

Background

Plastic – radical rethinking needed



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Summary

Plastic is a ubiquitous material used in many areas of everyday life. Global plastic production currently stands at around 460 million tonnes per year.

Plastic has far-reaching effects on ecosystems and human health. During their lifetime, plastic products release greenhouse gases that contribute to climate change. In addition, many plastics are long-lasting (persistent) and difficult to break down biologically, which leads to their accumulation in the environment. Microplastic particles, which are generated when larger pieces of plastic break down and can be ingested by organisms, are particularly problematic. Microplastic particles are also found in many products.

Furthermore, plastics often contain toxic additives such as plasticisers and flame retardants, which accumulate in the environment and can cause long-term damage. They also pose a risk to material recycling, as the often unknown additives can be transferred to new products. The pollution of indoor air by plastic particles or the vapours emitted by plastics in furniture, textiles or floor coverings also poses a risk.

Another major problem is the inadequate and inefficient recycling of plastics, which often leads to a loss of quality and increases the amount of plastic waste in the environment.

CALLS FOR A RADICAL RETHINK

BUND is therefore calling for a radical rethink on the issue of plastics. The recommendations are set out in detail in Chapter 9. The key starting points and demands for a more sustainable approach to plastics are:

Limit the use of plastics

Before plastics are used, it must be examined whether they are actually necessary. They should only be used if they have a clear benefit for the environment and society. Applications without a significant purpose or with a short service life should be avoided as far as possible. Where possible, natural alternatives such as wood or natural fibres should be preferred – provided that they do not jeopardise biodiversity and food security through the land use required for their production. If plastic use is deemed sensible, it must be ensured that the material is as reusable as possible or can at least be recycled. Legal regulations must be developed for this purpose.

Limited number of standard plastics and additives

Clear standards are needed to achieve this goal: a limited number of environmentally compatible standard plastics with known additives should be defined and regularly reviewed across Europe so that such plastic products can be sorted properly and reused to a high standard after use.

Restrict short-lived applications and introduce a plastic levy

Legislation at national and European level must establish requirements that significantly restrict short-lived and potentially environmentally harmful uses. An authorisation procedure must be carried out for plastics with a service life of less than one year. The social benefits must be demonstrated, alternatives examined and a concept for recycling and absence of harmful substances presented. If a manufacturer does not meet these requirements, a plastic levy is payable in the context of extended producer responsibility, the amount of which is based on the degree of non-compliance.

Minimise plastics in agriculture and soil

Open plastic applications, such as mulch films or soil additives, must be minimised. The entry of microplastics and nanoplastics, especially through abrasion or decomposition of products, must be urgently reduced. The use of liquid or water-soluble plastics – especially hydrogels – must be significantly restricted, especially when they enter the environment directly.

Assessment and regulation of plastics and additives

Plastic products, especially those that come into contact with food or children, must not contain any harmful substances. In order to better identify risks, plastics should be comprehensively tested for their effects on humans, animals and the environment in the same way as all other chemicals

– including possible transformation products from additives or emissions.

Ban hazardous additives

Hazardous ingredients and additives must be banned unless there is a compelling social need for their use. Such derogations should only be granted for a limited period and reviewed regularly. To enable high-quality material recycling, the variety of additives must be significantly limited and a transparent list of permitted additives must be drawn up.

Manufacturer responsibility for the recycling of plastics

The responsibility for recycling lies with the manufacturer. They must ensure that the plastics used are recycled to a high standard after use. The use of recycled materials must be maximised in line with the latest scientific and technical knowledge.

Priority for material recycling

Material recycling is always preferable to chemical or thermal recovery or composting. Composting, pyrolysis and other thermochemical processes may only be used if avoidance, reuse and material recycling are not feasible. The remaining residues – including those from the recycling processes themselves – must be disposed of in an environmentally compatible manner and the spread of pollutants must be prevented.

