particle characteristics besides size are density and shape. The **density** is the quotient of the mass and volume of a solid. Depending on the reference volume used for the particle mass, a distinction is made between

» the **solid density** (also **pure density**) = particle mass/solid volume,

» the **particle density** = particle mass/particle volume (incl. pores in the particle) and

» the **bulk density** = particle mass/bulk volume (incl. cavities).

» For particles in liquids (e.g. in seawater) the following applies:

» the **concentration** = particulate mass (dispersed or dissolved)/liquid volume,

» the **particle concentration** = number of particles/liquid volume.

» For particles in solid mixtures (e.g. soils, compost):

» the **content** = particulate mass/total mass.

In addition to particles and piece goods, materials are also described as fibres. These are thin, linear, flexible structures made of organic or inorganic materials. Fibrous microplastics can be textile-based or originate from other sources, where, for example, peeling results in long, thin, flexible fragments with the corresponding dimensions. Fibrous microplastics of textile origin are predominantly based on polymers of petrochemical (fossil) origin, such as polyester (PES), polyamide (PA), polyacrylonitrile (PAN) and polypropylene (PP), but also on polymers from renewable raw materials (e.g. polylactide (PLA)) or on derivatives of natural polymers such as cellulose acetates (CA and CTA).

Characteristic for fibres is a large ratio of length to diameter. For natural fibres it can range from 1000:1 (cotton) to 10,000:1 (virgin wool). Synthetic fibres are adapted in their length-to-diameter ratio to natural fibres by cutting filaments and are classified according to their length: **Filaments** are virtually endless, staple fibres usually have lengths of 30 - 80 mm. Flock or short fibres refer to very short fibres with typical lengths of 0.3 - 2 mm; they are not spun into yarns but printed on textile surfaces, for example, using special processes. Fibrous microplastics cannot therefore be clearly assigned to the size classes in Table 5.1.

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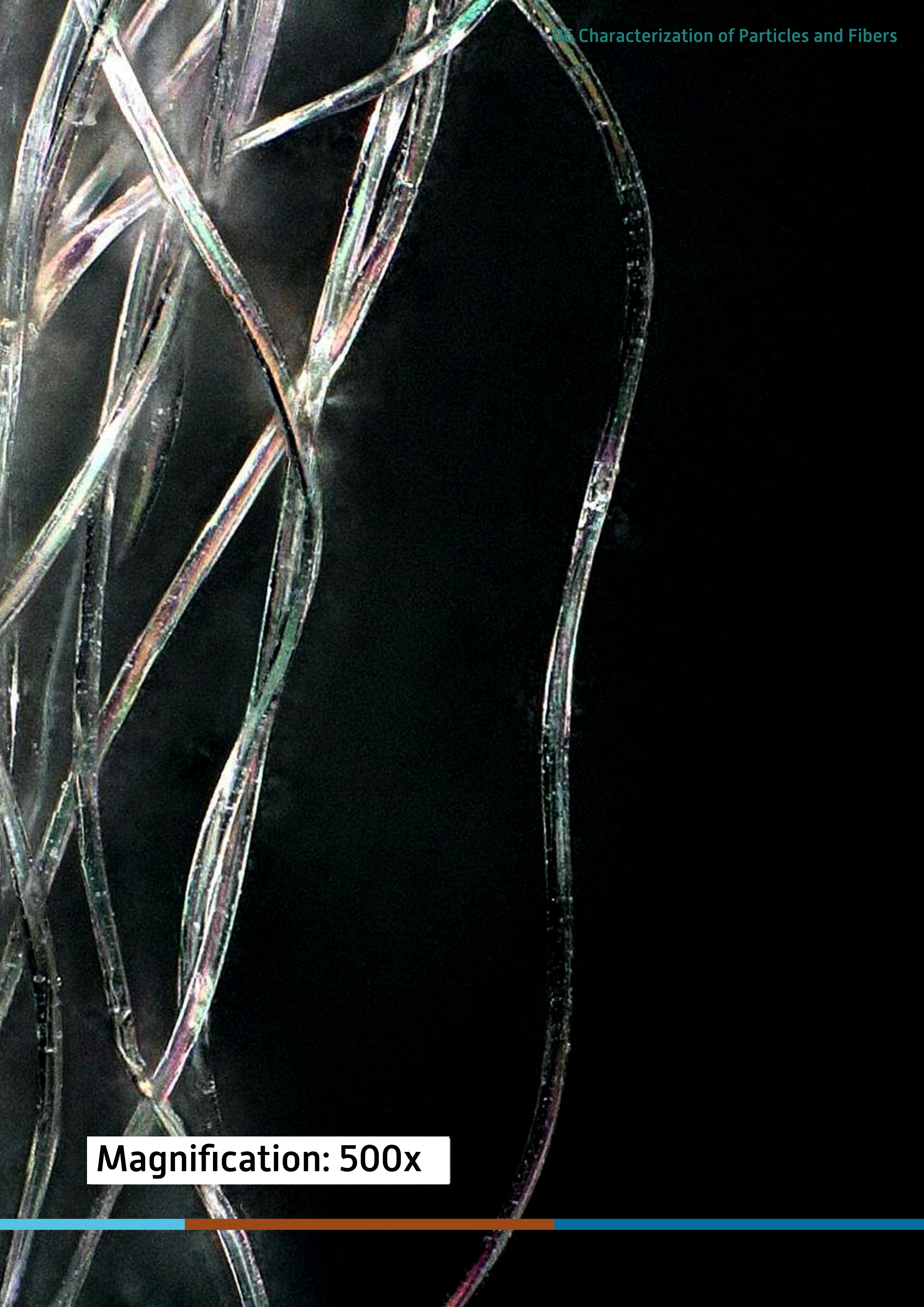
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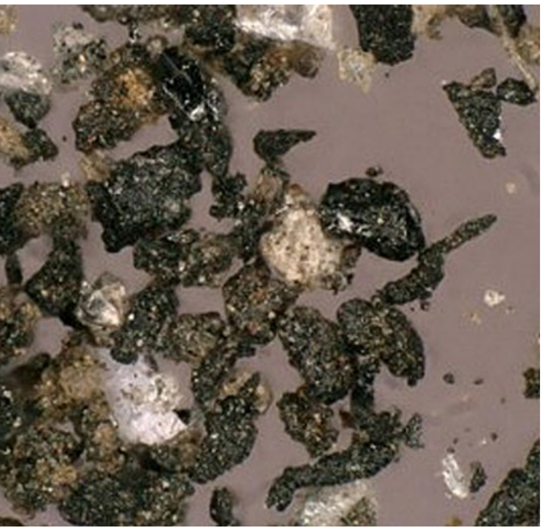
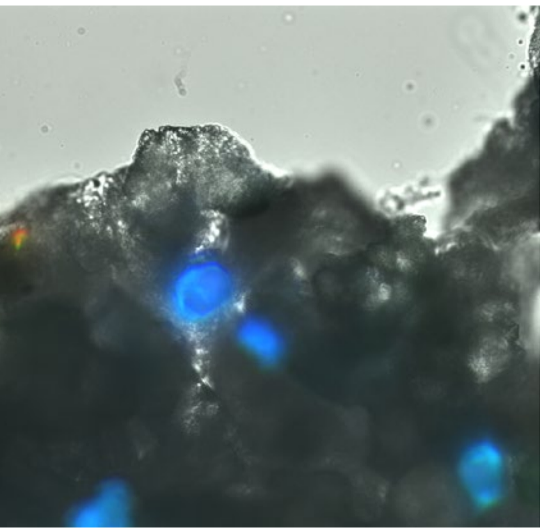
07 Transfer and Retention


Undefined road sweepings with tire and road wear particles.


