An Initiative of the German Federal Ministry of Education and Research

Plastics in the Environment
sources · sinks · solutions

BMBF-Research Focus "Plastics in the Environment – Sources · Sinks · Solutions"

Key messages

SPONSORED BY THE
Federal Ministry of Education and Research

FONA
Forschung für Nachhaltigkeit

Imprint

Publisher
Ecologic Institute Non-Profit GmbH
Pfalzburger Str. 43/44, 10717 Berlin, Germany
Managing Director: Dr. Camilla Bausch
Registered office: Berlin, AG Charlottenburg HRB 57947;
UST ID: DE 811963464

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Supported by the German Federal Ministry of Education and Research (BMBF)

1st edition, June 2022

Graphic concept, layout
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https://bmbf-plastik.de/en/Publikation/Kernbotschaften

ISBN: 978-3-937085-36-4

Suggested citation
Hinzmann, Mandy; Knoblauch, Doris; Mederake, Linda; Schritt, Hannes; Stein, Ulf (eds.) (2022):
Key messages of the research focus "Plastics in the Environment".

Contents

Glossary

Additive	Additive/intermolecular compounds in plastics in addition to the predominant polymer.
Analyte	Substance to be analyzed – in this case mostly microplastics.
Bioavailable	Proportion of a substance that takes effect in a living organism.
Biofilm	Organisms that actively attach themselves to a surface.
Blank value	Measured value generated without adding the sample under investigation.
Calorimetry	Analytical method for characterizing phase transitions of plastics.
Characterization	Material property of an analyte or medium.
Depolymerization	Decomposition of polymers into monomers.
Deposition	Sedimentation.
Detritus	Decaying organic matter in water bodies.
Diffuse source	Not precisely identifiable sources from which substances enter the environment.
Downstream	Lower part of the production/supply chain (storage, transport, use, disposal, recycling).
Elastomer	Polymer with elastic properties, commonly known as rubber.
Elemental analysis	Polymer mit elastischen Eigenschaften, umgangssprachlich Gummi.
End-of-pipe solution	Downstream measures to reduce environmental pollution, e.g. cleaning processes.
Environmental compartment	Delimitable area of the earth, e.g. water, soil, air.
Field-flow	Separation method for subsequent detection of microplastics at the fractionation nanoscale.
Human pathogens	Pathogens that can cause sickness in humans.
Laminar flow box	Laboratory device that creates a parallel air flow from top to bottom, thereby minimizing contamination from the environment/air.
Macroplastics	Plastic fragments larger than 5 millimeters.
Matrix/sample matrix	Constituents of an examined sample that are excluded from analysis.
Microbeads	Friction particles in cosmetic products.

Microplastics Plastic fragments ranging from 1 to 1,000 micrometers in size.
- » Primary: Used intentionally as a particulate material.
- » Secondary: Created by fragmentation of larger plastics.

Monomer Molecules that can react as a structural repetition units to form polymers.

Plastics Materials mainly based on (partially) synthetic polymers, colloquially referred to as plastic.

Point source Clearly definable source of substance input into the environment.

Polymer Macromolecular compound composed of structural repetition units (monomers).

Polymerization Reaction in which polymers are formed from monomers as starting materials.

Rebound effect The phenomenon of expected savings through efficiency improvements not being achieved because the resources saved are used elsewhere, thus increasing consumption.

Sink Local places or media (including living organisms) at or in which plastics build up or accumulate.

Soil microbiome The composition of microorganisms in the soil.

Spectroscopy Analytical methods for detecting microplastic particles based on their chemical structure.

Stakeholders Actors with a legitimate interest in the course or outcome of a process or project.

Thermoanalytics Analytical methods for the detection of microplastics particles by means of their chemical structure.

Thermoplastic Polymer that is plastically deformable within a temperature range.

Thermoset Polymer that hardens as a result of a chemical reaction (polymerization).

Upstream The upper part of the production/supply chain (raw material extraction, extraction, processing, design, manufacturing).

Validation Validation is the documented evidence that a process or system meets previously specified requirements in a repeatable manner.

Vibrions Genus of bacteria which includes, among others, the cholera pathogen.

Introduction

Plastic waste is a global ecological problem with consequences for the environment. Too little is known about how plastic particles are introduced and dispersed and how they affect humans and animals. Comprehensive research is urgently needed to close these knowledge gaps and develop effective measures to prevent or significantly reduce the input of plastic waste and microplastics into the oceans.

In 2017, the German Federal Ministry of Education and Research (BMBF) launched the national research focus "Plastics in the Environment". The aim of the work carried out is to initiate a systemic approach and gain a better understanding of the environmental impact of plastic waste. A total of 20 joint research projects with more than 100 participating institutions from the fields of science, industry and practice, as well as an accompanying scientific project, are being funded. The researchers are working together on an interdisciplinary basis covering five thematic areas along the entire lifecycle of plastics value chain: Green Economy, Consumption and Consumer Behavior, Recycling, Limnic Systems, Seas & Oceans.

Cross-cutting issues, which are addressed by several joint research projects, are summarized in seven cross-cutting topics: (1) Analytics and Reference Materials, (2) Evaluation Methods of Possible Effects of Plastics on the Environment (incl. toxicity), (3) Terms and Definitions, (4) Social and Political Dimension of Plastics in the Environment, (5) Modeling and Life Cycle Assessment (incl. data management), (6) Recycling and product design, (7) Biodegradability. In these cross-cutting topics, methods are jointly developed, research questions differentiated and synergies exploited in order to strengthen the exchange of knowledge between the projects and to ensure the scientific quality of the results. Important insights have been gained, basic knowledge expanded and developments advanced in all thematic areas. This includes, among others:

» Enhanced analytical know-how

Outstanding analytical know-how has been developed for the detection and analysis of microplastics. In this context, it was possible to build on preliminary work of the JPI Oceans Initiative (e.g. BASEMAN [1] and the BMBF projects MiWa [2] and OEMP [3]). This know-how forms a decisive basis for national and European standardization of the processes as well as for the development of international standards. [4]

» Ecotoxicological assessment of microplastics in the environment

Microplastics can be harmful to organisms, as the project work shows. The findings provide important contributions to the knowledge of the ecological impact of microplastics on freshwater and marine systems. [5]

» Well-defined: a compendium of important terms

Compiled by an interdisciplinary team, the compendium on plastics in the environment explains key terms based on existing definitions. It aims to contribute to a better understanding of plastics in the environment and to ensure that communication on the subject is based on correct terminology, even outside the scientific community. [6]

Within the context of this research work, the term "plastics" refers to all solid materials (partially) composed of synthetic polymers, i.e. thermoplastics and thermosetting plastics and elastomers, but also products such as varnishes, textile fibers or tire abrasion. Particles and fibers as well as fragments of these products are classified based on their largest dimension into macroplastics (> 5 mm), microplastics (5 mm – 1 µm) and nanoplastics (< 1 µm).

» Further research into microplastics using mathematical models
It is currently not possible to suffieciently or adequately collect comprehensive area-based data on microplastics. A synthesis paper shows the potential contribution of modeling to further area-based microplastics research: Mathematical models enable the assessment of the sensitivity of different parameters and processes to the microplastic distribution in the environment. This can be used to specify the requirements for the quantity, location, and frequency of future sampling. [7]

» Summarized knowledge on biodegradability
The progress paper on biodegradability provides a detailed summary of the current knowledge on what is meant by plastic biodegradability as well as on how and under what conditions biodegradability can occur. [8]

» Key messages for a more sustainable society
Compact and to the point: The 11 key messages formulated from the perspective of social sciences show how society can find and pursue ways to deal with plastics in a sustainable manner. [9]

» Using research results to raise consumer awareness
Consumers, along with politicians and companies, are central actors when it comes to avoiding plastic inputs into the environment. In order to increase the awareness of consumers, the research results can be integrated into educational concepts. In some projects, the transfer to the public has already been put into practice, for example in the citizen science project Plastic Pirates (plastic-pirates.eu/en) and in the creation of educational materials for different age groups. [10]

The following chapters summarize the key messages from all 20 joint research projects. The central results are organized by key topics in order to derive recommendations for different target groups. It should be noted that the individual collaborative projects have different durations; some have already been completed while others are still ongoing. In addition, there is still a need for further research on the subject of plastics in the environment, despite the great progress that has been made. Many of the results presented should therefore be regarded as preliminary and not conclusive. This also applies to the reliability of certain measured values and collected data. More detailed information on the collection method, robustness and context of the data can be found in the scientific results published by the individual projects.

01 Sources and pathways of plastics into the environment

Plastics enter the environment via various pathways – these are referred to as input pathways. Different sources of plastic inputs and how they spread have been studied.

Findings:

» **Industry and commerce:** Commercial and industrial wastewater discharged into municipal wastewater treatment plants **(indirect discharge)** in some cases shows increased concentrations of microplastics. In the **industrial** and municipal wastewater treatment plants investigated, microplastic particles are largely removed from the wastewater (see below).

During production and transport of plastic products (e.g. granulates), (micro-) plastics can be **released unintentionally**, e.g. due to improper storage and handling, unsuitable means of transport or operational disturbances. **Rainwater** from traffic and production areas is partly discharged into water bodies untreated. Drifting and erosion of industrial and commercial areas lead to **diffuse emissions** [1] *(see chapter 5)*.

» **Households and urban areas (consumers):** The use of products containing plastics gives rise to (micro-) plastic emissions, including emissions from **textile washing** [2], detergents and cleaning agents, and the abrasion of products during use. Especially during the first washing of clothes, a large amount of fibrous microplastics is emitted. In municipal wastewater treatment plants, the majority of the (micro-) plastic is removed from wastewater (including **domestic wastewater** and **precipitation water**) *(see chapter 3)*. Low residual levels in the **effluent of wastewater treatment plants** can reach surface waters. [3, 4] (Micro-) plastics removed from wastewater are mainly found in **sewage sludge** [4-6]. This is mainly thermally treated or utilized (soil-related sewage sludge treatment is on the decline, see below and *chapter 3*).

Initial studies suggest high emissions from untreated rainwater and **combined sewer overflows**.

A significant source of plastic waste in the environment is **littering**, i.e. careless disposal and discarding of plastic waste [3], for instance at large scale events [7, 8]. During extreme weather events, littered plastics can lead to punctually high inputs of (micro-) plastics into the environment. Furthermore, urban areas play an important role as a source of atmospheric inputs of microplastics. In addition, there are other diffuse sources, such as sports fields with artificial turf, construction sites, etc. [9] *(see chapter 7 and chapter 8)*.

» Traffic: According to the current state of knowledge, **tire abrasion** is one of the largest sources of microplastics in the environment. Hotspots of formation are bends, traffic lights and intersections. [10] Tire abrasion can enter water bodies through drifting, erosion, and stormwater runoff, accumulating in soils near roads, especially in non-urban areas. [11] In addition, particulate matter is released into the air *(see chapter 7)*.

» Waste: The collection and treatment of **(plastic) waste** generates **diffuse emissions**, for instance through unintentional release or drifting. Incorrect disposal leads to high concentrations of (micro-) plastics in **composts and digestate** *(see chapter 4)*. Untreated landfill leachates [3] are a source of microplastics that can be reduced by treatment prior to discharge into municipal wastewater treatment plants.