Non-fossil raw materials and environmental assessment

In order to achieve the climate targets, plastics may only come from non-fossil sources once the remaining greenhouse gas budget has been reached. An independent environmental assessment should be carried out for all plastic product classes, taking into account not only their climate impact but also their durability and potential hazards.

Regulate and minimise microplastics

The production, use and placing on the market of primary microplastics should be banned. The release of secondary microplastics resulting from the abrasion or degradation of plastic products must be minimised throughout their entire life cycle. Particularly problematic releases of microplastics must be avoided at source.

Same requirements for bioplastics

All of the above requirements also apply to so-called “bio” plastics, as they are often not environmentally friendly.

Global plastics agreement with clear reduction targets

A global plastics agreement must cover the entire life cycle of plastics, contain binding targets for reducing plastic production, require effective waste management, set binding recycling quotas and regulate hazardous chemicals associated with plastics worldwide.

Transparency and safety for plastic products at international level

Safety and sustainability must be assessed in a uniform manner internationally before products are placed on the market. Companies must disclose which plastic components they use. Countries and regions that are particularly affected need financial and technical support. Independent scientific monitoring is necessary to review progress and avoid conflicts of interest.

Independent research on the environmental impact of plastics

There is still a great need for political action in the areas of research and education. Independent research into the prevention of environmental pollution, the development of less-pollutant alternatives and recyclable mass plastics must be specifically promoted – including with funds from a plastics levy.

Integrating the sustainability of plastics into degree programmes

Sustainable chemistry, product development, life cycle analysis and material flow management must be made compulsory subjects in higher education and training.

Education on the sustainable use of plastics

Schools and further education institutions should cover the responsible use of plastics. Curricula should be adapted accordingly.

Freedom of information and consumer information

Access to verified information on sustainability and harmful substances in plastics must be improved for consumers. Manufacturing companies must disclose the relevant data so that informed decisions can be made.

→ See also the detailed recommendations in Chapter 9.

1 Definitions Classification, significant material flows

1.1 DEFINITIONS

Plastics have been produced for over 100 years. They are chemically manufactured compounds that did not previously exist in this form in the environment. They are called plastics because of their plastic deformability. Global production of plastics currently stands at around 460 million tonnes per year [OECD 2022b].

Plastics consist of long chains of identical chemical building blocks that repeat themselves. These building blocks are called monomers. The chains that result from them are called polymers, because the individual building blocks occur many times (= poly).

The technical names of plastics therefore all begin with the word “poly”, followed by the chemical name of the individual building block (monomer). Polyethylene and polypropylene, for example, are the names of two widely used plastics.

Many plastics can be reshaped by heating. If these thermoplastics can be separated into different types, they can be recycled effectively. Plastic waste can be used to manufacture new products through a process known as mechanical recycling, which involves melting the plastic down. However, as different plastics are not very compatible with each other, high-quality mechanical recycling is only possible if unifor-