As a result of fiber breakage during the washing process of textiles, microplastics enter the wastewater.


Fluorescent microplastic particles in the activated sludge of a wastewater treatment plant

Plastics can enter wastewater systems through a variety of sources (e.g., hygiene products, detergents and cleaners, abrasion of wastewater pipes, fiber breakage in textiles during wash cycles, manufacturing residues, tire wear, weathering of surfaces, artificial turf, outdoor building products, etc.). Cleaning of streets, where **street sweepings** – i.e. solids accumulated/deposited on road surfaces (primarily tire wear) – are sent for proper disposal, relieves pressure on wastewater systems, especially when performed on a regular basis.

» According to § 54 (1) German Federal Water Act[12], **wastewater** refers to service water whose properties have been altered by domestic, commercial, agricultural or other use (**sewage**) as well as water collected from precipitation running off built-up or paved areas (**rainwater**). Precipitation runoff from road traffic areas is commonly referred to as **road runoff**. Wastewater also includes liquids discharged and collected from facilities for treating, storing and depositing waste. The mass of material discharged with the wastewater or material flow is usually referred to as **freight**.

Urban wastewater and wastewater from indirect dischargers is collected and discharged in sewer systems. This is wastewater that comes primarily from households or similar establishments such as community accommodations, hotels, restaurants, campgrounds, hospitals and office buildings (urban wastewater) as well as from facilities that serve commercial or agricultural purposes, provided that the harmfulness of this wastewater can be reduced by means of biological treatments with equal success as with domestic wastewater. In Germany, more than 96 percent of households are connected to the public wastewater disposal system via urban wastewater treatment plants. A distinction is made between **separate sewer systems** and **combined sewer systems** in the urban sector. Both systems are found in Germany in roughly equal proportions.

12 German Federal Water Act (Wasserhaushaltsgesetz – WHG) of July 31, 2009 (BGBl. I p. 2585), last amended by the Act of December 4, 2018 (BGBl. I p. 2254), the German version is available at https://www.gesetze-im-internet.de/whg_2009/index.html#BJNR258510009BJNE000403118.

13 The German version is available at https://www.bmu.de/en/law/sewage-sludge-ordinance.

In the combined system, the wastewater mixture of sewage, external water and rainwater (**combined sewage**) is discharged jointly in a single pipe/channel system [DIN EN 16323:2014]. In the case of separate sewer systems, the wastewater flows of sewage and rainwater are discharged in separate sewer systems: The wastewater is discharged into the wastewater treatment plant and the rainwater, in some cases after temporary storage and mechanical treatment, is discharged into water courses and groundwater (through infiltration). Analogous to urban wastewater treatment plants, industrial wastewater treatment plants also exist in various sectors. These are regulated by the extensive requirements of the German Wastewater Ordinance (Abwasserverordnung – AbwV).

Although the term **wastewater treatment plant** used in § 60 German Federal Water Act is not defined there, it is stated that „wastewater plants shall be constructed, operated and maintained in such a way that the requirements for wastewater disposal are met." According to § 2 (5) of the Sewage Sludge Ordinance[13], a wastewater treatment plant is a fixed facility in which the harmfulness of the wastewater is physically, biologically or chemically reduced or eliminated.

From urban wastewater systems, plastics can enter the environment primarily through four different entry pathways:

» Depending on the wastewater treatment process, plastics can enter the environment via the discharge of the wastewater treatment plant, in that the treated wastewater from wastewater treatment plants is discharged into water bodies or used for irrigation. However, the majority of the plastics present in the raw wastewater are removed beforehand (mechanical treatment) or along with the sewage sludge.

Figure 7.1

Wastewater flows in Germany

Wastewater flow	Type of treatment	Volume in million m³
Wastewater (domestic/commercial)	treated in wastewater treatment plants	5080[a]
External water		2240[b]
Precipitation water		2570[b]
Total wastewater		9890
Wastewater from combined sewer system	not treated in wastewater treatment plants, partly mechanical treatment	1310[b]
Discharge of precipitation water	not treated in wastewater treatment plants, partly mechanical treatment or natural processes	3960[b]

a Destatis Technical Series 19 Series 2.1.2, Public water supply and public wastewater disposal - Public wastewater treatment and disposal, 2013, Federal Statistical Office, Wiesbaden 2015.
b Own estimate
c Rigolen, Infiltration ditch

Source: UBA 2019

- Plastics input into the wastewater treatment plant can via sewage sludge or co-fermentation of substrates in the digestion tower (e.g. from unseparated packaging residues in food waste) get onto and into soils when used in agriculture, landscaping and for recultivation.
- Plastics enter bodies of water via precipitation discharges when precipitation water is discharged from the separate sewer system – in most cases without having been purified effectively.
- A discharge into the environment also occurs via combined sewage overflows when, during heavy precipitation, combined sewer water is discharged into a watercourse, sometimes after mechanical pretreatment, to hydraulically relieve the combined sewer system or the wastewater treatment plant at an overflow (stormwater overflow structure, stormwater overflow basin).

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Water Resources Act (WHG)

§

The Act on the Regulation of Water Resources (Water Resources Act, WHG) is the central piece of legislation for water protection in Germany. It was adopted in 2009 and converts various European directives into national law - the most important of which is the European Water Framework Directive (Directive 2000/60/EC, WFD).

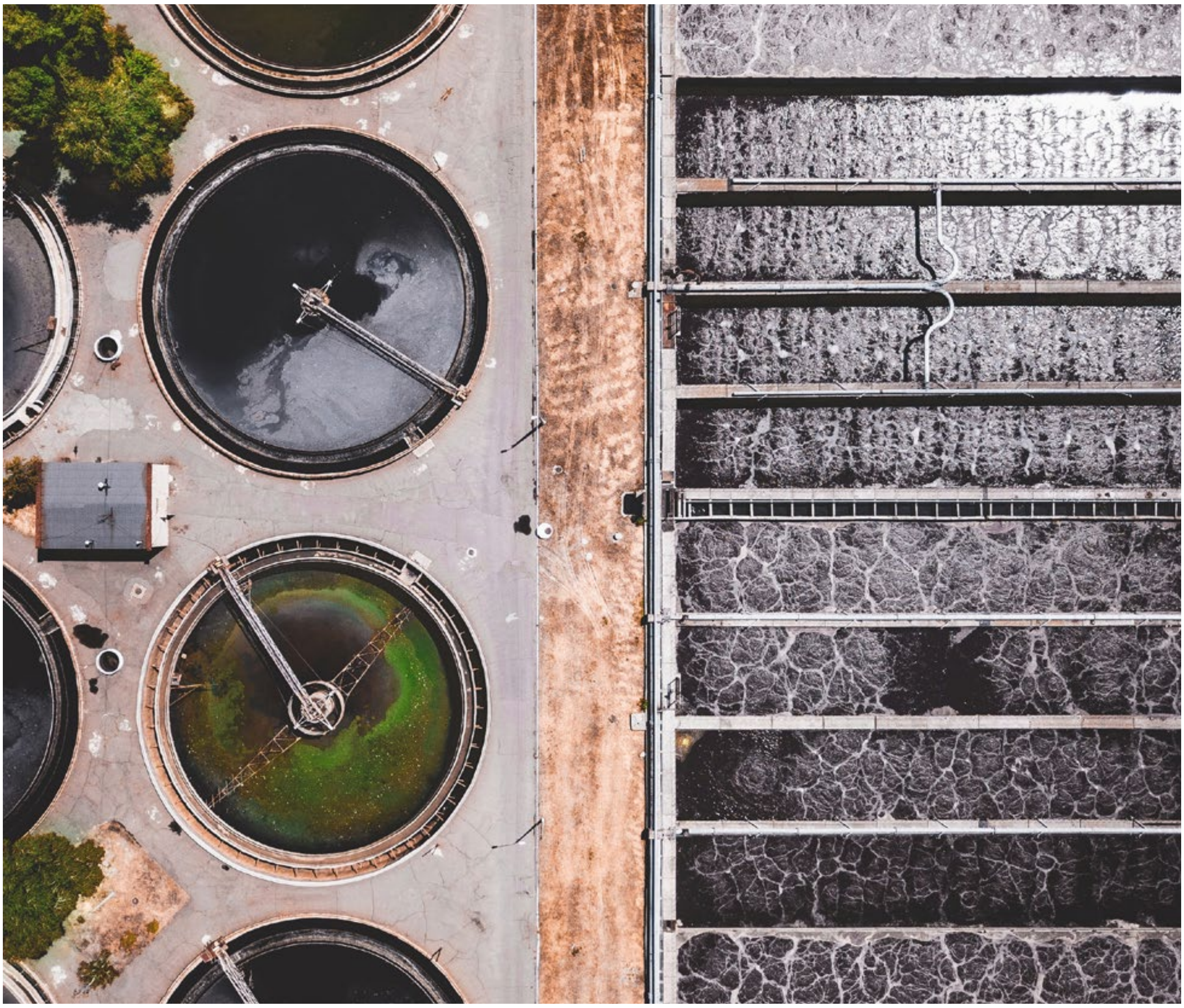
The purpose of the WHG is "to protect water bodies as a component of the ecosystem, as the basis of human life, as a habitat for animals and plants, and as a usable resource" (§1 WHG). Waters are managed according to defined river basin districts - a general prohibition of deterioration of the ecological and chemical status applies (§27 WHG). In six-year cycles, all water bodies are to be restored to an ecologically and chemically good condition by 2027 at the latest. Further important regulations for the implementation of the WHG are the Wastewater Ordinance (AbwV), the Surface Water Ordinance (OGewV) and the Groundwater Ordinance (GrwV) (BMU 2016).