» Agriculture: **Fertilizers and seeds** are often introduced into soils encased in synthetic coating. Through the use of **mulch and cover foils, fleeces and nets**, (micro-) plastics are also released into the environment, especially when they fragment, blow away or are improperly disposed of. Sewage sludge was used for decades as organic fertilizer in agriculture, which contributed to the relevant microplastic accumulation in the soil. Model calculations allow an estimation of the microplastic input from **compost**, sewage sludge, digestate and foils since the 1960s in individual study areas: About half of the input comes from compost and one third from **sewage sludge**. While compost and digestate as well as foils continue to be relevant input pathways, the use of sewage sludge in soil (2020: 16 %) will continue to decline in the future due to the predominant use of thermal sewage sludge in Germany *(see chapter 4)*.

» Transfer: (Micro-) plastics are subject to complex **transfer** processes in the environment. For example, **drifting** can lead to soil-to-air transfer and atmospheric transport to remote locations.

Precipitation (leaching) [3] and **dry deposition** (accumulation or sedimentation) return airborne microplastics to soils and waters. The air in urban areas is more polluted with microplastics than in rural areas. [12] Precipitation can lead to soil erosion, especially of agricultural land, and thus contribute to the transfer of microplastics to water bodies.

According to initial model-based estimates, the annual input into streams through **erosion** in agricultural areas is comparable to that generated by municipal wastewater treatment plants. On arable land, transfer to deeper soil layers occurs through tillage, precipitation, and mixing by soil organisms and, to a lesser extent, through movement into macropores (cavities in the soil). [3]

Within water bodies, (micro-) plastics **sediment** mainly in zones with low flow velocity, such as dams or floodplains. Biofilm formation on (micro-) plastics and subsequent mineral and aggregate formation causes even low-density plastic particles to sink. It can be re-mobilized during extreme weather events, such as heavy rainfall or flooding. Macroplastics accumulate mainly in shore zones. In **barrages**, macroplastics can be removed from the water bodies using hydropower trash rakes. [13] Non-sedimented (micro-) plastics reach the sea via watercourses.

In watercourses, no continuous increase of microplastics from the upper course to the estuary has been detected so far. This is partly due to the intermittent nature of the research in conjunction with the inhomogeneous distribution of microplastics in the water body.

In addition to transfer, the progressive **fragmentation** of plastics (macroplastics > microplastics > nanoplastics) by influences such as UV radiation or friction plays an important role in their occurrence and behavior in the environment. [3] The latter is determined by particle size and density, among other factors. [14]

Based on investigations conducted, the relevance of individual sources, pathways and processes for the input of synthetic materials into the environment can be estimated (*see Figure p. 11*).

Recommendations:

Spatial and temporal model calculations must be further optimized in order for them to be used for estimating and evaluating measures (e.g. further process technologies – *see chapter 3*). In order to effectively reduce (micro-) plastics in the environment, it is also necessary to develop approaches to reduce macro-plastic emissions (e.g. through littering).

» **Industry and commerce:** Industrial emissions can be reduced primarily through organizational and operational measures (e.g. cleaning of company premises), structural changes and the treatment of precipitation water. [7]

» **Households and urban space (consumption):** (Micro-) plastics emissions during and after the use phase of products can be significantly reduced by extending the life cycle of plastic products (e.g. less disposable or fast fashion). Regulatory measures can be taken to promote this, for example through the creation of stronger incentives for avoidance. Here, consumer behavior also plays a decisive role (*see chapter 8*).

(Micro-) plastics emissions from untreated wastewater that enters water bodies via combined sewer overflows and stormwater drains must be reduced by means of operational management measures and the technological development of retention facilities.

» **Waste:** Since the technical possibilities for the subsequent separation of (micro-) plastics from organic waste are limited and/or very costly, the greatest success in avoiding and reducing emissions in this area can be achieved by improving the waste separation behavior (e.g. incorrect disposal). The collection of plastic waste should be consistently changed from bag to garbage can collection. A demand-oriented optimization of street cleaning and waste collection in public areas can reduce the input into the environment (*see chapter 6*).

» **Agriculture:** Plastic materials used in agriculture must be collected and recycled as thoroughly as possible. The use of biodegradable plastics (films, fleeces, etc.) helps to reduce (micro-) plastic accumulation in the soil. To avoid microplastics inputs, sewage sludge should not be utilized for soil-related purposes. Alternative, research-based production methods with lower plastic consumption should be used, including increased consulting services for farmers.

» **Traffic:** The use of low-abrasion tires and a defensive driving style, in addition to reducing individual traffic, are approaches to decrease the generation of tire abrasion. Previously untreated rainwater from roads should be treated appropriately at urban hot spots. Tire wear can also be reduced by optimizing street cleaning, for example by sweeping the streets before rainfall events whenever possible.

Further Research:

» How can data be collected on the sources and pathways of plastic emissions into the environment, which have not yet been adequately investigated?

» What relevance do these have and which approaches could be effective in reducing them?

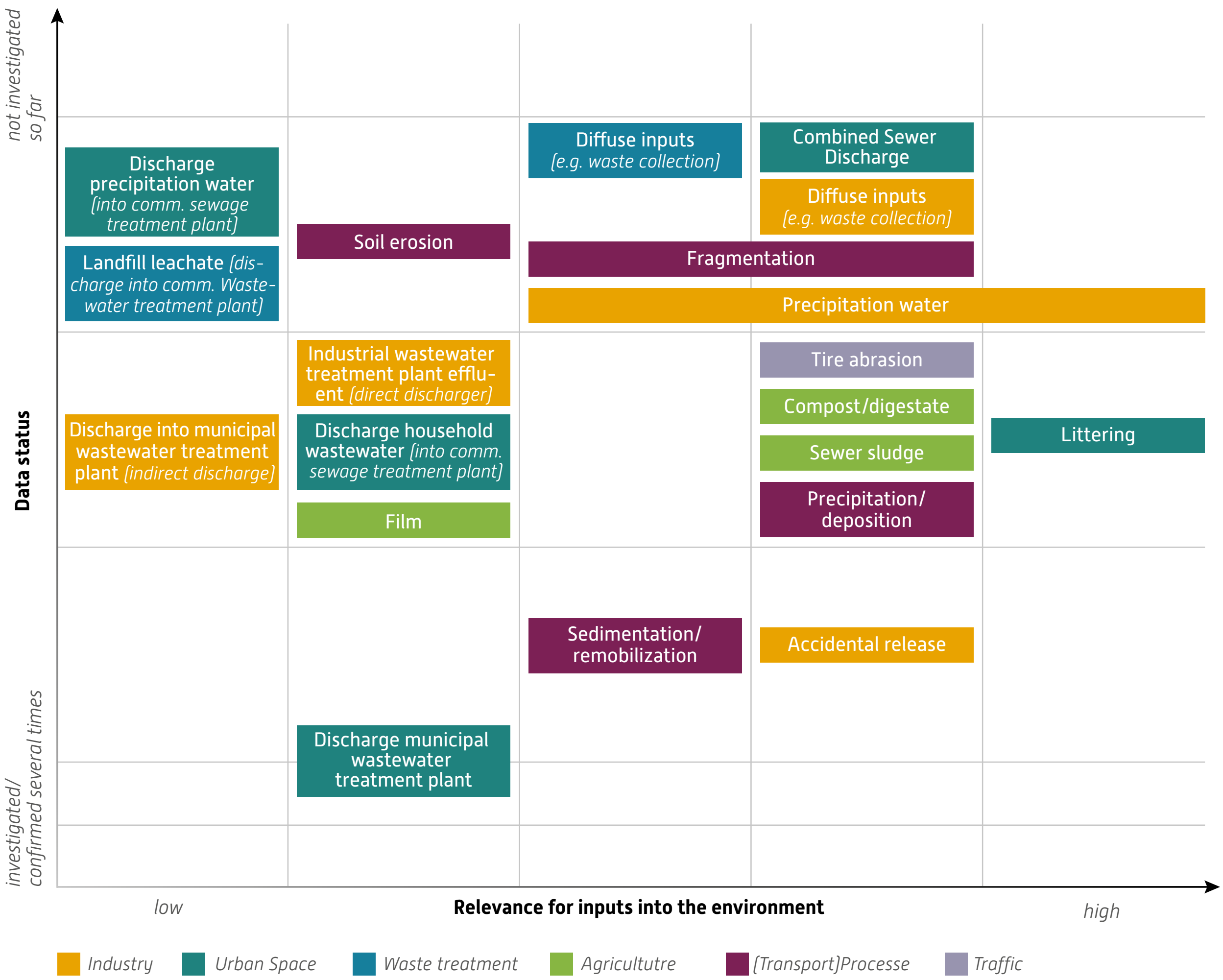

Fig.: Relevance of input pathways and processes for plastics in the environment.

The graph shows the relevance of individual input pathways and processes for plastics in the environment (relevance ascending from left to right). In addition, the reliability of the underlying data is indicated. The number of studies/projects that have investigated this within the research focus decreases from the bottom to the top and so does the robustness of the data. An assessment of the data situation as "investigated/confirmed several times" does not exclude that there are still open research questions.

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02 Ecotoxicological assessment of microplastics as a complex task

The effects of microplastics on plants and animals have not yet been fully described. Microplastics have different properties that determine whether and how they are taken up by living organisms and the extent to which they are harmful to them. Compared to other pollutants in the environment, microplastics may therefore have a more complex effect on different organisms.

Findings:

Composition, shape and properties of microplastic particles are diverse

» Microplastic particles are present in the environment as a heterogeneous mixture of substances (plastic type, size, shape, additives, etc.), which can have diverse combinations and properties. This causes different bio-availability and uptake in organisms.

» The shapes and properties of microplastic particles change in the environment, for example through weathering and biofilm growth. Thus, even microplastics with low densities can sink to the bottom of a water body, and microplastics with higher densities can rise to the surface of a water body. Much like natural particles, microplastics also provide multiple surfaces to which pollutants and pathogens can attach.

Microplastics may have a wide range of effects

» The results of ecotoxicological studies and the concentrations of microplastics > 10 micrometers found in the environment indicate that no immediate lethal effects are to be expected in the aquatic environment from the current occurrence of microplastics. So far, the data on smaller plastic particles (< 10 µm) is insufficient.

Long-term contact with microplastics may lead to harmful effects on various living organisms.

» Microplastic particles can cause physical injuries in the intestines of living organisms, which can subsequently lead to inflammation or alter the intestinal flora.

» Microplastics can release toxic additives. These have already been detected in various environmental media (water, soil, air). When microplastics are ingested through food, breath or skin contact, additives such as plasticizers or flame retardants from the plastic may be dissolved in the bodies of organisms.

» Experimental studies on the effects of microplastics on different aquatic organisms show that the effects are highly dependent on the species studied, but aging of the particles also influences the effects on living organisms. In addition, some species of fish show negative responses to certain parameters, while other species do not show any signs of exposure to microplastics.

» Biofilms growing on microplastics can have different proximity qualities depending on the material. Overgrown microplastic particles such as these can become part of the food chain. Both the concentration of natural food particles and that of the microplastics are critical to potential impacts. If creatures mistake microplastics for their food, it can lead to malnutrition. In addition, plastic can inhibit the growth of invertebrate organisms by causing the bio-film growing on it to have poorer food quality (less algae) than that growing on natural surfaces. The composition of bacterial communities on plastic surfaces is often influenced by the location and not by the plastic material.

Risk to environment and organisms cannot be assessed conclusively

» A generally valid risk assessment and comparability of studies is hindered by the fact that the chemical-physical properties of the particles used in the laboratory are often not adequately described, and that sufficient or representative figures on environmental concentrations of many types of microplastics are still largely lacking. Comparative tests with plastic reference particles can help to better assess contradictory findings from similar studies and to define meaningful positive controls for microplastic effects.