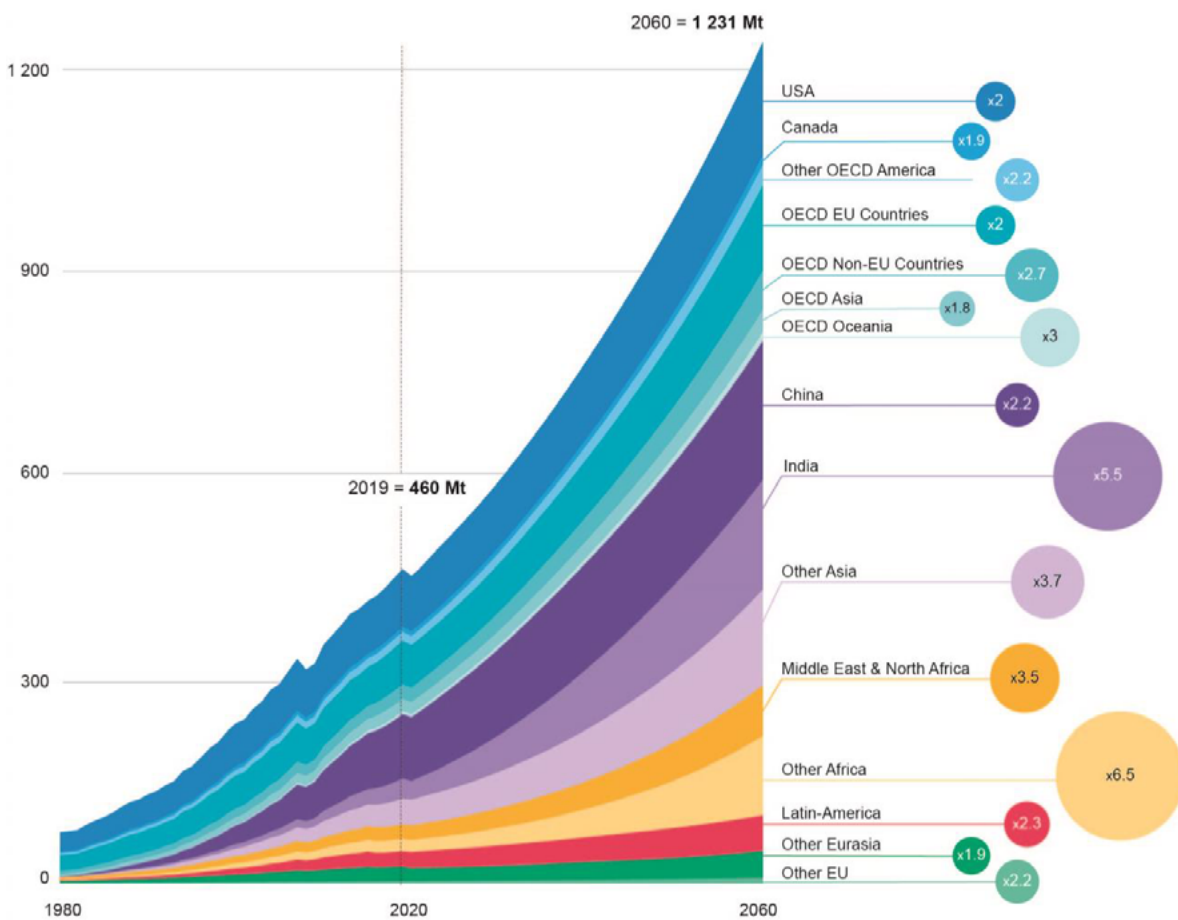


Figure 1: Global production of plastics [OECD 2022b]

mous polymers are used as the basis. Mixed plastics either cannot be used to make usable products or can only be used to make products of significantly reduced quality.

Some plastics can no longer be formed plastically after reheating. These plastics are called thermosets. They are usually formed when the long individual chains of the plastics used react with each other during processing, creating three-dimensionally cross-linked plastics or resins. This is the case, for example, with table tops, paints, some hard plastics and mattresses. The group of elastomers also cannot be melted after manufacture. Elastomers are also cross-linked by bonds between the polymer chains and are characterised by high elasticity. They deform elastically under load and return to their original shape when the load is removed. They are found in rubber bands, car tyres, sports floors and many other materials. Recycling by plastic deformation at higher temperatures is not possible for thermosets and elastomers. They decompose at a temperature specific to the respective plastic.

The most commonly used plastics, polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC), all have a continuous carbon chain. They differ in the side groups on these chains. Polystyrene contains aromatic groups and polyvinyl chloride contains chlorine. Polyethylene, polypropylene and polystyrene are often found in packaging, but also in bottles and other technical products. Polystyrene is also used to make insulation materials (trade name: Styrofoam). Polyvinyl chloride is used to make many construction products such as drain pipes and window frames. The caps on plastic bottles are also made of PVC.