Circular Economy Act (KrWG)

§

The Act to Promote Circular Economy and Safeguard the Environmentally Compatible Management of Waste (Closed Substance Cycle Waste Management Act, KrWG) has existed since 1994 and has been revised several times, for instance in 2012 and, most recently, in 2020.

It aims to "promote the circular economy to conserve natural resources, to ensure the protection of people and the environment in the generation and management of waste" and to support the implementation of the European Waste Framework Directive (2008/98/EC) (§1 KrWG).
The contents of the law focus on waste prevention, recycling, and disposal according to the waste hierarchy. The amendment to the KrWG includes additional prevention and recycling requirements as well as new requirements for public sector procurement. In addition, manufacturers are held increasingly accountable through the 'duty of care' (BMU 2020).



08 (Bio-)degradability and Persistence

The seedling functions as a symbol for industrial compostability in accordance with the DIN EN 13432 standard.

Decomposition process of a PET bottle cap

Biodegradable plastics currently available on the market do not degrade down in garden compost.

In the environment, plastics are subject to **abiotic degradation processes**, i.e. **physico-chemical aging** due to the influence of sun, wind, tides, etc. In the case of many plastics, this process is accompanied by, for example, embrittlement and/or cracking or even **fragmentation**. In addition, plastics are also subject to **biotic** or **biological degradation** by living organisms or their enzymes. In both cases, oxidative and/or hydrolytic degradation processes are the basis, whereby the polymers are decomposed into shorter molecular chains through chain splitting or **depolymerization**, up to carbon dioxide and water (**mineralization**). Frequently, abiotic degradation processes are a precondition for subsequent biotic degradation.

The degradation times of various plastics are sometimes estimated at 100 to 1,000 years, but reliable data are not available from experiments or simulations, especially for the degradation of polymers that are difficult to degrade.
With isolated exceptions (especially biodegradable plastics), chemical-physical and biological degradation processes cannot decompose polymers at an acceptable[14] rate. Plastics therefore exhibit a high degree of **persistence**[15]. Furthermore, non-degradable transformation products often remain in the environment.

Essential criteria for assessing biodegradability are the degradation environment (e.g. in water, in soil) and the degradation mechanisms with core parameters such as time, temperature, light, enzymes present, etc. Furthermore, a general distinction is made between **aerobic** (in the presence of oxygen) degradation **processes** and **anaerobic processes** (in the absence of oxygen).

Information on biodegradability should always be accompanied by information such as environment, degradation type and, if applicable, the underlying standard.

14 For some materials in certain applications, acceptable times are defined by standards (ISO 14851 „Aerobic degradability in aqueous media"), ISO 17556 („Aerobic degradability in soils"), OECD 301/302 „Facile/inherent degradability in aquatic environments"). For others, there is no general agreement yet.

15 The term persistence is used here in the sense of longevity and permanence, but not in the legal sense of chemicals.

The general OECD guidelines (relevant for all substances, not only for plastics) are of fundamental importance. In the case of aerobic degradation of substances, a distinction is made according to these guidelines between easy (rapid), inherent (basic), hard and persistent (non-degradable) and defined by the following tests and target parameters:

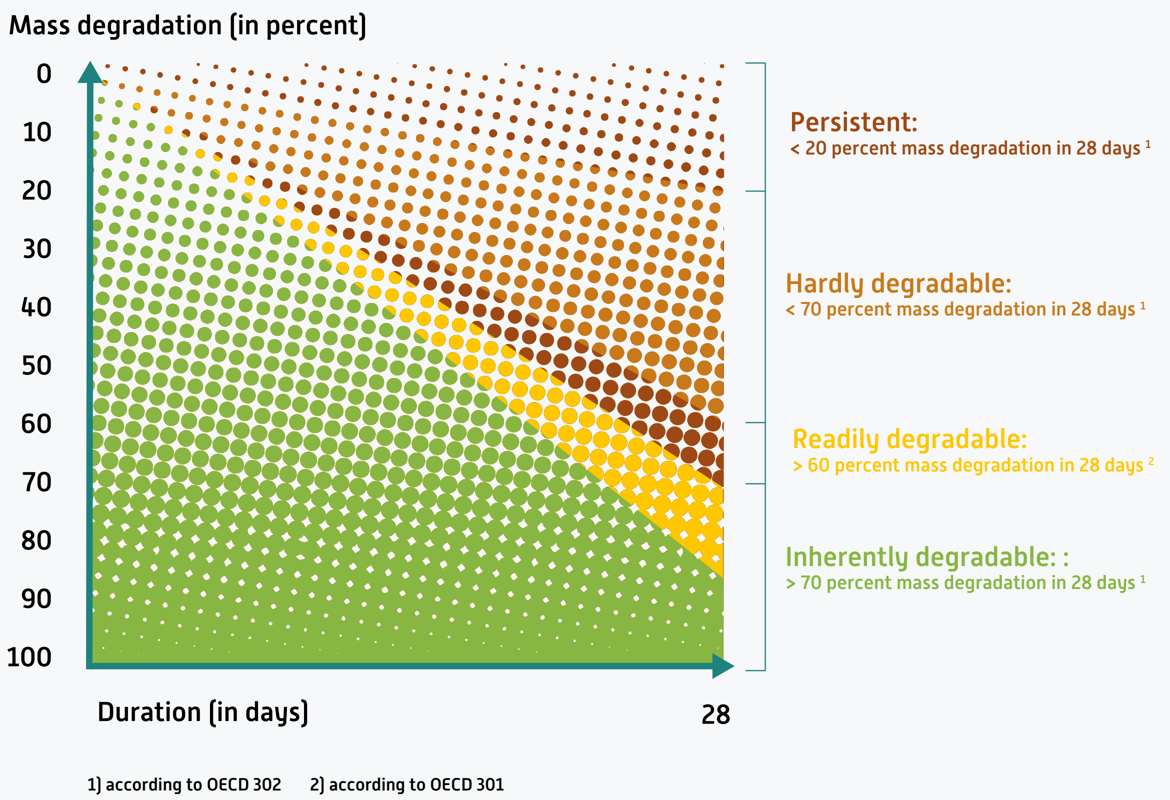
» **Readily degradable**: > 60 percent mass degradation in 28 days according to OECD 301.
» **Inherently degradable**: > 70 percent mass degradation in 28 days according to OECD 302
» **Hardly degradable**: < 70 percent mass degradation in 28 days according to OECD 302
» **Persistent**: < 20 percent mass degradation in 28 days according to OECD 302

The REACH Regulation, which is essential for the evaluation, authorization and restriction of substances under substance law (polymers being excluded to date), focuses, among other things, on „persistence" under chemical law, see footnote 7, and differentiates these further on the basis of simulation tests (OECD 307 and 308). The **half-life** is the period of time after which only half of the mass remains.