» The effects of microplastics are often not clearly distinguishable from the adverse effects of other particles and (dissolved) substances in the environment, and may also be masked by more powerful effects of other stressors or environmental toxins.

» It is not yet clear whether microplastics have adverse effects due to their physical and chemical properties, which differ from those of numerous natural particles (e.g. clay particles).

» Small microplastic particles may exist in nature in various states, e.g. free or incorporated in detritus and aggregates. Therefore, the size and form in which they become effective cannot be evaluated.

Recommendations:

» In accordance with the precautionary principle, policymakers are responsible for minimizing the input of plastics into the environment, as microplastics may potentially have adverse health effects on humans and the environment.

» To ensure the quality of ecotoxicological studies involving microplastics, minimum reporting requirements must be met. A guideline [1] prepared for this purpose is also intended to help the authorities to better assess the quality of published studies and to formulate practical recommendations.

» The characterization and harmonization of ecotoxicological studies should be further advanced and include comparisons with effects of other particles.

» For control purposes, experiments on the effects of microplastics should additionally analyze the effects of natural organic or mineral particles.

» Exposure should always be considered when assessing the risk of microplastics because of the relationship between observed effects and environmental concentrations.

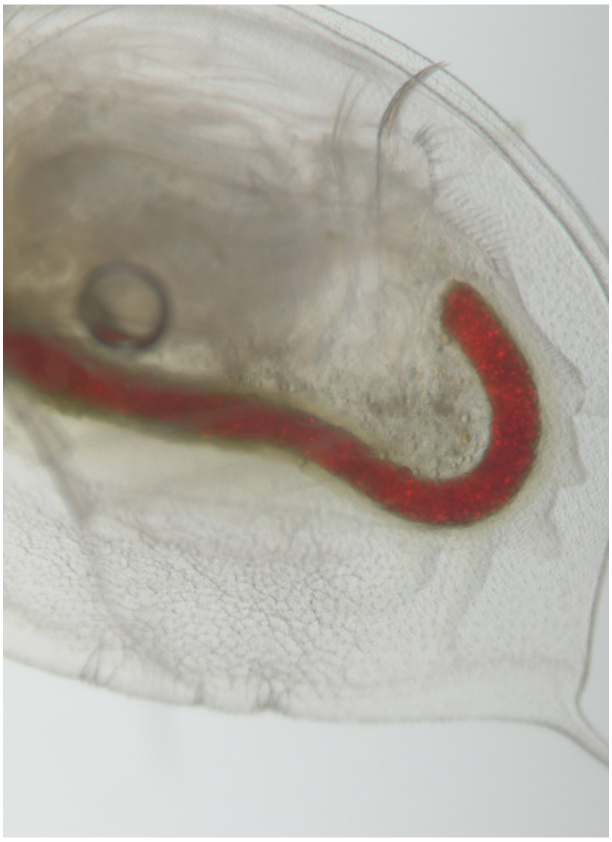
» Toxicity thresholds for microplastic particles must be identified as a basis for a risk assessment.

Further Research:

» Additional studies involving as many environmentally relevant plastics as possible, different forms and aged plastic particles (including particles from the environment) are required in order to better reflect the natural conditions in the aquatic and terrestrial environment in the tests.

» For the risk assessment, a further development of the effect-related analysis is necessary, which should be based on whether harmful effects can be detected for microplastic particles at certain environmental concentrations.

» Microplastics in the size classes <10 micrometers or <1 micrometer (nanoplastics) exhibit increased membrane permeability, surface activity and thus potentially increased toxicity and should be the focus of greater investigation.



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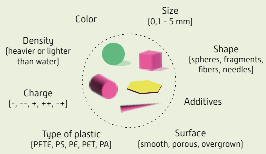
Are microplastics harmful?

The ecotoxicological assessment of microplastics in the environment is a complex task.

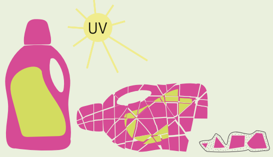
Whether or not microplastics have harmful effects on plants and animals has not yet been conclusively established. The different properties of microplastics determine whether and how the microplastics are absorbed by living organisms and whether they are harmful to them.

Compared to other pollutants in the environment (e.g. pesticides), microplastics do not have a uniform effect on living organisms. In addition, the effects of microplastics often cannot be distinguished from the harmful effects of other particles and substances found in the environment.

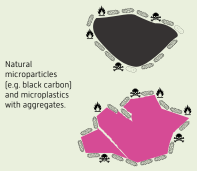
Microplastics occur in many forms



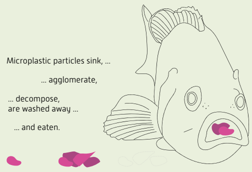
Microplastic particles are a very heterogeneous substance class (plastic type, size, shape, additives, etc.), which can be found in many different combinations of characteristics.



Forms and properties of microplastic particles change and expand in the environment, e.g. through weathering and biofilm growth.

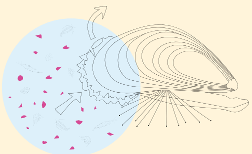


Similar to natural particles, microplastic particles provide a variety of surfaces for the accumulation of pollutants and pathogens.

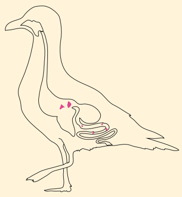


The diverse microplastic particles can exhibit a wide range of behaviors in the environment and be taken up by organisms.

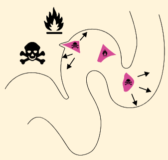
Microplastics can have very different effects



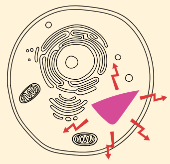
When living creatures mistake microplastics for with their food, this can lead to malnutrition. Microplastics can also be passed on in the food web.



Microplastic particles can cause physical injury in the intestines of living creatures or alter the intestinal flora.

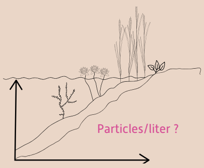


After ingesting the microplastics, toxic additives such as plasticizers or flame retardants may be dissolved from the plastic particle and released into the body.

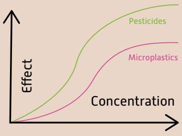


The smallest plastic particles can penetrate into the tissue cells of a living organism where they can cause inflammatory reactions.

The risk to environmental organisms cannot be unambiguously assessed



Accurate figures on environmental concentrations of microplastics are scarce, making risk assessment based on laboratory results difficult.



In the natural environment, weak effects of microplastics are often masked by stronger effects of other environmental pollutants.

It is not yet known whether the physical and chemical properties of microplastics constitute an additional burden to the effect of the numerous natural particles.

It is not yet clear whether microplastics can accumulate in the food web and whether this has long-term effects on organisms.

It is currently virtually impossible to make generally valid statements concerning the harmfulness of microplastics.

This infographic was created as part of the BMBF's research focus on plastics in the environment:
www.bmbf-plastik.de |

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03 Plastics in wastewater: detection, analysis, removal

Plastics frequently enter wastewater – which comprises sewage, rainwater and combined sewage, particularly from households, trade and industry, and traffic areas – and can be discharged into bodies of water *(see chapter 1)*.

Findings:

» **Sampling, sample preparation and detection of plastics** in wastewater are significantly more complex in terms of analysis time and equipment compared to common test parameters such as the number of germs in drinking water. Therefore, no harmonized or standardized methods were available at the time of the investigations *(see chapter 9)*. Currently, **correlations** between the number and mass content of plastic particles and common wastewater parameters can only be presented in individual cases.

» Since plastic contents in **wastewater** have been determined using different methods, it is always necessary to take the metadata (wastewater characteristics, investigated plastics, particle sizes and sampling, sample preparation and detection methods) into account in order to compare and evaluate such measurement results. The findings on plastic contents are based on a few studies with a limited number of measured values, but allow initial trend statements.

» **In untreated wastewater**, fragments of about 150 different plastic products and plastic-containing composites have been identified, which can be classified as **macroplastics** (> 5 mm) and large **microplastics** (1 - 5 mm). In total, about 500 to 1,000 particles (> 1 mm) per inhabitant and year are discharged into wastewater. [1]

» No data is available for **small microplastics** (< 1 mm) in untreated wastewater, since its determination would require great efforts. Likewise, no concrete statements can yet be made on the quantity of **microplastic particles of < 10 micrometers** discharged by wastewater treatment plants or remaining there. However, investigations in wastewater treatment plants show that such tiny plastic particles also accumulate in the sewage sludge. [6]

» **In (mechanical-biological) wastewater treatment plants**, plastic particles and parts can be removed from the wastewater depending on size, shape and polymer. Most of the plastic particles are retained in the mechanical stage (screen + grit trap + primary clarification). The particles finally collect in the screenings and grit traps (mainly macroplastics) and in the sewage sludge (microplastics). Currently, over 95% of micro- and macroplastics of > 10 micrometers are removed from wastewater. However, not all stormwater and combined sewer discharges are captured by wastewater treatment plants. In clear water, microplastics concentrations of 0.00001 to 0.1 milligrams per liter [2], [3] respectively 10 to 10,000 microplastic particles per cubic meter (> 10 µm) remain. [4-6] With the aid of further process technologies (e.g. downstream filter systems such as sand filters, cloth filters, microsieves or membrane processes), microplastics retention can be increased to almost 100%. This corresponds to a microplastics concentration in the wastewater treatment plant effluent in the order of 0.0001 milligrams per liter or 10 to 100 microplastic particles per cubic meter (> 10 µm). [2], [4-6]

» **Fibrous particles** are not as well retained as spherical (ball-shaped) particles.

» In pilot tests with **industrial wastewater**, microplastic removal of approx. 60% in sedimentation and 70% in flotation stages was achieved. If these precipitation processes are combined with the addition of special flocculants, up to about 99% of the particles can be removed. Ultrafiltration membranes retain microplastics > 1 micrometer more effectively (99.9% removal efficiency). Large-scale pretreatment stages (sand filtration and chamber filter presses) prior to the indirect discharge of industrial wastewater contaminated with plastics also showed a removal rate of over 99% in tests. [7]

» **Sewage sludge** is the sink for microplastics removed in wastewater treatment plants. In primary, surplus and digested sludge, concentrations in the range of 1 to 10 grams of microplastics per kilogram of dry matter [2], [5] or particle counts of 100 to one million microplastic particles per kilogram of dry matter [4] have been determined. In sewage sludge digestion (anaerobic stabilization), no statistically clear (negative) effects on the degradation process and digester gas production can be determined. In the case of downstream dewatering of digested sludge with centrifuges and chamber filter presses, the transport of microplastic particles depends to a large extent on the treatment. Up to 30% of the microplastic mass in the sludge is carried into the sludge water. [2]

» In the case of **soil-related sewage sludge utilization** (as fertilizer in agriculture), plastic particles are released into the environment *(see chapter 1 and chapter 4)*. Due to the amendment of fertilizer and waste legislation (in particular the Waste and Sewage Sludge Ordinance of 2017), sewage sludge will in future be increasingly **treated thermally** (incineration), so that the microplastic inputs associated with soil-related sewage sludge treatment will decrease.

» **Effluents from municipal and industrial wastewater treatment plants** play a minor role as a point source of microplastic emissions > 10 micrometers to waters. It is assumed that combined sewer overflows (from combined sewage systems) and stormwater discharges (from separate sewer systems) as well as direct stormwater runoff from traffic areas are the main sources of inputs into the aquatic environment *(see chapter 1)*.