The polyamide (PA) group, often known under the brand name nylon, is characterised by the fact that the carbon chain is regularly interspersed with nitrogen-containing amide groups. Polyamides are largely processed into fibres that are used in textiles for clothing, but also in fishing-nets, tents and parachutes. Polyamides are also used to make dowels, housing components and gear wheels.

Another important group of plastics is polyester. These contain oxygen-containing ester groups at regular intervals in the carbon chains. An important representative of this group is polyethylene terephthalate (PET), which is used to manufacture both textiles and beverage bottles (disposable and reusable).

In Germany, most plastics are collected as packaging waste or via the “yellow bag”. However, some plastics also end up back in the environment, as can be seen in parks, on roadsides, beaches and in rivers. When plastics are used directly in the environment, such as in car tyres, fishing nets, plastic tunnels or mulch film in agriculture, it is almost impossible to prevent some of the plastic from remaining in the environment. This happens because pieces break off and because most plastics quickly become brittle under the influence of sunlight, temperature fluctuations and mechanical abrasion, crumbling into smaller pieces, including microplastics and nanoplastics. Such applications that are exposed to the environment are therefore particularly problematic.

1.2 MAIN AREAS OF APPLICATION

Around 40% of the plastics produced in Germany are used in packaging. The packaging sector in particular offers a number of applications that could be entirely eliminated by selling loose goods or that could be replaced very well by reusable systems.

2 Particularly problematic polymers and applications

Some polymers are particularly problematic. This is especially the case when there are no equivalents for their structure in the natural environment. This can make these plastics even more difficult to degrade than other plastics. This applies in particular to polymers with halogen atoms. Two examples of this group of substances are discussed here.

2.1 PARTICULARLY PROBLEMATIC POLYMERS

Polyvinyl chloride (PVC)

Polyvinyl chloride (PVC) is one of the most widely used plastics in the world and is used in numerous applications due to its versatility. Its main areas of application include construction products such as window frames, pipes and floor coverings, packaging materials, toys and medical products such as tubes and blood bags. PVC is of great economic importance and, at the same time, extremely problematic from an environmental point of view.

PVC is manufactured from ethylene (derived from petroleum) and chlorine and, particularly in the case of soft PVC, requires the use of numerous additives such as plasticisers (e.g. phthalates), stabilisers (e.g. heavy metals such as lead or tin compounds) and flame retardants (see 5.3). The production phase itself causes considerable environmental pollution, including the release of hydrogen chloride, vinyl chloride and potentially highly toxic dioxins, which are by-products and persistent in the environment [Thornton 2001].

The disposal of PVC also poses a major problem. Material recycling is only possible to a limited extent, as old PVC usually contains cadmium or lead compounds as stabilisers,

which are now mostly banned [Friege et al. 2018, Borgmann et al. 2019, Lahl & Zeschmar-Lahl 2024]. When PVC is incinerated, the chlorine it contains is released, which severely interferes with chemical recycling (see Chapter 7) and also with use as fuel in cement kilns. Furthermore, toxic dioxins can be released, which are harmful not only to the environment but also to human health. In addition, the variety of additives used makes recycling considerably extremely difficult (see 5.6), with the result that PVC is often landfilled or disposed of improperly. This allows harmful substances such as phthalates to enter the soil and groundwater, where they can have a long-term detrimental effect on the environment [Rahman & Brazel 2004].

PVC is also a health concern. The phthalates used as plasticisers cause hormonal disorders, while heavy metals in stabilisers have neurotoxic effects [Thornton, 2001]. Despite technically possible, PVC is rarely recycled, and the environmental impact of its persistent nature remains unresolved.

Fluoropolymers (PFAS)

Another group of problematic plastics are fluoropolymers, which belong to the so-called per- and polyfluorinated alkyl substances (PFAS). PFAS are extremely persistent and in many cases have as non-polymeric compounds highly toxic properties [Brunn et al., 2023, Grandjean et al., 2015]. PFAS are also characterised by their unique chemical properties, including high resistance to heat, chemicals, water and grease. One of the best-known examples is polytetrafluoroethylene (PTFE, known as Teflon), which is used in non-stick coatings, seals and cable sheathing, among other applications.