» **Persistent (P)**
» Half-life in seawater > 60 d
» Half-life in freshwater > 40 d
» Half-life in sea sediment > 180 d
» Half-life in freshwater, estuarine sediment or soil > 120 d

Figure 8.1

General OECD guidelines for biodegradability



Source: Ecologic Institut

» **Very persistent (vP):**

» Half-life in marine, freshwater or estuarine environments > 60 d

» Half-life in marine, freshwater or estuarine sediment or soil > 180 d

In addition to these general degradability standards, there are also numerous standards developed specifically for plastics that **specify biodegradation test conditions** [soil: ISO 17566, freshwater ISO 14851, marine ASTM D6691] and **degradation level requirements** [soil: EN 17033, ASTM D7081 (withdrawn)]. Technologically, degradation is used in composting and fermentation facilities. With regard to the degradation conditions, the degree of degradability and plant compatibility, there are corresponding standards for degradation under compostability or fermentation conditions.

In this respect, the criterion of **compostability** is of great importance. It describes whether a substance degrades under certain composting conditions. A biodegradable plastic that degrades – particularly under the conditions of an industrial composting facility – is not necessarily biodegradable according to OECD guidelines. This is mainly due to the fact that biodegradation is reproducible to a limited extent and only takes place under defined conditions. This means that compostability standards such as DIN EN 13432 only apply in a controlled composting facility, but not under degradability conditions in the sea, freshwater or soil. The individual standards are therefore not applicable to other areas. In each case, there are special standards for the application in composting facilities, anaerobic digestion facilities and also for the targeted metabolization of special plastics in certain mulch films under controlled application in accordance with DIN EN 17033.

» Industrially compostable: > 90 percent after 180 days (< 55 °C) [DIN EN 13432]

» Suitable for home composting: > 90 percent after 365 days (< 30 °C) [AS 5810, NF T51-800]

» Degradable in soil: > 90 percent after 730 days (< 28 °C) [DIN EN 13432; EN 17033]

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09 Plastics in the Circular Economy

The term „circular economy" is subject to different interpretations and expressions in different cultures or regions such as the German-speaking countries. In general, the different terms close to the term circular economy are typically used in a synonymous manner. Circular economy is, thus, understood as follows.

In a circular economy, the materials used remain in a material cycle beyond the life cycle of products. Waste, emissions, **dissipative losses** and the extraction of raw materials from the environment have to be reduced as far as possible. Dissipative losses include losses due to abrasion or weathering. The useful life of products should be extended as much as possible and their recirculation at the end of their useful life should be as quick as possible. A secondary condition that plays a major role in determining the quality of a circular economy is the minimum possible energy requirement – ideally covered by renewable resources – for maintaining the material cycle.

Materials that cannot be circulated should be utilised by energy recovery. Materials from which emissions cannot be avoided should ideally be degradable, provided this does not compromise longevity and resource efficiency.

The concept of circular economy can be equally applied to regions, industries, companies or individual goods.

While the different terms and interpretations of circular economy, circularity etc. are being used synonymously, the overall debate on circular economy focuses currently mainly on the eco-design of products whereas circular economy in the narrow sense concentrates on the management of wastes.

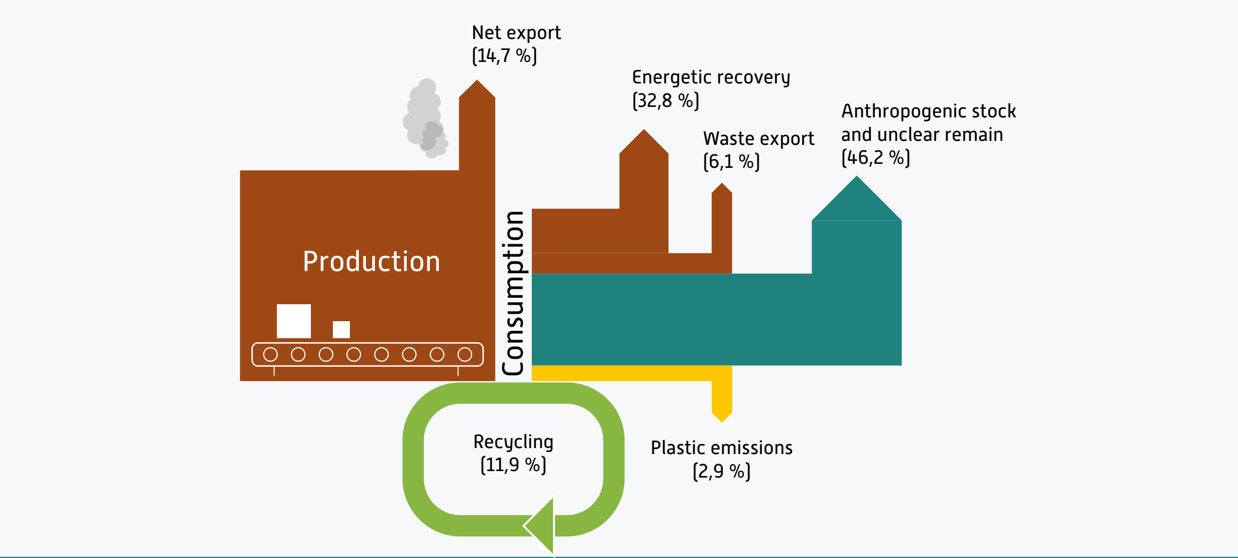
The concept of circular economy can also be applied to polymers, plastics and the products made of them and has particular potential for these materials due to a very low circularity to date. Figure 5 shows the annual fate of plastics after production in Germany. The graph shows that 14.7 percent of the plastics produced are exported as products. Of the plastics that are consumed in Germany, 32.8 percent are incinerated for energy recovery, 6.1 percent are exported as waste, 46.2 percent end up in anthropogenic stock (still in use or landfilled) or their fate is unclear, and 2.9 percent end up in the environment. Only 11.9 percent is recovered by material recycling.

In Germany, the **Circular Economy Act** (Kreislaufwirtschaftsgesetz – KrWG)[16] regulates the handling of waste and promotes the transition from a linear to a circular economy with the aim of conserving resources and protecting people and the environment. Important elements for the implementation of a circular economy are regulated in the German Circular Economy Act, for instance through **producer responsibility** (Section 23 KrWG). Accordingly, producers should consider waste as a starting point when developing products. This includes the reuse (in the sense of multiple use) of products, the recycling of materials and substances, and the ecological design (eco-design) of products, which allow them to be recycled without loss

16 German Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG) dated February 24, 2012 (BGBl. I p. 212), last amended by Article 2 (9) of the Act dated July 20, 2017 (BGBl. I p. 2808), available at https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Abfallwirtschaft/kreislaufwirtschaftsgesetz_en_bf.pdf.