» **Measures for the reduction of plastic emissions in residential water management** are associated with high technical and economic costs. As an end-of-pipe solution, they can therefore only accompany measures that are focused on the production and use of plastic products.

Recommendations:

» For better comparability of measurement results, **methods for sampling and detection** of water, wastewater and solid samples (sewage sludge), especially with complex matrix, need to be further harmonized.

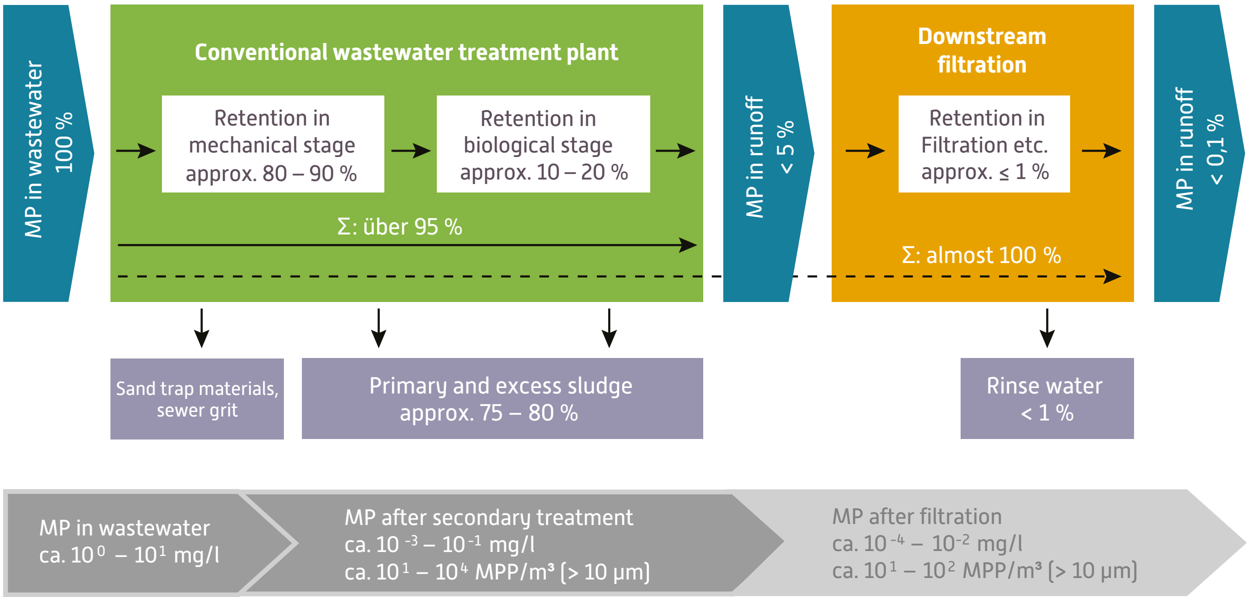

Fig.: Approximate balance of the microplastic loads (> 10 µm) in wastewater treatment plants

» **Industrial microplastics emissions** via the water pathway should be further reduced by internal preventive measures.

» **Soil-related recycling** of sewage sludge should be further minimized.

» Efforts should be made to reduce **plastic emissions from stormwater discharges and combined sewer overflows** in order to reduce uncontrolled emissions into water bodies.

» **For a comprehensive modeling and balancing** of the inputs of plastic particles via residential water management as well as of the effectiveness of individual measures, further robust data must be collected. In particular, more extensive measurements are required for the evaluation of emissions of plastics from wastewater treatment plants and from stormwater discharges and combined sewer overflows.
The same applies to the elimination rates of individual measures. Here, mass concentrations, particle counts as well as the distribution of plastics for different size classes have to be considered.

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Further Research:

» What quantities of plastics are discharged into water bodies via stormwater discharges and stormwater runoff? Which measures are suitable to reduce them as efficiently as possible?

» To what extent are plastic particles of < 10 micrometers, including nanoparticles, retained in wastewater treatment plants by existing treatment processes, and do these existing processes need to be optimized?

» What is the overall balance of plastic inputs via the different input pathways in wastewater and what data is needed for its quantification?

04 Plastics in soils: inputs, behavior and fate

In addition to oceans, soils are also significant sinks of plastics that enter soils through various pathways, such as agricultural practices. Inputs affecting soils include:

» Use of secondary fertilizers (e.g. composts, digestate, sewage sludge),
» Aging of intentionally inserted or injected plastics (e.g., planting aids, films, drainages),
» Use of polymeric additives (e.g. encapsulation of fertilizers, seeds, or soil conditioners),
» Inputs via littering/littering hotspots,
» Inputs from roads (especially tire abrasion),
» Atmospheric inputs from a wide variety of sources.

The plastics are either directly inserted as microplastics or plastic parts decompose over time through weathering, abrasion and fragmentation.

Analysis

Findings:

» Sample collection and preparation must be adapted to the solids to be analyzed. In the field of sample preparation, an enzymatic-oxidative method for application to soil samples for spectroscopic analysis was successfully further developed. [1]

» A representative sample size is determined by the size of the plastic to be analyzed in conjunction with its abundance. Given that small particles are much more abundant in the environment, the general rule is that the larger the particle, the greater the amount of sample required. [1] The applicable detection methods are essentially the same as those used for water samples *(see chapter 9)*.

» For secondary fertilizers such as compost, fermentation residues and sewage sludge, the sampling required to date has been too infrequent (1 sample/1,000 tons). Current investigations show that the lowering of the separation limit from 2 millimeters to 1 millimeter in the Fertilizer Ordinance (DüMV, 2019) is not sufficiently validated. Retries with one liter of test volume showed significantly greater variances in the plastic findings at the 1 millimeter separation limit. The visual determination of particles larger than 1 millimeter is not representative for the determination of plastics in composts according to previous findings, and a consideration of the fine fraction is urgently required.

Recommendations:

» The EU Fertilizer Regulation includes requirements for determining the total content of plastics in composts, which should be extended to the fraction smaller than 2 millimeters. In addition, the national biowaste regulation

[1] Generally, the term "plastics" refers to both macroplastics and microplastics - unless explicitly stated otherwise.

should also determine the total plastic content of the fraction smaller than 1 millimeter.

» The microplastic analysis should always include the particle size distribution in addition to the mass concentration. Time- and cost-efficient extraction and analysis methods should be used for these investigations.

Further Research:

» To what extent do soil sampling, treatment and detection methods for classifying microplastic pollution need to be further developed in order to achieve harmonization and standardization?

Assessment

Findings:

» An estimate of the spatial distribution of microplastic inputs from potentially major sources in agriculture nationwide and in two river basins revealed significant spatial variability. This suggests that regional agricultural structures have a significant influence on the distribution of pollution hotspots.

» Microplastics were detected in all samples, in all sites - with or without sewage sludge application. While this indicates ubiquitous contamination, the sources remain unclear in some cases. If sewage sludge is used as secondary raw material fertilizer, microplastics removed during wastewater treatment may end up in areas used for agriculture (*see chapter 1 and chapter 3*).

» During heavy rain events, fields fertilized with sewage sludge may erode, transporting microplastics to adjacent water bodies (*see chapter 1*). Models of such events have shown annual inputs of the same order of magnitude as the simulated inputs from treated wastewater from sewage treatment plants (*see chapter 3*). In addition, repeated field rainfall experiments have demonstrated that microplastics are discharged primarily by surface runoff.

» Despite these preliminary findings, the data basis for the assessment of microplastics in soils and their emissions to water bodies remains insufficient overall.

Recommendations:

» When developing monitoring plans and the corresponding model calculations, regional and culture-related microplastic pollution focal points in particular must be taken into account: agricultural practices (mulch films, etc.) and the associated inputs, fertilization with sewage sludge or compost, littering focal points, inputs via the atmosphere or runoff from sealed surfaces, such as road runoff.

Further Research:

» How and in what quantities do plastics accumulate in soils and are discharged into water bodies? What is the aging and degradation behavior of plastics in soils?

Effects on soil and organisms

Findings:

» Plastics become entrapped in the soil structure through biological and physicochemical processes and accumulate. Depending on the soil structure, microplastics can be transported into water bodies by erosion.

» The uptake of microplastics by soil fauna has been widely documented. For some important groups of organisms, concentrations such as those found in heavily contaminated soils cause damage to health, which can lead to a restriction of their function in the soil ecosystem. This effect appears to be much stronger for small particles (<100 µm) than for larger microplastics.

Recommendations:

» Since the harmful effect of microplastics increases as particle size decreases, meaning that the fine fraction in particular has the potential to disrupt soil life and impair soil functions, such developments should be monitored. In addition to the amount of microplastics, the state of soil life including the soil microbiome must also be taken into account.

Further Research:

What are the long-term impacts of microplastics at low concentrations (such as those found in arable soils) on soil organisms, soil life, and soil functions?

Fate / Biodegradability

Findings:

» Conventional plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS) are generally considered to be non-biodegradable. [2] The degradation processes by microorganisms known to date are too inefficient to be able to speak of actual biological degradation.

» The potential degradability of so-called biodegradable plastics in industrial treatment plants or environmental media (e.g. soils) is described in standards that classify biodegradability based on laboratory tests. These standards always refer to very defined conditions (e.g. temperature, dimension of the material being tested ["test specimen"]), which are often not realistic for the environment as well as technical fermentation or composting plants. Depending on the site conditions, degradation in soils is significantly slower than in standardized laboratory tests.

The polymers polybutylene succinate (PBS), polylactide (PLA), polybutylene adipate terephthalate (PBAT), polyhydroxyalkanoates (PHA), polybutylene succinate co-adipate (PBSA) as well as lignin, cellulose (acetates) and starch have been certified as biodegradable for industrial plants on the basis of laboratory tests. However, in the environment, i.e. in soil and water (sea and freshwater), mainly cellulose, PHA and starch degrade completely in short periods of time.

Further Research:

» Which experimental approaches can be used for biodegradation under real conditions (also for standardization)?

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05 Companies have to take more responsibility

Companies play a key role with regard to the use of plastics and their input into the environment, because companies

» produce/process plastic pellets (including recycling),
» transport and handle them,
» manufacture products and packaging containing plastics,
» transport and sell them,
» engage in trade and intermediate trade in plastic-containing products and packaging,
» process plastic-containing products and packaging, or
» dispose of them.

Findings:

» Despite measures taken by trade associations, plastics are released into the environment to a considerable extent during the production, transport and processing of plastic pellets, even if the pellets are used as end products. [1] As a result, companies contribute to the (avoidable or unavoidable) release of plastic products into the environment just as much as private consumers. *(see chapter 8)*. In addition, microplastics are discharged into the environment via industrial wastewater and rainwater from the plastics manufacturing and processing industry as well as from logistics processes *(see chapter 1)*.

» Processors of plastic pellets (compounders) determine, amongst other things, which additives are used and thus indirectly how environmentally harmful the plastics are.

» Companies determine the materials from which they manufacture their products and, by designing and shaping their products, have a decisive influence on the extent to which plastics are released into the environment either in whole or in part, during their use and application.

» As "gatekeepers," retailers can influence the range of products on offer through their product range policy, including the proportion of products containing plastics and their packaging.

» Textiles made of purely synthetic or bio-based synthetic fibers become a source of secondary, fibrous microplastics through processing, transport, use, and cleaning and care.