PFAS are often referred to as “forever chemicals” because they are extremely persistent in the environment and do not biodegrade. Worldwide, PFAS plastics and the associated chemicals from manufacturing and disposal are now ubiquitous in air, water, soil and human tissue.

All fluoropolymers are associated with significant environmental and health impacts, particularly in the production phase (which is associated with significant emissions of toxic non-polymeric PFAS) and the waste phase (in which break-down to problematic low-molecular-weight PFAS can occur). The claim that the OECD has classified fluoropolymers as “polymers of low concern” is incorrect. The comparatively low risks associated with some fluoropolymers in the use phase are not an argument for exempting fluoropolymers from regulation, given the risks associated with their production and disposal [Brunn et al. 2023]. The claims made by some industry associations that these hazards in the life cycle have been resolved are not scientifically documented. On the contrary, scientific publications confirm PFAS emissions associated with the production of fluoropolymers: the environments surrounding European fluoropolymer production sites are extensively and heavily contaminated with PFAS.

There are undoubtedly several industrial applications for polymeric PFAS that are also of great importance for further technological development in the EU in terms of sustainable transformation and currently appear indispensable. These substances can be easily integrated into the ECHA’s existing regulatory approach by granting a temporary extension of the transition period until the restriction comes into force, which will allow and promote the (further) development of more environmentally friendly alternatives. However, applications for which alternatives are already available should

be banned quickly. In addition, the lack of infrastructure for the safe disposal or recycling of polymeric PFAS complicates the task of addressing this problem.

Both PVC and polymeric PFAS must be viewed critically from an environmental and health perspective. The persistence of these plastics and their problematic properties – from production to use and disposal – urgently require more comprehensive regulations and the development of sustainable alternatives. In particular, innovation in recycling and research into safe substitutes must be promoted in order to minimise the long-term impact on the environment and health. It is estimated that in the United States alone, the use of PFAS in plastics causes health costs of 22.4 billion US dollars every year.

2.2 ENVIRONMENTALLY OPEN APPLICATIONS OF POLYMERS

Polymers are used in numerous applications where they enter the environment intentionally or unintentionally. In addition to solid plastics, liquid and water-soluble polymers used in agricultural, industrial or everyday processes are of particular concern. These environmentally open applications pose a particular challenge from an ecological point of view, as plastics are usually non-degradable in the environment.

2.2.1 Solid polymers in environmentally open applications

Some solid plastics are frequently used in applications that involve direct exposure to the environment. Examples include:

Mulch films in agriculture:

Mulch films made of polyethylene (PE) or biodegradable polymers are used to inhibit weed growth and regulate soil temperature and moisture. Conventional films often remain in the soil as microplastics, while biodegradable

alternatives decompose (very) slowly. However, there are also mulch films that can be recovered, reused several times and recycled [Initiative ERDE 2022].

Biodegradable plastics that can remain in the environment at the end of their life cycle are being promoted for various applications. One example of such a deliberately open plastic application is the use of **mulch films** in agriculture, which is supported by fundamentally sound arguments such as season extension and pesticide reduction. Non-degradable plastic films such as polyethylene must be recovered after use and have a high microplastic potential. As a result, the use of films based on PLA blends or PBAT, a very slowly biodegradable copolyester, is increasing. Previous standards on the toxicological impact of biodegradable plastics are incomplete. The DIN EN 17033-2018 [DIN 2018] standard, which came into force a few years ago, provides for toxicity tests on biodegradable mulch films for earthworms and microorganisms. A comprehensive study on the toxicological impact of PE and PLA-PBAT is available from Weltmayer & Roß-Nickoll 2024.

Erosion control mats:

Mats made of polypropylene (PP) or polyvinyl alcohol (PVA) are used for soil stabilisation. If these are not removed, plastic residues remain in the environment [Hayes et al. 2019].