Figure 9.1

Post-production fate of plastics



Source: Illustration according to Fraunhofer UMSICHT 2018 (based on data from Conversio from 2017, German Rubber Industry Association 2015).

of quality and without the accumulation of pollutants.

The aim of **eco-design** is to take environmental aspects into account at an early stage in product design and development in order to reduce adverse effects on the environment throughout a product's life cycle.

The term **design-for-Environment (DfE)** can be used as a synonym. **Design-for-Recycling (DfR)** is a subcategory in which the design takes particular account of recycling aspects. In many cases, it is important to distinguish between products and waste, as they are subject to different legal regulations. According to § 3 (1) German Circular Economy Act, **waste** is any material or object that has ceased to be useful to its owner and which the owner discards or intends or is required to discard.

§ 6 (1) German Circular Economy Act contains the so-called waste hierarchy. The first priority is to avoid waste. If it cannot be avoided, it should be prepared for reuse. If this is also not possible, the waste hierarchy requires recycling. Other recovery, in particular energy recovery, is subordinate to recycling. Only as a last resort waste is to be disposed of, i.e. landfilled or incinerated without energy recovery. Based on this ranking, priority should be given to the measure that best ensures the protection of people and the environment in the generation and management of waste, taking into account the precautionary and sustainability principles. § 3 of the German Circular Economy Act sets the terms and definitions of waste, its treatment, recycling and recovery procedures.

According to § 3 (20) of the Circular Economy Act, **prevention** means measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the reuse of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of hazardous substances in materials and products.

In this context, **reuse** (§ 3 para. 21 KrWG) means to reuse products or components that are not waste for the same purpose for which they were originally intended. Examples of waste prevention measures that can be framed in waste prevention programs are contained in Annex 4 of the German Circular Economy Act .

§ 3 (24) German Circular Economy Act defines **preparation for reuse** as any recovery operation consisting of testing, cleaning or repair in which products or components of products that have become waste are prepared in such a way that they can be reused for the same purpose for which they were originally intended without further pretreatment.

According to § 3 (23) German Circular Economy Act, **recovery** is any process as the main result of which waste is put to a useful purpose within the facility or in the wider economy, either by replacing other materials that would otherwise have been used to fulfill a specific function, or by preparing the waste to fulfill that function.

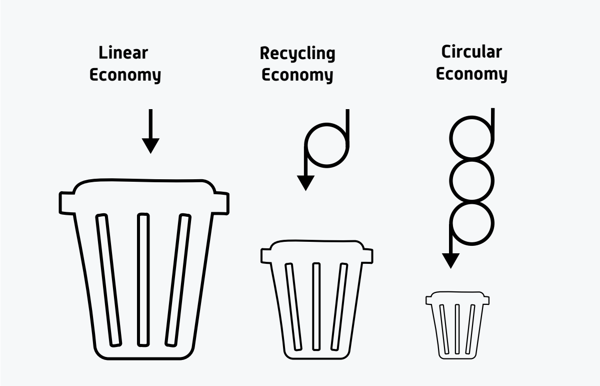
According to § 3 (25) German Circular Economy Act, **recycling** is any recovery process by which waste is reprocessed into products, materials or substances either for the original purpose or for other equivalent purposes; it includes the reprocessing of organic materials, but does not include energy recovery or reprocessing into materials intended for use as fuel or for backfilling. Annex 2 of the German Circular Economy Act contains a list of recycling processes.

According to Section 3 (26) German Circular Economy Act, **disposal** describes any process that is not recovery, even if the process has the secondary consequence that substances or energy are recovered. Disposal processes are listed as examples in Annex 1 of the German Circular Economy Act.

Important technical prerequisites for the recycling of plastics are the waste management measures of **collection** and **sorting**, which enable subsequent recovery (recycling). The collection system collects waste in a kerbside collection or bring system. For households, there are kerbside collections where containers

Figure 9.2

Linear, recycling and circular economy



Source: own illustration

such as the yellow garbage bin, the yellow bag or the recyclable bin for packaging or material equivalent non-packaging. Bring systems are, for example, depot containers "in the street" or recycling stations at the municipality.

After collection, which includes transport of the collected material to handling and/or sorting facilities, sorting enables the collected material to be separated according to recycling-oriented **sorting specifications**. While industrial waste are often available with known composition and high purity, plastic waste from households, thereby packaging waste to a large extent, is highly mixed and soiled. In addition to separation according to particle size and shape, **spectroscopy** (see Chapter 10) is primarily used in sorting plants for the separation of types of plastics. Sorting recovers material streams of defined quality with high proportions of the target material (e.g. PE, PP, PS or PET) and low proportions of impurities from the packaging waste collected accordingly[17]. **Mixed plastics** are also generated in the process. If these target materials do not have sufficient specifications for the corresponding product use as a **recyclate**, they cannot be recycled. Other chemical or energy recovery processes may therefore be necessary.

When recycling plastics, a distinction must be made between mechanical recycling and chemical recycling. **Mechanical recycling** of plastics refers to the processing of plastics waste into new plastic products (recyclates). It includes

17 See, for example, the specifications of DSD GmbH, the German version is available at: https://www.gruener-punkt.de/de/downloads.html.

processes for grinding, but also reprocessing via the melt (including melt filtration) or in solvents for selective extraction of the targeted plastic. The polymer chains are retained, albeit in part shortened, and are used to manufacture a new product [ISO 15270:2008].

Chemical recycling (also called **feedstock recycling** or **advanced recycling**) of plastic waste aims to convert the waste into low-molecular-weight, reusable building blocks [ISO 15270:2008]. It includes processes such as gasification, pyrolysis, solvolysis and depolymerization. In this process, the polymer chains present in the plastic are broken down into smaller building blocks, such as monomers. The reaction products can be reused as starting materials for the production of plastics.

Terms such as **upcycling** or **downcycling** are often used in the context of plastics recycling. However, they are rather distorting and clearly depend on the perspective of the user. They should not be used or only used in conjunction with comprehensive explanations. The term **cascade use** is more adequate. Cascade utilization refers to the reuse or recycling of plastic products or plastic waste in applications other than the original one, where they substitute primary raw materials such as recycled materials. In this process, so-called utilization cascades are run through, flowing from higher levels of value creation to lower levels. This increases raw material productivity. The end of the cascade is energy recovery.

In the current debates about a circular economy of plastics, a distinction is made between recycling of **post-consumer waste** on the one hand and recycling of **post-industrial waste** on the other. Post-consumer waste is generated by end users, i.e. consumers. Post-industrial waste, on the other hand, is waste that is generated during the manufacturing or processing of plastic products.

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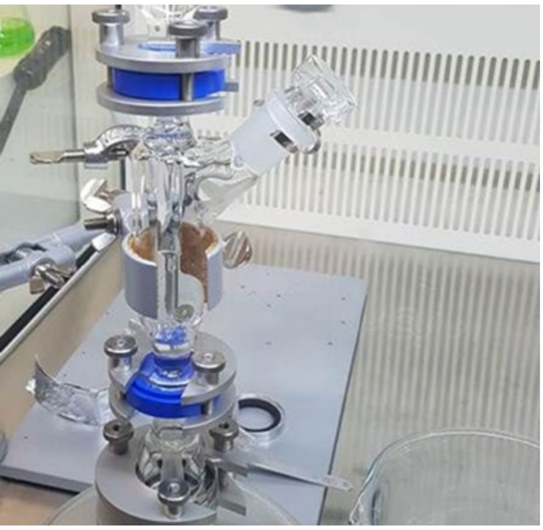
10 Environmental Analysis

Sampling basket for sampling street sweepings.