» The newly developed Plastic Index (PLIX) enables a comparative life cycle assessment of products and technologies. As a result, plastic-containing products and packaging can be evaluated in terms of the particularly relevant ecological criteria of CO_2 footprint, plastic mass and recyclability.

» The measures currently in place to reduce plastic inputs from industry are insufficient *(see chapter 10)*:

- The existing legal regulations (including the EU Single-Use Plastics Directive) do not cover all relevant plastic-containing product and packaging types that are discharged completely or partly into the environment *(see chapter 10)*.
- Producer responsibility as regulated in the EU Single-Use Plastics Directive only applies to a few products and wrongly assumes that the inputs can be recovered from the environment.
- The very low prices for single-use solutions and primary plastics, as well as the high cost of reusable solutions, make it difficult to substitute these materials.
- Focusing on technological solutions for individual input pathways (e.g. sewage treatment plants, washing machines) is not sufficient in view of the large number of inputs and their global distribution.
- Voluntary commitments by plastics associations are not sufficiently effective (see the example of plastic pellets).

Recommendations:

» There is a need for comprehensive approaches with companies as the central players. Following the waste hierarchy, the avoidance of products containing plastics must also be taken into account.

» In particular, products whose intended use leads to their coming into contact with or remaining in the environment should - with sustainability aspects in mind - be replaced by products without plastics. In the case of single-use products for which plastic-free substitutes are already available, the use of these alternatives should be encouraged.

» For products/packaging in which plastics are essential for the functionality (e.g. for certain medical products) or are ecologically sensible (e.g. for certain consumer goods and/or some [reusable] packaging), the following aspects must be taken into account:

- Products and packaging containing plastics should be designed in such a way that no parts or components can detach. They should also contain information on the proper disposal of the materials.

- Products and packaging should be designed in a manner that allows for domestic recycling and reduces material consumption.

- In the case of packaging, regulatory measures are required for greater uniformity of standard forms for various reusable container sizes and areas of application *(see chapter 10)*.

- Manufacturers should be obliged to provide a transparent declaration regarding additives, auxiliary materials and other substances in their products and to ensure that only safe additives are used (in accordance with the REACH Regulation).

- Products and packaging containing plastics should contain information on the proper disposal of the materials.

» Emissions from industrial wastewater can be effectively reduced by a combination of internal prevention measures (no direct discharge) and adapted cleaning technologies.

» In the case of textiles made of synthetic fibers, all stages of processing must be optimized. Fiber abrasion, fiber breakage and airborne fibers due to exposed cut edges must be minimized by selecting high-quality fibers and manufacturing processes.

» It is recommended to pre-clean textiles prior to processing in order to remove excess fibers. However, pre-cleaning should be performed only where adequate wastewater treatment is available in accordance with Western European standards to ensure that the fibers are actually retained.

» When designing and implementing innovations, the entire value chain must always be taken into account to ensure that environmental benefits at one point (e.g. product packaging) are not offset by drawbacks elsewhere (e.g. transport packaging). [2]

» A plastic emissions budget - similar to the 1.5° degree climate target - could be introduced at national or EU level. It is calculated from the concentration in the environment and the natural degradation rate. Since the levels of plastics in the environment are only vaguely known at present, the plastic emission budget cannot as yet be determined with any degree of certainty. While it still needs further development, it could serve as a reference standard in the future if officially introduced.

Further Research:

» To what extent can producer and retailer responsibility contribute to reducing littering?

» Which simplified models can be applied to reflect harmful plastics emissions into the environment as well as degradation rates in different environmental compartments in life cycle assessments?

» How can manufacturers design and produce products containing and emitting reduced amounts of microplastics?

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06 Still insufficient: waste management and recycling

A true circular economy for plastics is crucial not only to reduce the environmental impact of plastics, but also to save fossil raw materials. To achieve this the interaction of plastic waste collection, sorting and recycling is of great importance.

Findings:

» Inputs of plastics into the environment throughout waste collection occur, on the one hand, during the collection of domestic light packaging via "yellow bags" and, on the other hand, during the placement for disposal and emptying of residual waste garbage cans. Other sources of emissions are landfill collection points and municipal waste collection containers.

» If plastic products are disposed of or returned to the economic cycle, incorrect handling can likewise result in inputs into the environment and/or poor recyclability.

» The current standard of sorting technology still has considerable deficiencies in distinguishing between food and non-food packaging, between single-layer and multi-layer films, and in separating material subclasses such as PET trays and PET bottles. For more efficient processing and high-quality recycling, however, single-variety and specified fractions are necessary. This holds true not only for plastic packaging, but also for other plastic items (e.g. automobiles, textiles, and white goods such as refrigerators).

» Sortability and recyclability in particular are of great importance in the ecological evaluation of various packaging alternatives. Material mixtures that are difficult to separate can, in principle, be technically recycled, but the effort required to do so is currently still too high.

» Tracer-based sorting enables labels, prints and materials such as plastics to be directly equipped with a material-independent recognition feature (e.g. fluorescence tracer) to improve the sorting of waste. Tracer detection works independently of the shape, design, deformation and movement of the marked objects. As a result, even small, non-printed, black, flexible and multi-layer packaging, for instance, can be detected with a high degree of reliability and forwarded for recycling.

The use of tracers proves to be beneficial for the environment in a life cycle assessment compared to current packaging recycling. [1]

» As an addition to already established recycling processes, modern chemical recycling processes can contribute to higher recycling rates. The use of complex waste streams in particular, which have so far only been thermally recycled, may help to tap valuable resources.

» The revolPET® technology enables the recycling of PET-containing waste streams that currently cannot be recycled (complex composites and mixtures). PET is selectively depolymerized and the monomers thus obtained have the same quality as virgin materials from fossil sources and can be re-polymerized to PET. Other materials such as PE, PP or PA pass through the process unchanged and can be fed to further recycling processes.

» Polystyrene (PS) can be usefully recycled from PS waste streams by means of a depolymerization process. This process for generating styrene for the subsequent re-polymerization into polystyrene offers ecological and economic advantages.

» Initial life cycle assessments of the developed recycling processes have shown that, compared to conventional production routes of monomers from fossil raw materials, the innovative recycling technologies have reduced energy requirements and result in fewer CO_2 emission equivalents; the consumption of water and fossil raw materials is also lower. [2]

» A new ship-based recycling plant concept with the capacity to recycle approximately 64,000 tons of mixed plastic waste per year has been developed. This concept would be fully financed by the revenue generated from the recyclates. The purchase of plastic waste, pre-sorting near the port, and the maritime recycling facility would create approximately 1,500 jobs and additional value in, among other places, western Africa. [3]

Recommendations:

» Waste collection in Germany requires further innovative conceptual and technological advances in order to optimize collection qualities and reduce environmental losses. Examples include the expansion of separate collection systems for particularly high-grade plastics, using deposit systems where appropriate, the switch from bags to garbage cans in the collection of domestic light packaging, and sensor-supported control mechanisms in the collection process to reduce misdirected waste, such as in the collection of organic waste.

» Since purely organizational measures (e. g. garbage cans instead of bags) and a minor enhancement of existing technologies (e.g. near-infrared sorting) are not sufficient to substantially increase the actual recycling rate in packaging recycling, all stakeholders in the value chain must introduce real innovations and coordinate them with one another: Design-for-Recycling, consistent collection, precise sorting into all the distinct fractions, and innovative, CO_2-efficient processing technologies.

» Tracer-based sorting offers a comprehensive technical solution for a much more efficient sorting of all plastics and should therefore be used more widely.

» The technical and environmental advantages of both the revolPET® and ResolVe processes justify legal recognition of chemical recycling to meet the recycling quotas of the Packaging Act. [4, 5, 6]

» The implementation of new recycling technologies must encompass the entire value chain, from materials development and marketing to the waste management industry. Accompanying technical and legal regulations should support the market entry of innovative processes.

» The social and legal pressure to reduce waste exports demands the creation of a value-based circular economy and to use appropriate technologies. Plastic waste exports must be prevented as much as possible by building recycling capacities for high-quality and efficient recycling in the European producer countries, thus reducing inputs to the environment via secondary countries with poor waste management systems and recycling structures.

» Even if recycling does not directly reduce plastic inputs into the environment, consumers associate the recycling of plastics with a higher value of the material. This change in perception can help reduce the careless discarding and littering of plastic waste. At the same time, high-quality recycling can help reduce the use of primary raw materials for plastic production.

Further Research:

» Improving the availability of data for life cycle analysis to map the value chains in the circular economy and existing recycling processes.

» Closing the data gaps e.g. regarding technology readiness level, the integration into an existing site infrastructure and the degree of optimization compared to established production technologies.

» Promoting pilot plants on an industrial scale to demonstrate innovation, technological performance and economic viability and to expand the data base and increase market penetration.

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07 How municipalities can help reduce plastic emissions

Municipalities are the level of government closest to citizens. As such, they are in the best position to communicate government action and to take up, set and pass on impulses. In Germany, a number of municipalities have already developed their own strategies for the avoidance of plastic waste, incorporating the ideas of the Zero Waste or Circular Cities initiatives. Some municipalities even officially label themselves as zero-waste municipalities.

As a result, municipalities are acting both as agents who pass on regulations and ensure that they are implemented, and as stakeholders who are called upon to adapt their practices to make them ever more sustainable in their capacity as disposal agents, consumers of plastics, operators of public facilities, and organizers of a wide range of events, markets, etc. in urban areas.

Findings:

» There are numerous sources of plastics emissions in municipalities. The main factors influencing the volume of (plastic) waste generated in public spaces are (i) the type and intensity of building development, (ii) the economic structures of industry, commerce and the gastronomy sector, and (iii) municipal structures, especially with regard to street furniture (bus stops, etc.), the type of waste collection and street cleaning. In addition, there are temporary sources such as community-specific events (Christmas markets, carnival parades, public festivals, etc.), New Year's Eve fireworks and construction sites.

» Municipalities are primarily affected by plastic emissions in public spaces due to littering. The most relevant plastics are packaging and cigarette butts, which each account for one third of all macroplastics emissions, and building materials - especially polystyrene foam - which account for an average of 50%

of large microplastics (1-5 mm). In Germany, the cleanup costs for the collection and disposal of littered single-use plastics covered by the EU Single-Use Plastics Directive amount to nearly 760 million euros annually. [1]

» Municipalities can act immediately to prevent plastic waste or littering from causing problems in the first place. This saves disposal and cleaning costs and prevents inputs into wastewater and the environment.

» Tire abrasion is one of the largest sources of small microplastics (< 1 mm) (see chapter 1). In inner-city streets, solids and tire wear mainly accumulate within 1.6 meters of the curb. Tire abrasion hot-spots are street corners, traffic lights, and other traffic signal installations. The prototype of a digital GIS-based planning and decision-making tool was developed in order to implement tailored measures to reduce the input of tire abrasion into the environment. It facilitates the creation of potential/hotspot maps and suggests appropriate measures. It can also serve as a basis for general drainage planning. [2]

» Plastics are discharged into wastewater at a wide variety of locations, both via rainwater runoff (storm drains) and via wastewater in buildings *(see chapter 3)*.

Recommendations:

» A variety of scientific approaches should be used to identify problems within individual municipalities and to develop solution strategies that are acceptable to the affected stakeholders.

» Although the options for municipal measures and their scope are limited in the German multi-level federal system, municipalities have a number of options at their disposal to influence trade and commerce, companies and citizens to reduce the use of plastics.