Plastics for artificial turf and riding arenas:

Plastic granules, often made of ethylene-propylene-diene rubber (EPDM) or styrene-butadiene rubber (SBR), can be washed out of artificial turf pitches by rainwater and enter the environment as microplastics. An estimated 60% of all riding arenas also contain plastic granules: chopped fleece is used as an additive in the sand in quantities of 1 to 5 kg/m² [Ehret 2023]. In recent years, environmentally

friendly substitutes, such as fillers based on nut shells or coconut fibres, have been developed and used for artificial turf and riding arenas.

Although it has received little public attention to date, the agricultural sector is one of the most important users of intentionally added microplastics. These enter the environment through the use of plastic-coated fertilisers and pesticides and are one of the most direct and avoidable sources of increasing microplastic pollution in agricultural soils. This type of pesticide use is increasing as manufacturers market “controlled release” as the key to more sustainable agriculture. As a result, microplastics are reaching more remote areas and continuing to accumulate in the environment, where they may be inhaled by people working in agriculture [CIEL 2022].

2.2.2 Liquid and water-soluble polymers

Water-soluble polymers are used in a wide range of applications where they are deliberately introduced into or released into the environment. Such applications can be particularly problematic if the polymers are very long-lived (persistent). Even if no direct environmental damage has been described yet, these substances may still be problematic in the long term and would then be irreversible. Examples include:

Polyacrylamide (PAM):

PAM is used in agriculture as a “soil improver” and in water treatment. It stabilises the soil and reduces erosion [Sojka et al. 2007].

Environmental issues: Residual monomers such as acrylamide, which are toxic and carcinogenic, can remain in PAM during production, and the substance can remain in the soil for a long time.

Polyvinyl alcohol (PVA):

PVA is used in textile processing, water-soluble packaging and as a carrier in cleaning agents. PVA is water-soluble but only biodegradable under certain conditions. It can be long-lasting in cold or oxygen-depleted environments.

Superabsorbents (e.g. polyacrylates):

Superabsorbent polymers are used in hygiene products such as nappies and in agriculture or gardening and landscaping for water storage [Buchholz & Graham 1997]. Polyacrylates are difficult to degrade and can remain in the soil for a long time.

The deliberate release of polymers into the environment requires a thorough assessment of their degradability and potential environmental impacts. Conventional polymers such as polyacrylamide or polyvinyl alcohol are only biodegradable under specific conditions and can be persistent in the environment. Regulatory measures, such as the EU biodegradability standards or international standards for biodegradable materials, are crucial to minimise the environmental impact of applications that are open to the environment. In addition, research should focus on the development of new, environmentally friendly polymers that both meet functional requirements and are completely degradable. Lahl et al. therefore advocate the consistent use of biodegradable polymers in applications where they are likely to enter the environment, e.g. as microplastics [Lahl et al. 2025].

EXCURSUS ON BIOPLASTICS [BUND 2022]

Against the backdrop of the plastic crisis, so-called “bio” plastics are associated with a variety of expectations for sustainable material use: there is hope that fossil raw materials can be replaced by renewable ones and that the biodegradability of plastics can contribute to solving the waste problem. However, so-called “bio” plastics can only fulfil these hopes to a very limited extent. A neutral discussion on bioplastics is also made difficult by the fact that the label “bio” is often misused as a marketing strategy and raises false expectations among consumers. Another misleading factor is that the EC Organic Regulation (Regulation (EC) No. 834/2007) defines criteria for agricultural products using the terms “organic”, “eco”, “biological” and “ecological”, but these criteria do not apply to so-called “bio” plastics.

Unlike organic cotton, for example, which is grown under controlled organic cultivation, the plant products used to make so-called “bio” plastics largely originate from conventional agriculture.

In any case, “bio” plastics are not a simple solution to the plastic crisis, because the quantities of fossil-based (single-use) plastics currently in use cannot and should not be completely replaced by “bio” plastics, even in the future.