The sampling device „Rocket" is used to take samples in limnic systems.



Two-stage filtration apparatus designed to prepare microplastics for analysis.

In essence, environmental analysis involves the three steps of sampling, sample preparation, and detection.

Sampling refers to the singular or continuous taking of a random or composite sample according to a specified procedure from an environmental medium (e.g. water from a river, soil from a field or air from a room). Using water as an example, some sampling terms are explained below, but these can only be applied to soil and air to a limited extent.

The sampling must have a representative proportion of the sampled medium and at the same time sufficient quantities of plastics for the selected detection method. A **random sample** is defined as an individual sample taken at a specific point [DIN EN 16323:2014; § 2 No. 1 AbwV[18]] or one or more individual samples taken directly one after the other and combined to assess a momentary condition [DIN 38402-11:2009]. A **composite sample** corresponds to two or more samples that are mixed in a suitable and known ratio [DIN EN 16323:2014], or a sample that is taken continuously over a certain period of time, or a sample consisting of several samples that are taken and mixed continuously or discontinuously over a certain period of time (§ 2 No. 2 AbwV). In the wastewater sector, for example, 2h or 24h composite samples (daily samples) are common. A **qualified random sample** corresponds to a composite sample of at least five random samples taken and mixed at intervals of no less than two minutes over a period of no more than two hours (DIN 38402-11:2009; § 2 No. 3 AbwV). A **representative random sample** is one that is expected to yield a sample sufficiently similar to the basic distribution of the characteristics to be determined. When sampling particle-laden gas or liquid flow, for example, this is attempted by means of **isokinetic sampling**.

Accompanying substances are inorganic or organic components that may be present in the sample and interfere with the subsequent detection. Therefore, appropriate precautions must be taken during sampling, sample preparation and analysis. In order to prepare the sample taken for subsequent analysis, **sample preparation** or **sample purification** is first carried out,

18 German Waste Water Ordinance (Abwasserverordnung – AbwV), of 17 June 2004, available at https://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/wastewater_ordinance.pdf.

which differs depending on the properties of the sample (e.g. proportion of inorganic and organic substances), the sample quantity to be examined and the detection method.

Sample preparation often begins with **hygienization** in order to reduce the number of germs to a level that is deemed harmless to health for further processing. When preparing samples to determine the plastic content, all pieces visible to the naked eye are first removed. Any macroplastics are identified, removed from the sample and documented, in some cases with the aid of microscopes. **Oxidation** and density separation processes are frequently used as further purification steps. In this context, oxidation is understood as a chemical process in which natural organic matter (e.g. algae, fats or animal and plant residues) is converted into carbon dioxide. **Density separation** is a physical process in which the analyte (in this case plastic) in a suspension is separated from accompanying inorganic substances as a result of the differing densities of the various particulate components.

Sample preparation is followed by analysis. The **detection** of microplastic particles, for example, is carried out using thermoanalytical, spectroscopic or chemical methods. Depending on the method, the results generated include information on polymer type (e.g. PE, PET, PP, PS), particle number, particle sizes, masses and, in some cases, particle shape.

Thermoanalytical methods include detection methods in which chemical and physical properties of a substance or mixture of substances and their change as a function of temperature are measured. As a rule, the results include polymer types and associated masses.

Spectroscopic methods are a group of optical detection methods based on the interaction of electromagnetic radiation of specific energy/wavelength with molecular components of a substance. The relationship between the detected signals or signal changes and the energy/wavelength is called the **spectrum** and provides information about the polymer type. This information is often supplemented by microscopic images. The results can reflect polymer type, particle sizes and particle numbers.

Reference materials are used for the validation of processes and preparation steps. A **reference material** is a sufficiently homogeneous substance with one or more defined properties suitable for use as a comparative value [ISO Guide 30:2015-02].

The **blank value** refers to the measured value generated without adding the sample to be analyzed. With the blank value, all work steps are carried out identically to a real sample, but without the use of sample material. It thus indicates possible contamination, e.g. by the introduction of microplastics from the laboratory air. The blank value is often measured for validation of the method and should be stated in the result.

Monitoring comprises all systematic documentation, measurements or observations of specific processes or a substance within a defined system over a longer period of time. It is generally used to monitor changes or to ensure compliance with legal requirements (e.g. limit values in drinking water).

Further clarifications regarding methods and terminology in the field of microplastics can be found in the status report Analysis of Microplastics (Braun et al. 2021).

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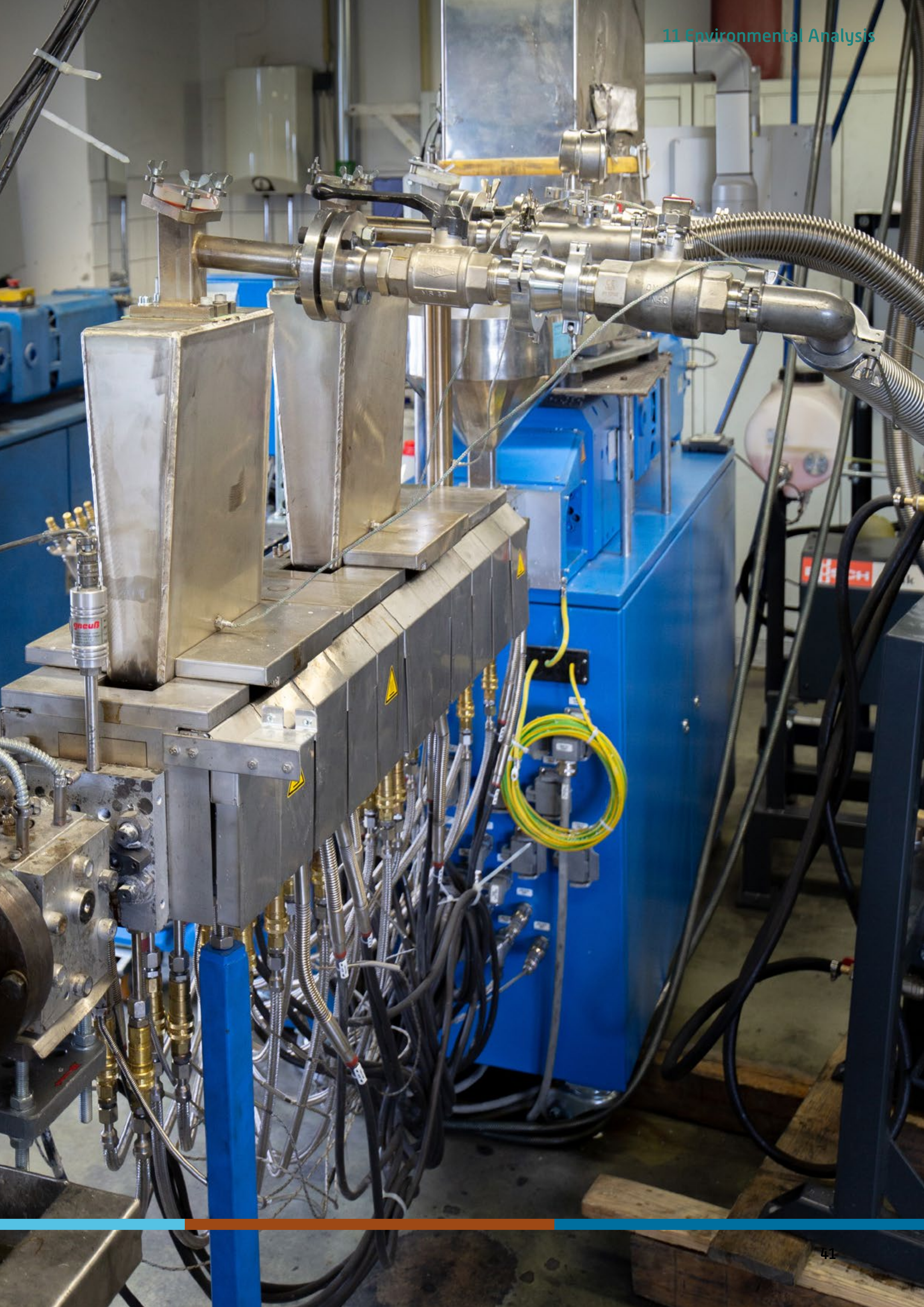
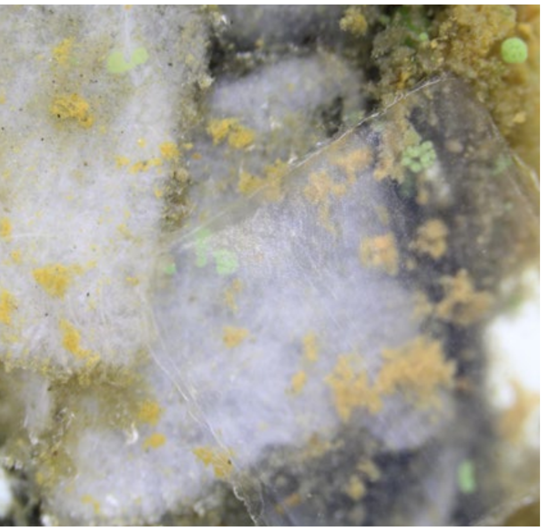