» Municipalities should combine different measures (downstream and upstream) and involve all stakeholders. Raising awareness and providing all stakeholders with information are the key to achieving this. Financial incentives, for example in the form of packaging taxes or subsidies, are also conceivable. Finally, regulations such as bans on single-use plastic (packaging) can be stipulated in statutes, for example for weekly markets or public festivals on municipal grounds.

» Requests from municipalities to other policy levels should be given greater consideration.

Recommendations for reducing plastic inputs into the environment:

» Implement technical and organizational solutions systematically (e.g. waste collection, cleaning of street drains), in particular at local input locations identified as particularly relevant (e.g. in the vicinity of street furniture, plastics industry operations or construction sites).

» Establish measuring points at tire abrasion hotspots to monitor input quantities and properties of street sweepings and identify appropriate measures on this basis (e.g. installation of filters, optimization of street cleaning). Identifying measures to reduce the input of street sweepings into the sewer system with areal GIS-based planning tools, especially in catchment areas with separation systems and direct discharge into a water body.

» Investigate whether a 1.60-meter curb margin can be created (temporarily) during street cleaning in order to make the corresponding areas accessible for cleaning.

» Identify potential uses for smart city approaches in the digitization of waste collection in private and public spaces, for example through the use of garbage can level sensors to ensure that garbage cans are emptied as needed.

Recommendations for avoiding plastic (waste) at the municipal level:

» Draw up guidelines and issue directives with the aim of low-waste and low-packaging pub-

lic procurement (Green Public Procurement) in municipal departments and facilities (e.g. canteens, kindergartens and schools) as well as municipal enterprises and place a clear focus on waste avoidance in municipal departments, e.g. through education, appropriate fee structures and embedding in municipal statutes.

» Intensify outreach campaigns for the avoidance of plastic waste, e.g. by organizing events, publishing sustainability columns in municipal gazettes, or providing zero-waste guides.

» Develop and make available information material on the correct disposal of waste that is tailored to the relevant collection system. If necessary, the material should be multilingual and aimed at specific target groups.

» Establish training events and participation formats such as round tables and the like between the municipality, trade, commerce and NGOs with the aim of developing a low-waste product range.

» Consulting services for regional companies on how they can create industrial symbioses (material waste or residual materials from one company being used as raw materials by another) and develop joint approaches to avoid waste flows.

» Create ecologically innovative framework conditions that expand the range of options available to municipalities (e.g. for greater regionalization of economic cycles) and strengthen regional and local logistics chains to shorten the delivery routes of goods to retailers.

» Support companies offering low-packaging products, e.g. grocery stores that do not use packaging, in establishing themselves; this includes appropriate regulations and incentives in leases, rental agreements and ground leases, as well as tax reductions in the future, if necessary.

» Establish and expand regional multi-use systems (industry-specific or cross-industry), especially in the area of packaging (sales and transport packaging). Moreover, establish infrastructure to avoid single-use plastic containers, such as public drinking fountains and refill stations.

» Promote ecologically beneficial modes of transportation (such as cargo bikes) in the neighborhood to avoid traffic-energy rebound effects caused by shopping behavior where longer distances must be traveled so as to consume fewer plastic products.

» Recognize good practices, develop a common (possibly regional) marketing label, and develop and disseminate appropriate guidance for consumers on product and packaging selection in the retail sector.

Further Research:

» What is the potential for optimizing and reducing waste streams containing plastics at the municipal or regional level, and how can this potential be tapped?

» How can synergy potentials be activated at the municipal level, e.g. plastic avoidance in connection with climate protection activities?

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08 Limited options: How much influence do consumers have?

Frequently, media communication and political measures to reduce plastic inputs into the environment focus on private consumers. This is insufficient, as their scope for action, i.e. their actual impact, is severely limited. In addition, other groups of actors (including commercial and public actors as well as other organizations) use products and packaging containing plastics and can therefore also be classified as consumers.

Findings:

» **Plastic inputs into the environment** are partly due to incorrect handling of products, resulting from ignorance or convenience. However, some emissions are unavoidable, for instance when plastic-containing products are designed in a way that particles detach unnoticed during use and end up in the environment. [1]

» Overall, consumers are highly aware of the environmental impact of microplastics. However, their own contribution to the input of microplastics is only known in relation to certain product groups and their scope for action is rated very unevenly depending on the product group.

» In general, all consumers can contribute to plastic prevention by (i) choosing alternative purchasing practices (e.g. buying unpackaged products), (ii) buying optimized products (e.g. with regard to packaging), (iii) using multi-use systems, (iv) considering regional socio-ecological supply systems and economic cycles, and (v) disposing of plastics correctly.

» However, the necessary knowledge, the appropriate supply of goods and infrastructure, and disposal options are often lacking. [2] Thus, the consumers' only possibilities for action are when it comes to purchasing products, their use phase and their disposal. The only other possible action is protest..

» A change in product demand by consumers alone does not suffice to stimulate companies to make plastics avoidance a key task in their product design *(see chapter 5)*.

» Additional information on products (e.g. on correct disposal) does not automatically lead to "correct", environmentally conscious behavior on the part of consumers. At present, many products and packaging are cluttered with information to the point where consumers are unable to take in everything. This has been shown in studies on the effectiveness of labels with more than 1,000 participants. [3]

» Existing (national and international) **regulatory approaches** (e.g. the EU Single-Use Plastics Directive) are strongly targeted at private consumers and are not sufficient in light of their limited influence. [4]

» Innovative pioneers, such as zero waste stores, are trendsetters who provide social impulses. As such, they are a key element in reducing plastic consumption along the entire value chain. [3]

» The existing contradictions between "perceived" sustainability from the consumer's point of view and calculated life cycle assessments make it clear that there is a lack of specific, easy-to-understand and easy-to-implement suggestions that address side effects and challenges to sustainability and establish a connection to current economic structures.

» Opinions expressed by school graduates show a considerable **lack of knowledge** on the subject of microplastics. [5] In addition, the topic has hardly been included in curricula and is not yet part of teacher training. Even university students feel poorly informed about the issue, but are very concerned about the potential risks to their own health, the health of future generations and the environment. [3]

» A change in the use and disposal practices of consumers is most likely to occur when, as in the case of cosmetic products, a direct effect resulting from the consumer's behavior is evident or can be conveyed, and when practicable alternatives are available.

Recommendations:

» A comprehensive and binding legal framework is needed to ensure the reduction of plastic inputs into the environment throughout the life cycle. This requires a **mix of regulatory instruments** designed to provide clear corridors of action for both manufacturers and consumers *(see chapter 5)*. This mix should include (i) direct regulatory instruments (bans and requirements), (ii) economic instruments that address socio-ecological consequential costs, and (iii) measures that strengthen consumers' motivation and decision-making capacity. These must be designed in such a way that they incorporate findings from behavioral science research on key factors influencing the choices and behavior of the various plastic-using actor groups. [6]

» Effective regulation of environmentally friendly product design must start with the manufacturers of (plastics) products and aim at aviodance [7], since consumers can only choose from the products available on the market *(see chapter 5 and chapter 10)*. This also applies to environmental inputs that are **unavoidable** due to product design.

» Substantially strengthening environmentally friendly decision-making skills of all segments of the population should be encouraged in the spirit of **lifelong learning**. For this purpose, a solid foundation of interdisciplinary knowledge should be built throughout the school curriculum, which is then further developed in the course of vocational training and professional education, and integrated into the organization of the workplace.

» The educational materials currently available on the subject of (micro-) plastics should be made systematic use of, e.g. in educational institutions.

Further Research:

» How should reusable solutions, packaging and infrastructures be designed for the various sectors of goods (products and packaging) so that consumers are able to make decisions in the interests of sustainability?

» Which framework conditions are necessary to ensure correct and appropriate waste disposal by consumers at all times?

» Which direct and indirect incentives (e.g. information, economic or motivational instruments) are effective in preventing consumers from releasing plastic waste into the environment?

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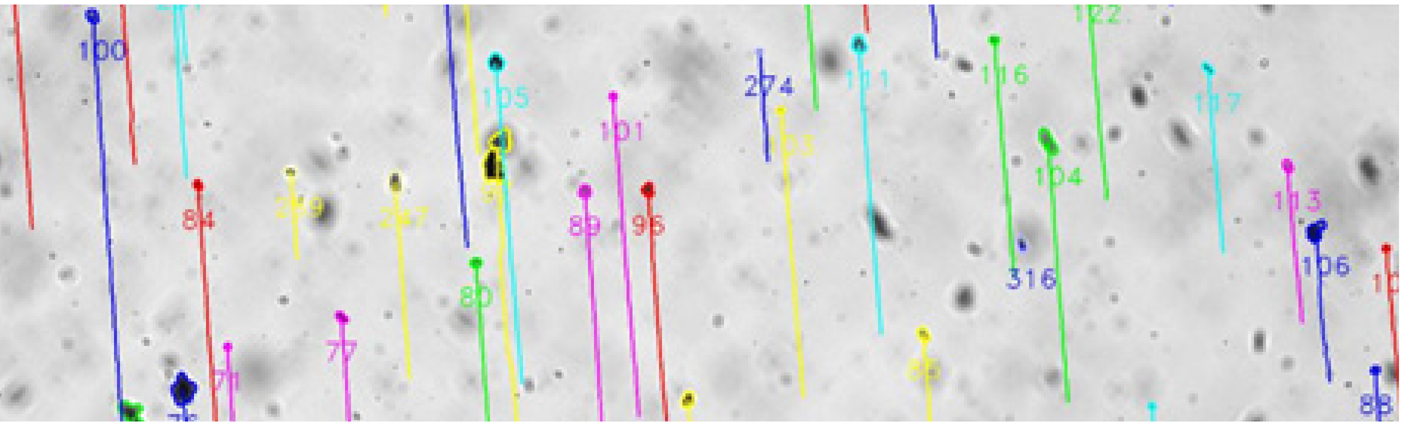
09 Significant progress in microplastics analysis



The majority of studies on microplastics focus on their occurrence in aqueous media. Other media were also considered, but were not the main focus *(see chapter 4)*. Many of the results obtained either already found or are now finding their way into international and European standardization *(see chapter 10)*.

The analysis of microplastics consists of the following steps: sampling, sample preparation and detection. All process steps are interconnected, affect the analytical result and cannot be considered separately. The selected sampling procedures vary depending on the investigation objective, environmental medium or material and must be representative. Sample preparation converts the collected field sample into an analytical sample. The detection methods differ according to the parameters to be investigated.

Analytics:

» Detection

On the one hand, there are detection methods that measure the polymer type, particle number, particle shape and size/distribution, as well as the specific surface structure of the particles in environmental investigations. Spectroscopic/imaging techniques such as micro (Fourier Transform) Infra-red spectroscopy (µ-FTIR), micro-Raman spectroscopy (µ-Raman) or micro-near-infrared spectroscopy (µ-NIR) have proven effective in this method. On the other hand, there are detection methods that can be used to determine the polymer and mass contents in environmental matrices. These include thermoanalytical/integral methods such as pyrolysis or thermal extraction-desorption gas chromatography/mass spectrometry (Py-GC/MS, TED-GC/MS).

Spectroscopic methods identify different plastics on the basis of vibration spectra, which vary depending on the polymer. Thermoanalytical methods detect the mass content of different polymers using specific fragments of the thermal decomposition. In addition to these detection methods, light or electron microscopic methods can be used in specific cases to determine particle numbers/sizes, for instance in samples from laboratory experiments with known polymers. Alternative methods, such as calorimetry or elemental analysis, may also be used for specific types of microplastics.