A consistent policy of sufficiency, i.e. a significant reduction in consumption, is therefore a prerequisite for the success

of any further measures to solve the plastic crisis and must always be considered and integrated in parallel with the debate on “bio” plastics as possible “better plastics”.

The market for “bio” plastics is still small: in 2020, they accounted for around 1% of plastic consumption in Europe. However, as with conventional plastics, the production of “bio” plastics is growing steadily, in some cases even significantly faster. Around half of “bio” plastics are currently used for packaging – compared to around 30% of fossil-based plastics [European Bioplastics 2020]. Other significant applications for “bio” plastics include agricultural films and single-use consumer goods such as tableware and cutlery. In principle, however, various “bio” plastics are also suitable for the production of high-quality plastic components (e.g. furniture, technical parts for electrical engineering and automotive engineering).

Given these frame conditions, “bio” plastics are currently a false solution to the plastic crisis. The first goal in response to the plastic crisis is and remains the avoidance of unnecessary plastic applications, especially in the packaging and disposable sectors. From the BUND’s point of view, the often heated debate about the use and potential advantages of “bio” plastics mainly distracts from the necessary restructuring of the packaging and plastics sector in general. Here, consistency (e.g. reusable instead of single-use) and sufficiency (lower quantities) must be given greater priority. Necessary

binding avoidance targets must also be backed up with target figures and measures, otherwise they will remain symbolic goals.

In a second step, the plastic already in the system must actually be recycled in a high-quality manner – this includes priority reuse through the widespread use of reusable systems. In addition, all plastic products manufactured must be recyclable in practice, not just in theory. To this end, recycling-friendly product design (single materials, suitable colours, ease of dismantling, etc.) must be pursued in order to ensure the highest possible recyclate quality.

“Bio” plastics should not be used for packaging as long as they cannot be recycled in the current market. For the recycling of “bio” plastics, this means that, in addition to drop-in polymers that can be recycled with the chemically identical fractions of conventional plastics, it is advisable to limit the use of new “bio” plastics to a few applications in order to increase their share and thus make material recycling economically viable. Appropriate political incentives are also key here, especially given the need for a socio-ecological transformation in which economic efficiency by today’s standards can no longer be the central criterion for or against a measure.

Only then can a decision be made as to whether and where bio-based plastics can sensibly replace polymers made from fossil raw materials. It is questionable whether biodegradability can

bring real benefits, e.g. in agricultural applications close to the soil, due to its function. This is of central importance because the composting of biodegradable plastics is purely a form of disposal, which in turn contradicts the concept of a circular economy. In addition, labels such as “compostable” or “biodegradable” can lead to products ending up in the environment in greater quantities, which is extremely critical.

The standards for all “bio” plastics, but especially for those certified as biodegradable, should be supplemented by tests on for human and ecotoxicological safety, in particular (eco)toxicity studies are necessary for substances unintentionally introduced with the plastics (NIAS). In addition, harmonisation of the standards regarding the reference material is necessary.

Furthermore, the land consumption for the cultivation of plants from which “bioplastics” can be produced is far too high to replace a relevant proportion of the fossil-based plastics currently produced [Helm et al. 2025].

3 Relevant material flows

In addition to plastics with (eco)toxicological relevance, applications in which material flows are of particular relevance due to their large quantities, their fundamental openness to the environment or a lack of recycling strategies are considered here.

3.1 PRODUCT WASTE

In 2023, the total amount of plastic waste collected in Germany was approximately 6.35 million tonnes [Conversio 2024]. Of this, approximately 5.58 million tonnes was private and commercial post-consumer waste. One of the largest groups here is light packaging (“yellow bag”) with a share of just under 23%. Packaging waste is associated with considerable littering, i.e. the disposal of waste on streets or in the countryside, amounting to up to 2,500 tonnes per year in Germany alone [Umweltbundesamt 2019].