gneuß

11 The Impact of Plastics


Biofilm growth on polyethylene.


Marine animals perish due to entanglements and the resulting strangu-lations.


Larger marine organisms are repeatedly starved to death by the ingestion of large quantities of plastics.

Microplastics can be ingested by organisms. Key factors for uptake in the aquatic environment are the size of microplastic particles. A high uptake takes place in the size range of plankton (μm-range), as plankton generally has a very low selectivity for the uptake of food. **Bioavailability** refers to the proportion of a substance to which a living organism is exposed to that actually enters the systemic circulation (organs, tissues, cells) and takes effect there. Whether plastics accumulate in organisms, i.e. **bioaccumulate**, has not yet been clarified. But microplastic particles are also excreted again.

The contents of microplastic particles vary greatly depending on the concentration of pollution in the respective environmental compartment. These differences can be explained by transport-determining properties such as size, shape and density of the particles as well as by environmental factors such as currents and **biofilm** growth (see chapter 2).

Microplastic particles in water can also accumulate pollutants from their environment. The hydrophobic character of many synthetic polymers causes hydrophobic pollutants to adhere to the microplastic particle, similar to the way they adhere to natural particles. Pollutants are detected there in concentrations that can be several orders of magnitude higher than the concentration of the surrounding medium. Polymer scientists generally refer to this as **sorption**. In addition, sorption describes an equilibrium process between uptake (**adsorption** or **absorption**) and release (**desorption**) of a substance. **Leaching** refers to the extraction or release of additives from the polymer matrix.

Well-documented effects of macroplastics in the environment include **entanglement** of marine animals (marine macrofauna) in plastic debris (nets) and resulting **strangling**, which can lead to death of the animals through stress, injury, or starvation. **Ingestion** (feeding) of plastic can cause internal injuries to the digestive tract or, like strangling, lead to starvation. This has been widely documented for larger marine organisms (crustaceans, fish, birds and whales). Negative effects have also been demonstrated for coral reefs as a result of the covering of corals by areal macroplastics.

In addition, **blockages** of drainage channels by (plastic) waste are a frequent cause of flooding with negative effects on the environment, especially in the Southeast Asian region.

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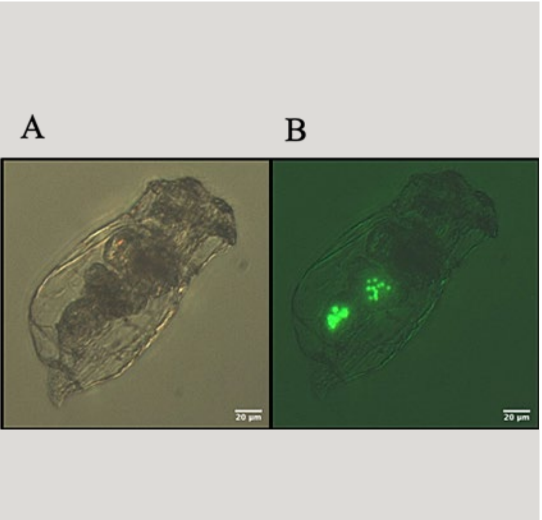
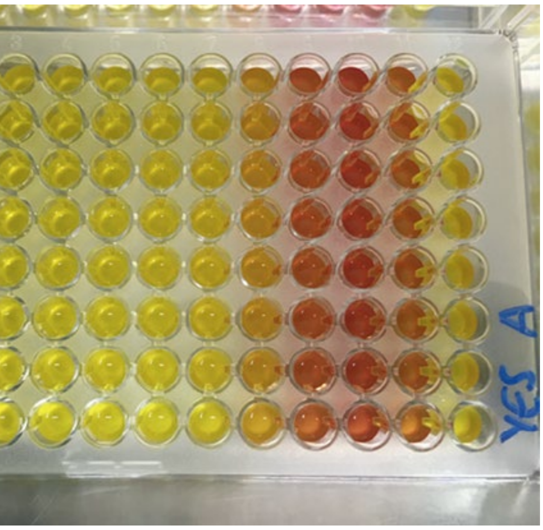
12 Toxicological Studies



Ingested polystyrene particles in a rotifer (B. calyciflorus).



Samples are subjected to ecotoxicological tests to determine whether they are hormonally active.


Mesocosms are usually simplified and partially enclosed experimental facilities used to simulate near-natural conditions.

Toxicological studies serve to assess the effects of a substance. A basic distinction is made between the fields of **ecotoxicology** and **human toxicology**. While ecotoxicology deals with the effects of substances on the living environment, human toxicology examines the effects of substances and substance mixtures on humans. The **toxicity** of a substance depends on its mechanism of action (e.g. DNA damage [genotoxicity] or hormonal damage) and the quantity or concentration ingested. If a tested substance or a specific substance reaches a dose or concentration that is lethal to a living organism, it is referred to as a **lethal concentration**. **LC_{50}** describes the mean lethal dose at which 50 percent of the individuals of the test organisms (daphnia, zebrafish, etc.) died after a certain exposure time. If the observed effect does not involve the death of the test organisms, the 50 percent occurrence of the observed effect is also referred to as the **EC_{50}**.

An analysis of the biological effect of substances (known or unknown active [single] substances or substance mixtures) on living cells or tissues can be performed with the aid of so-called **biotests** or **bioassays**. In this context, it is important to distinguish between different **endpoints** at which the investigation of a bioassay can be directed (survival rate, growth, behavioral change, etc.).

As a rule, toxicological tests are carried out in the laboratory as standardized and reproducible procedures. In the field of ecotoxicology, the closest possible approximation of test conditions to real environmental conditions can be achieved by using mesocosms. **Mesocosms** are artificially created, usually simplified and semi-enclosed experimental facilities for simulating near-natural conditions.

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13 Assessment Methods for

Various assessment methods can be used to evaluate the effects of plastic inputs to the environment.