Attenuated total reflection FTIR spectroscopy (ATR-FTIR) or near-infrared spectroscopy (NIR) are particularly suitable for characterizing macroplastics.

» Sampling

Sampling is usually standardized. This means that defined procedures are used for the individual environmental compartments (soil, air and water). However, there are no validations for microplastics to date, while for macroplastics there are not even recommendations.

Plastic particles can be found in the environment in various densities, sizes and shapes. Some of them are also present in agglomerates, for example as components of floating, suspended or sedimentable materials. Depending on the number of substances containing microplastic particles in the aqueous system under investigation, and in order to collect sufficient quantities (representativeness), very large sample volumes may have to be taken for random sampling. The solids are then recovered by fractional (pressure) filtration or centrifugation. An alternative is continuous sampling by means of passive samplers.

» Sample preparation

The aim of sample preparation is to create optimal conditions for measuring and subsequently evaluating a sample. The plastic particles contained in a sample or the amount of plastic must not be changed by the preparation steps. [1] For spectroscopic detection methods, inorganic impurities are usually removed by means of density separation, while organic impurities are removed chemically or enzymatically. Thermoanalytical methods often require less complex sample preparation - or no sample preparation at all.

» Contamination and blank values

Plastic is ubiquitous - even in laboratories, where tiny plastic particles can be found in the air. It is therefore important to determine identically processed blank values. In this way, the analysis results can be corrected for possible foreign contamination. Particularly in the case of very low plastic particle contents in the sample, blank values are decisive for the quality and significance of the analysis.

A number of laboratory materials and chemicals are not specifically designed for the analysis of plastic particles. In many cases, they have come into contact with plastic materials during production or storage, directly or indirectly, e.g. via the ambient air. Therefore, chemicals have to be purified (e.g. filtered), and equipment or filter materials have to be rinsed or annealed with filtered solutions. Field and laboratory work should be carried out with a maximum reduction of potential sources of contamination, for instance by avoiding clothing containing or made of synthetic materials, immediately covering samples with glass or aluminum foil, and working under a laminar flow box in the laboratory.

» Framing of analytical methods

To meet the requirements of monitoring and regulatory agencies, measurements must be robust, cost-effective, time-efficient and routinely applicable. Methods that continuously collect samples to determine total contents are particularly suitable for this purpose. For other target groups or in risk assessment for the environment and human health, particle numbers, sizes and shapes as well as the polymer type of a particle are relevant. Among other areas, this applies to research, the medical sector and plastic contents in foodstuffs. Single samples in combination with (high-resolution) spectroscopic detection methods are particularly suitable in these cases. However, such samples are usually associated with an increased time and measurement effort. Particle number results should not be converted into mass contents or vice versa. Here, standardizing assumptions on particle volumes are a major source of error, since the variety of shapes of plastic particles in environmental samples ranges from fibers to irregularly shaped particles.

Standardization & Reference Material:

The standardization of methods for sampling, sample preparation and detection is of central importance for the analysis of microplastics. Standardization includes the development and application of microplastic reference materials. The specific properties of the reference material must be adapted to each of the three analytical steps (sampling, sample preparation, detection) and to the respective problem. In addition to the matrix in which the microplastic particles are embedded, polymer type, shape, size, aging condition and mass must also be adapted accordingly.

First microplastic reference materials have been successfully developed. Based on these materials, a comparative test for the detection of microplastics showed that both thermoanalytical and spectroscopic methods are suitable for identifying microplastics and quantifying them with sufficient accuracy. [2]

Further Research:

» **Development of practicable methods for macro-, micro- and nanoplastics, which allow for a high sample throughput and are applicable in different environmental media and ecosystems (water, soil, air, biota) and which form the basis for long-term monitoring concepts.**

» **Validation of the methods with the help of realistic microplastic reference materials to support the harmonization and standardization of the methods.**

» **Uniform recommendations for the sampling of solids and atmospheric samples as well as standardization of macroplastic analyses. [1]**

» **Further refine detection in the lower micrometer range as well as in the nanoscale, e.g. based on the combination of field-flow fractionation and μ-Raman spectroscopy.**

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10 Legal recommendations for reducing plastic emissions

A legal framework is essential to effectively reduce inputs of plastics into the environment. However, due to the number of relevant plastic products, the multitude of potential input pathways *(see chapter 1)* and the different (environmental) goods affected, formulating legal measures is a complex task. For this reason, solutions should not only address the direct input of individual products or the material itself *(see chapter 8)*, but also take into account manufacturing, packaging, product design, reuse and recycling, as well as use and consumer behavior. [1]

To create an adequate legal framework, technical-conceptual expertise is necessary. This includes, in particular, the development of analytical methods (sampling, sample preparation, detection) *(see chapter 9)* to reliably detect microplastics in water. These methods now form the basis of international and European standardization projects. As soon as the technical standards for the analysis of microplastics are available, they can be used to establish legally binding levels.

Findings:

» Since around 90% of German environmental legislation is now based on European requirements and plastics pose a global threat, international and European recommendations in particular are taking center stage. However, national or local solutions can also contribute to a reduction of plastics emissions into the environment. The solutions discussed here represent a selection of the most important efforts to date.

International level

» The 2015 Paris Agreement's "zero fossil fuel" target under international climate law (Art. 2 para. 1) can also provide a key framework and objective for the regulation of plastics: This would mean that the main raw material for plastics production would no longer be used within a short period of time, within a period of maximum two decades. This general target provides an ecological framework prior to all other detailed considerations. It covers not only individual plastics, but fossil-based plastics as a whole.

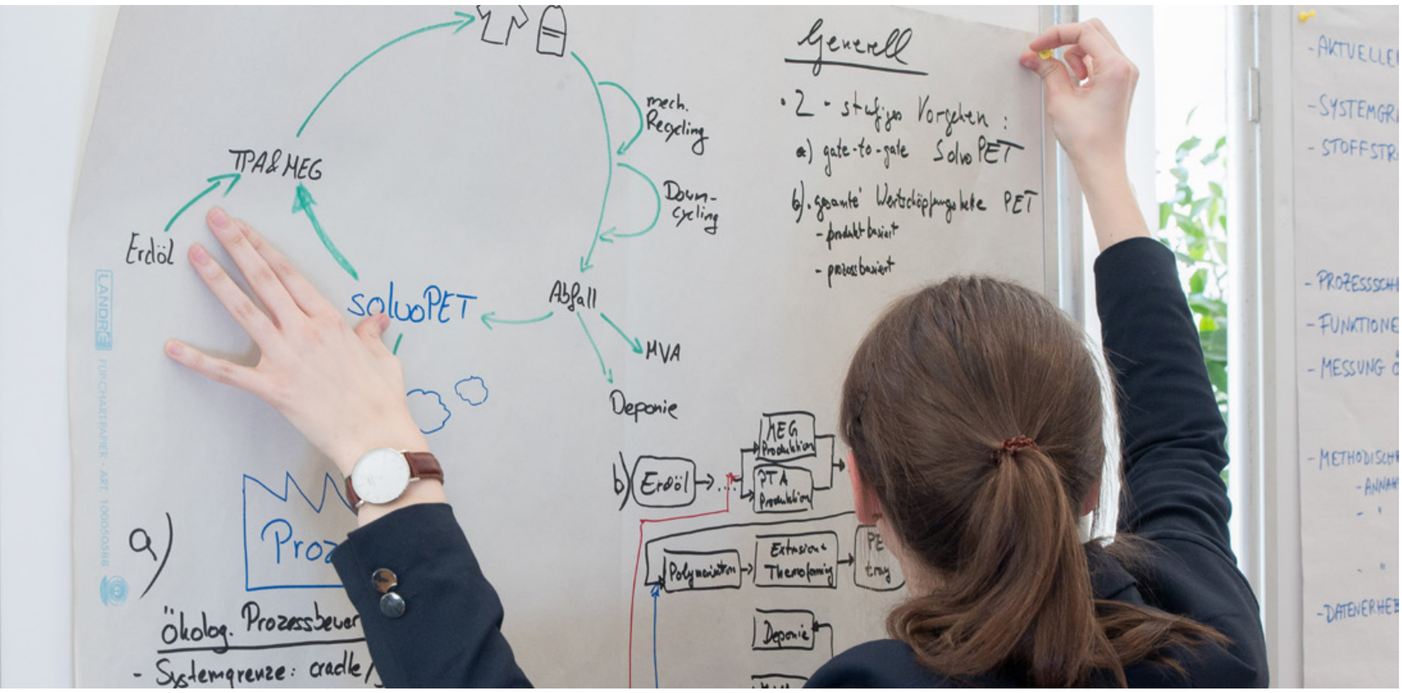
» Germany was one of the first countries to make an international commitment to reduce the discharge of persistent plastics into the oceans as part of the concept for healthy oceans and seas and resilient coastal communities adopted at the 2018 G7 summit in Charlevoix. The commitments adopted at this meeting have been taken up in principle by the United Nations Environment Assembly (UNEA). A resolution was adopted in Nairobi on March 2, 2022, to conclude a multilateral agreement against plastic waste by the end of 2024.

» So far, there is no international agreement on plastics - except for the Basel Convention on the Shipment of Hazardous Wastes and, since 2019, also hazardous (polluted) plastics. there is still no global agreement on plastics. However, out of 193 UN members, 146 countries have already introduced national regulations on plastic products, including plastic bags, single-use plastic products, and even microbeads [2]. However, it is difficult to find common ground in these different national regulations beyond efforts to tackle a wide range of plastic products, because the motivations for the regulations and their implementation differ widely (e.g. the regulation of plastic bags [3]).

The European level

» The European plastics strategy of 2018 and the Green Deal of 2020 set an initial European framework for dealing with plastics. It is further specified with the help of various regulations and directives, through which the member states are given regulatory leeway in their implementation.

» A large number of EU regulations is suitable for the implementation of requirements to reduce plastic inputs into the environment: the EU Fertilizer Regulation, the Single-Use Plastics Directive, the Waste Shipment Regulation, the delegated acts of the Eco-Design Directive and the Drinking Water Directive. The issue of plastics will also be addressed in the 2022 revisions of the Urban Wastewater Directive and the Sewage Sludge Directive.



» Between fall 2021 and spring 2022, the European Commission has initiated and conducted two public participation projects to help define measures to reduce the unintentional release of microplastics from tires, textiles and plastic granulate into the environment and to regulate the handling and use of biodegradable plastics. Policy frameworks on bio-based and biodegradable plastics are to be published in the third quarter of 2022 and the results on the release of microplastics are to be included in a proposal for a regulation in the fourth quarter of 2022. In addition, the Commission has a proposal from ECHA to place certain plastics under the European chemicals legislation REACH.

» The EU's Single-Use Plastics Directive regulates selected products and packaging (individual single-use plastic products such as plastic tableware and cutlery, plastic bags). It obliges member states to take a variety of measures with regard to these products, such as marketing restrictions, consumption reductions, product requirements and labeling, separate collection, consumer information and education, and the introduction of extended producer responsibility, which also includes the costs of clean-up campaigns.

» Studies have shown that the regulations are not sufficient because significantly more and different plastic-containing products and packaging (including plastic pellets) are introduced into the environment by different actors. They have also shown that information and education measures only have a very limited effect. [4]

» Similarly, the extended producer responsibility only has a limited effect. Although cleaning measures can reduce the input of macro-plastics, they have only a selective and minor effect given the diversity and volume of environmental inputs (see chapter 1). Effective approaches should therefore aim to reduce or avoid plastic inputs into the environment from the outset. To this end, all input pathways of plastics into the environment should be systematically analyzed and taken into account in regulatory terms (one possible starting point is, for example, stricter requirements for product design).

National level

» The majority of the requirements of the Single-Use Plastics Directive have been directly adopted in Germany, although the extended producer responsibility has not yet been fully implemented.

» The analysis of fertilizers derived from secondary raw materials - which are a source of input to the soil - shows that the existing analytical procedures pursuant to the Biowaste Ordinance for the quality assurance of composts and digestate are not sufficient to determine the total load of plastic inputs.

Conclusion

» Although the many activities at the various levels of action represent important starting points, the existing regulatory requirements and rules are not yet sufficient. This is because they only address individual aspects of plastic discharges and lack a knowledge-based, comprehensive conceptual approach.

Recommendations:

The international level

» The German government should play a decisive role in the upcoming UNEA negotiations on a legally binding convention against plastic pollution. In addition, German participation in international initiatives at the G7 and G20, the World Health Organization (WHO) and the OECD should be intensified and comprehensive and binding solutions should be sought.

» In addition, Germany should take into account the ongoing work of the international and European standardization organizations (ISO and CEN) on the development of methods and recycling concepts, and provide greater support than hitherto in order to accelerate the submission of the necessary standards. Furthermore, the German Institute for

Standardization (DIN) should exert influence on ISO to ensure that the technical committees, which currently have a strong sectoral structure and are active in the field of e.g. analytical plastics properties, technical plastics, elastomer products and/or biodegradable materials, bring their work together in a cross-sectoral technical committee. This is the only way to avoid the currently anticipated uncoordinated mix of different, sometimes unsuitable methods.

» It is furthermore desirable to support the work of global regional organizations such as the African Union, the Association of Asian Nations (ASEAN), the Asian Pacific Association (APEA) and the South American alliances in the field of plastics regulation.

The European level

In the upcoming revisions of the EU directives, Germany should ensure that high standards for the prevention of plastic discharges are set. More specifically, the following is suggested:

- EU Municipal Wastewater Directive: anchor requirements for wastewater quality with regard to plastic loads and microplastics for the areas of combined sewer overflows and stormwater.
- Revision of the EU Sewage Sludge Directive: specify requirements for the total content of plastics in analogy to secondary raw material fertilizers *(see chapter 4)*.
- Packaging Directive: include concrete requirements for the reduction and avoidance of (plastic) packaging and requirements for necessary plastic packaging (e.g. recyclability), further strengthen the use of reusable alternatives and pay attention to substitution movements, which may in turn be associated with other environmental consequences.
- Waste Framework Directive: supplement with regard to the handling of plastics and align with the prevention requirement in this respect.
- The Marine Strategy Framework Directive has introduced the input of (plastic) waste into the oceans as an indicator for assessing "good environmental status". An equivalent approach is required for the Water Framework Directive and, derived from this, the development of national monitoring and action programs.
- EU Drinking Water Directive: in order to monitor microplastics in the risk assessment of drinking water quality from 2025, the standardization bodies working on this should be supported in presenting a methodology for measurement and monitoring.
- Compulsory declaration of the composition of plastics and added additives along the entire value chain is necessary to provide all stakeholders with information on the content of plastics and to provide a basis for related legal regulations.

The national level

» A National Plastics Strategy needs to be formulated that takes up the approaches of the EU plastics strategy and the Green Deal, but goes beyond them in terms of content and structure. This would help close any gaps in EU legislation. The plastics strategy should cover the entire life cycle of plastics and take into account the heterogeneity of the relevant actors, processes, products and entry pathways.

» The National Plastics Strategy should be used to develop a "Plastics Master Law" containing legally binding, overarching framework conditions and requirements for the handling of plastics. This would form the basis for adapting existing legal regulations and introducing new ones. It should also include general (reduction) targets as well as principles and requirements for the (sustainable) handling of plastics. It should furthermore address the most comprehensive circular management of plastics possible and, finally, establish binding mechanisms and specifications for the development, implementation, review, reporting and updating of the measures required for the handling of plastics.

Based on the "Plastics Master Law", the regulations in specialist laws and non-legislative standards on plastics must be adapted, supplemented or revised.

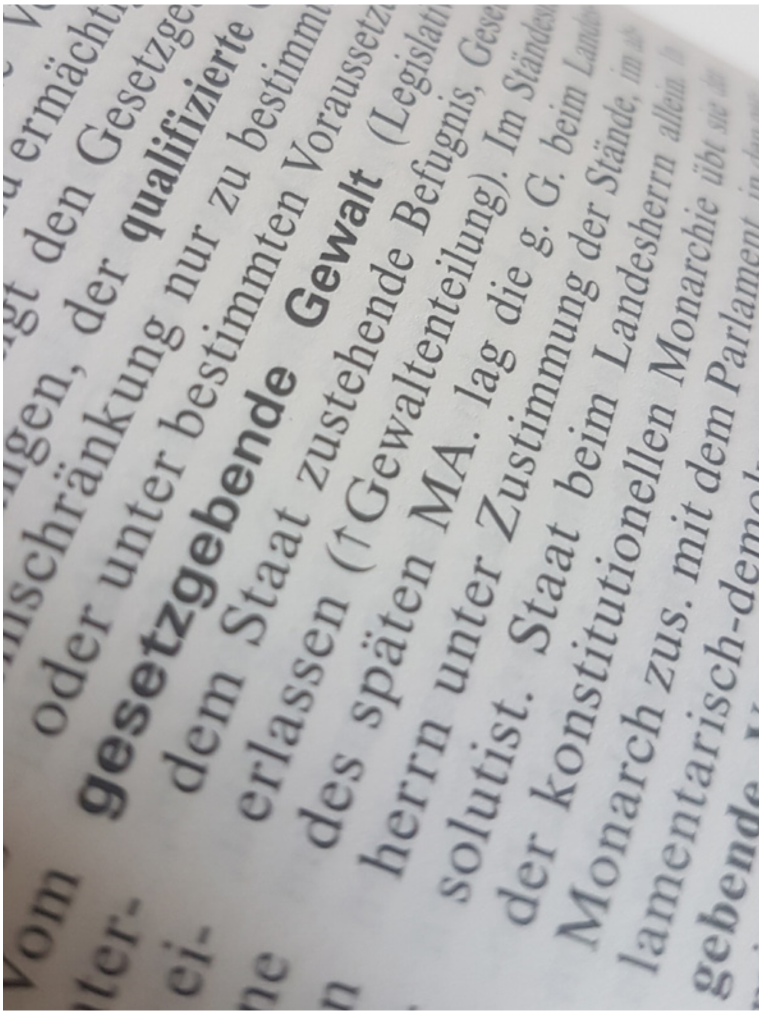
» The Federal Soil Protection and Contaminated Sites Ordinance is a concrete starting point for this. Here, work can begin directly on deriving precautionary values - defined as total contents - for plastics in soils to set an upper limit for further inputs.

Further Research:

» The data and information base for future legal regulations must be expanded. This includes solutions that legally address conflicting targets in the handling and recycling of plastics (e.g. hygiene aspects in the food sector through recycled content, mandatory high-quality recycling quotas).

» Which legal regulations need to be anchored in a binding international agreement in order to contribute to the reduction of plastic generation and input?

» Which environmental media-specific assessment concepts are suitable for setting limit values - and how can corresponding monitoring concepts be developed?



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Conclusion

Research has come a long way – but much remains to be done

The aim of the research focus was to investigate the input, distribution and effects of plastics in the Environment and to obtain an overall picture of the occurrence and behavior of plastics along their entire life cycle.

The joint research projects have made a significant contribution to expanding our understanding of the sources and sinks of (micro-) plastics *(see chapters 1-10)*:

- Plastics enter the environment through various pathways. There, they are either transported further or accumulate in soils or waters, sometimes as barely visible microplastics. In addition to the ocean, soils are also significant sinks.
- The analysis of (micro-) plastics has led to new research challenges. Many of the resulting findings are now contributing to future standardization and subsequent monitoring concepts, as well as to the expansion of the measurement range to include nanoplastics.
- A large proportion of plastics is removed from wastewater in sewage treatment plants. However, not all rainwater and combined wastewater runoff is captured by sewage treatment plants. Sewage sludge is the sink for the microplastics removed in wastewater treatment plants. Its further utilization, for example in agriculture, leads to discharges into the environment.
- Measures to reduce plastic emissions in residential water management are associated with high technical and economic costs. As an end-of-pipe solution, such approaches can only accompany measures that address the production and use of plastic products.
- It has not yet been clearly proven whether microplastics have harmful effects on plants and animals. The different properties of microplastics determine whether and how microplastics are absorbed by living organisms and whether they are harmful to them. In addition, the effects of microplastics often cannot be clearly distinguished from the harmful effects of other particles and substances in the environment.
- In line with the precautionary principle, environmental policy should aim to minimize the input of plastics into the environment, since microplastics can potentially lead to adverse health effects for humans and the environment if they are exposed to them.

The research activities carried out in the Research Focus Area have expanded systemic knowledge as well as knowledge of complex interrelationships and mutual dependencies. This has created the essential prerequisites for identifying and implementing suitable solutions and measures to reduce and prevent plastic discharges into the environment in the future. At present, the following recommendations can be given:

- Comprehensive approaches are required, with prevention being the most important issue and companies playing a central role. These should be supported by a national innovation and conversion strategy to develop or introduce plastic-free or plastic-reduced and/or reusable, recyclable product and packaging alternatives.
- The scope for action and consequently the actual influence that private consumers can exert are severely limited. Even solutions based on quality seals, labels, etc. only have a limited effect due to the multitude of information consumers are confronted with and are only useful as complementary measures.

- Municipalities, being the closest level of government to the citizens, have a range of possibilities to influence trade and commerce, companies and consumers towards reducing the use of plastics, even if the options for municipal action and their scope are very limited within the German federal multi-level system.

- Waste collection in Germany must be further developed in terms of conceptual and technological innovation in order to optimize collection qualities and reduce losses to the environment. This also includes the sorting of (plastic) waste to enable more efficient processing and high-quality recycling.

- In addition to already established processes, modern chemical recycling processes can contribute to higher recycling rates. In particular, the use of complete waste streams that have so far only been thermally recycled helps to tap valuable resources.

- Effective recycling of plastics can increase the value of the material. Even if recycling does not directly reduce the amount of plastic entering the environment, it can reduce the amount of plastic waste that is carelessly discarded or left lying around. At the same time, high-quality recycling also means fewer (fossil) primary raw materials are used for plastic production. The social and legal pressure to reduce waste exports necessitates a value-based circular economy and corresponding technologies.

Overall, the findings and recommendations presented in this document highlight that the existing legal framework is insufficient and contains loopholes that need to be addressed at various policy levels. In the short term, the focus must be on consistent implementation of existing regulations. In the medium to longer term, however, existing laws must be revised and adapted. In addition, the project results point to the need to create a coordinated, binding and comprehensive legal framework in Germany that aims to reduce plastic inputs into the environment and goes beyond the current approaches of regulating individual products and input pathways.

Due to the thematic diversity of the projects and the broad social relevance of the topic, the results beyond these key messages are disseminated through various formats and transfer activities such as factsheets, thematic webinars, educational materials, guides, discussion papers, special issues/ magazine articles, (traveling) exhibitions and workshops.

An overview can be found at:
www.bmbf-plastik.de/ergebnisse.

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Chapter 01 Sources and pathways of plastics into the environment

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ISBN 978-3-937085-36-4