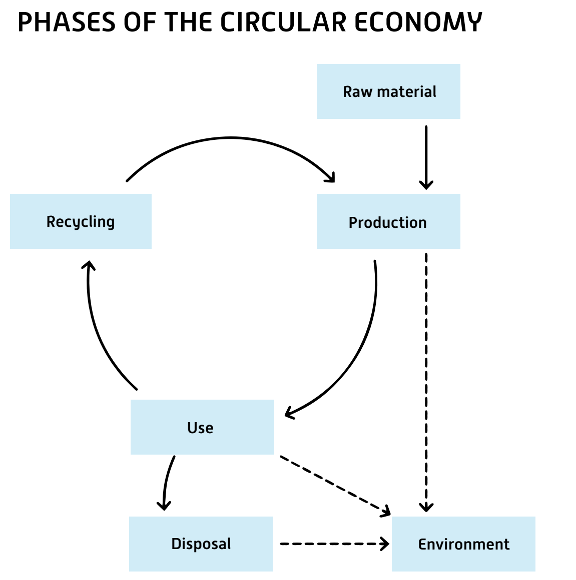
A standardized [ISO 14044:2006] and widely used method for recording environmentally relevant processes is the **life cycle analysis** (also known as **environmental balance** or **life cycle assessment**, LCA for short), which focuses on the systematic analysis of the environmental impacts of a product throughout its entire life cycle. Nowadays, this approach is not only used for product assessment, but can also be applied to processes, services and behaviors. So far, life cycle assessments have not taken plastic inputs into the environment into account. There are, nevertheless, current developments in this area.

A very similar methodological approach to life cycle assessment is the **material flow analysis**, also known as **material flow balancing**, in which material and substance flows are recorded. The two methods cannot always be clearly distinguished from each other. However, material flow analyses tend to focus on the quantities and paths of a system's substance, material and energy flows, whereas life cycle assessments tend to examine and evaluate the environmental impacts associated with these flows more closely. Moreover, as opposed to the above-mentioned life cycle assessment, material flow analysis is not internationally standardized. Material flow balancing is an essential prerequisite for the implementation of **energy and material flow management** (ESSM), which aims to influence material and energy flows ecologically and economically. Optimizations focus on increasing resource or material efficiency and creating sustainable cycles.

An (emission) **budget approach** can be based on such a balancing of individual substance flows by considering – starting from the current level of a substance in the environment – continuous direct and diffuse inputs and comparing them with natural decay and degradation processes over a defined period of time. The concept, which was originally developed by the German Advisory Council on Global Change in the context of the climate policy debate, can be further used to derive per capita budgets for various materials or substances.

Figure 13.1

Phases of the circular economy



Source: Ecologic Institute

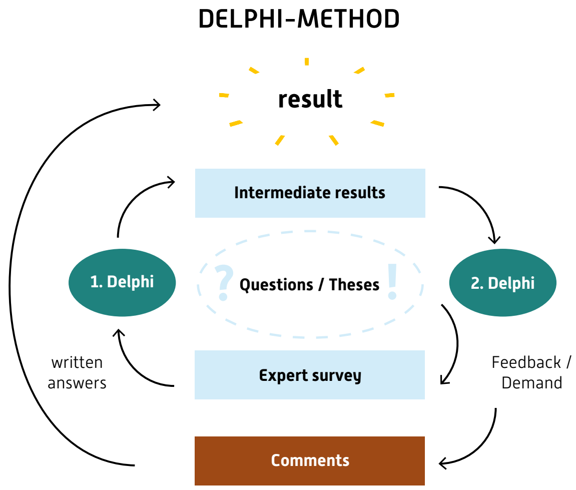
Multi-criteria evaluation procedures can help the decision maker to evaluate and compare different possible courses of action and provide a rationale for the selection of a preferred alternative according to objective criteria. They are applied when the decision maker simultaneously pursues several objectives, which may be completely independent, congruent, complementary or competing. For multi-criteria evaluation, a large number of evaluation procedures exist in the literature that can be used for different purposes and are all based on predefined guidelines and rules (criteria, calculation procedures, mathematical methods) for decision-making. A large part of these procedures uses **indicator** sets, with the help of which the individual criteria can be evaluated qualitatively or quantitatively.

If the focus of the assessment is more on observing and analyzing global trends in science and technology, a **technology assessment** can assist in assessing the opportunities and risks of various technological developments in order to provide policy recommendations or guidelines for avoiding these risks and making better use of the opportunities.

However, the above-mentioned evaluation methods are only suitable to a limited extent for answering complex questions for which little reliable knowledge exists or which are strongly normative. Rather, explorative research approaches such as expert interviews can be considered for this purpose. Different methods of (**stakeholder**) **participation** may be used for this case. If a large number of experts is consulted, it is common to apply the **Delphi method**, a survey of experts in two or more „rounds".

Figure 13.2

Delphi method



Source: Ecologic Institute

The aim is to reduce the range of answers and – in this case – to come closer to an expert consensus. For this purpose, the experts receive feedback after their individual questioning in the form of a statistical evaluation of the group results. In each round, the experts are encouraged to review their previous answers in relation to the comments of other experts.

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Authors

Corresponding author:
Jürgen Bertling (Fraunhofer UMSICHT)

Further authors:
Claus Gerhard Bannick (German Federal Environment Agency)
Luisa Barkmann (Darmstadt Technical University)
Ulrike Braun (German Federal Environment Agency)
Doris Knoblauch (Ecologic Institute)
Caroline Kraas (WWF Germany)
Linda Mederake (Ecologic Institute)
Franziska Nosić (INEOS Styrolution)
Bodo Philipp (University of Münster)
Maike Rabe (Niederrhein University of Applied Sciences)
Ingo Sartorius (BKV GmbH)
Hannes Schritt (Ecologic Institute)
Ulf Stein (Ecologic Institute)
Kristina Wencki (IWW Water Centre)
Katrin Wendt-Potthoff (Helmholtz Centre for Environmental Research - UFZ)
Jörg Woidasky (University of Applied Sciences Pforzheim)

Contribution/feedback from the projects:
Marco Breitbarth (Kassel University)
Stephanie Cieplik (BKV GmbH)
Britt Clauß (Chemnitz University of Technology)
Maria Daskalakis (Kassel University)
Elke Dopp (IWW Water Centre)
Carsten Eichert (RITTEC Umwelttechnik GmbH)
Markus Engelhart (Darmstadt Technical University)
Klaus Freimuth (Miele & Cie. KG)
Anja Hentschel (Darmstadt University of Applied Sciences)
Natalia Ivleva (Technical University of Munich)
Franziska Klaeger (Baden-Württemberg Foundation)
Robert Klauer (Vaude GmbH & Co. KG)
Kristina Klein (Johann Wolfgang Goethe-University Frankfurt am Main)
Oliver Knoop (Technical University of Munich)
Claus Lang-Koetz (University of Applied Sciences Pforzheim)
Rainer Mantel (BKV GmbH)
Jochen Moesslein (Polysecure GmbH)
Annett Mundani
Malin Obermann (Niederrhein University of Applied Sciences)
Mandy Paschetag (Technical University Braunschweig)
Sarah Piehl (Leibniz Institute for Baltic Sea Research Warnemuende)
Christina Röleke (Henkel AG & Co. KGaA)
Frieder Rubik (Institute for Ecological Economy Research (IÖW))
Andreas Schedl (Neue Materialien Bayreuth GmbH)

Christian Scheid (Technical University of Kaiserslautern)
Ulrich Schlotter (BKV GmbH)
Stephan Scholl (Technical University Braunschweig)
Daniel Venghaus (Technical University of Berlin)
Bianca Wilhelmus (INEOS Styrolution)
Cordula Witzig (DVGW Technology Centre for Water in Dresden)
Katharina Wörle (Bavarian State Office for Environment)
Nicole Zumbülte (DVGW Technology Centre for Water in Dresden)

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