Single-use packaging is one of the largest material flows. The chemical industry in Germany is the largest industrial consumer of energy [BUND 2023a]. It consumes one fifth of its total energy requirements for the production of disposable packaging. A quarter of all plastic consumed in Germany is used for packaging. Almost four million tonnes were produced in 2023 [Conversio 2024].

Production volumes in the construction industry amounted to 3.3 million tonnes in 2017, including pipes, profiles and insulation materials. Take-back systems and material recycling have become established for a number of applications. Insulation made from EPS, XPS polystyrene and polyurethane requires new recycling methods in some cases; mechanical recycling and solvolysis processes, in which

the polymer chains are chemically broken down using solvents to obtain monomers for the production of new plastics, are gaining ground here (see Chapter 7). Special reporting requirements apply to waste electrical and electronic equipment under the WEEE Directive. According to this, the collection rate in 2022 was 31.7% [BMUV 2022].

Large quantities of fibre-reinforced plastics are used in transport, infrastructure, pipe systems and wind turbines [Kühne et al., 2022, Composites United 2022]. In Europe, 1.138 million tonnes of thermosetting and 1.586 million tonnes of thermoplastic composite plastics were produced in 2022. This represents around 5% of the total amount of plastics in Europe. Thermosetting composite plastics are particularly problematic for recycling because the fibres are almost impossible to separate from the plastics. When carbon fibre-reinforced plastics are recycled, only the expensive carbon fibres are recovered using a pyrolysis process. Glass fibre-reinforced thermosetting plastics are used in cement plants as a substitute fuel and subsequently as a substitute for sand in cement. Although recycling is the aim, efficient material recycling is not in sight.

In addition to their considerable abrasion (see Chapter 6.2), tyres are also problematic as product waste. As rubber materials, they are not included in many plastics statistics. In Germany, over 500,000 tonnes of used tyres are collected annually [AZUR 2025]; in many other countries, they are often disposed of in irregular landfills. Material recycling consists of the production of rubber granulate, but its areas of application are also controversial (e.g. litter in sports turf). Chemical recycling appears to be

gaining ground, producing carbon black and pyrolysis oil [Maga et al. 2023].

3.2 LOSSES IN LOGISTICS AND USE

Plastics are usually supplied in the form of small pellets for further processing. These can be transported in bags or as bulk goods. Right at the start of the value chain, during the global transport of pellets [BUND 2025] made from thermoplastics, large quantities of plastic accidentally end up in the environment. In Germany alone, this amounts to around 15,000 tonnes per year, which corresponds to approximately 750 billion individual pellets [Bertling et al. 2018]. In October 2023, the EU published a proposal to reduce pellet losses [European Commission 2023].

Significant environmental emissions from polymeric substances originate from tyre abrasion [BUND 2019d], which amounts to over 1,200 g per capita per year (g/cap a) (Figure 2). Plastic emissions from waste disposal (compost, construction waste and metal shredding, plastic recycling) rank second. Compared to the latter, pellet losses are approximately half that

amount at 182 g/cap a. A relevant source of emissions from the private sector is abrasion during textile washing [BUND 2019a], which accounts for 76.8 g/cap a [Bertling et al. 2018]. In particular, non-woven fabrics made from synthetic fibres (e.g. face masks, wound dressings, tea bags) quickly disintegrate into individual fibres that are emitted into the environment [Tang et al., 2025]. Artificial turf [BUND 2019b] and riding arenas also contribute significantly to emissions, amounting to 131.8 g/cap a. The significance of the aforementioned emissions is discussed in more detail in chapter 4 on microplastics.

The loss of fishing nets in the sea is enormous. Fishing products account for almost 50% of global marine litter [BMUV 2023]. This form of marine pollution is the most dangerous for marine animals [Roman et al. 2021]. Germany joined the Global Ghost Gear Initiative (GGGI) in 2023. It is the world's largest cross-sector alliance working on a scientific basis to develop solutions to the problem of lost, abandoned and otherwise discarded fishing gear around the world.

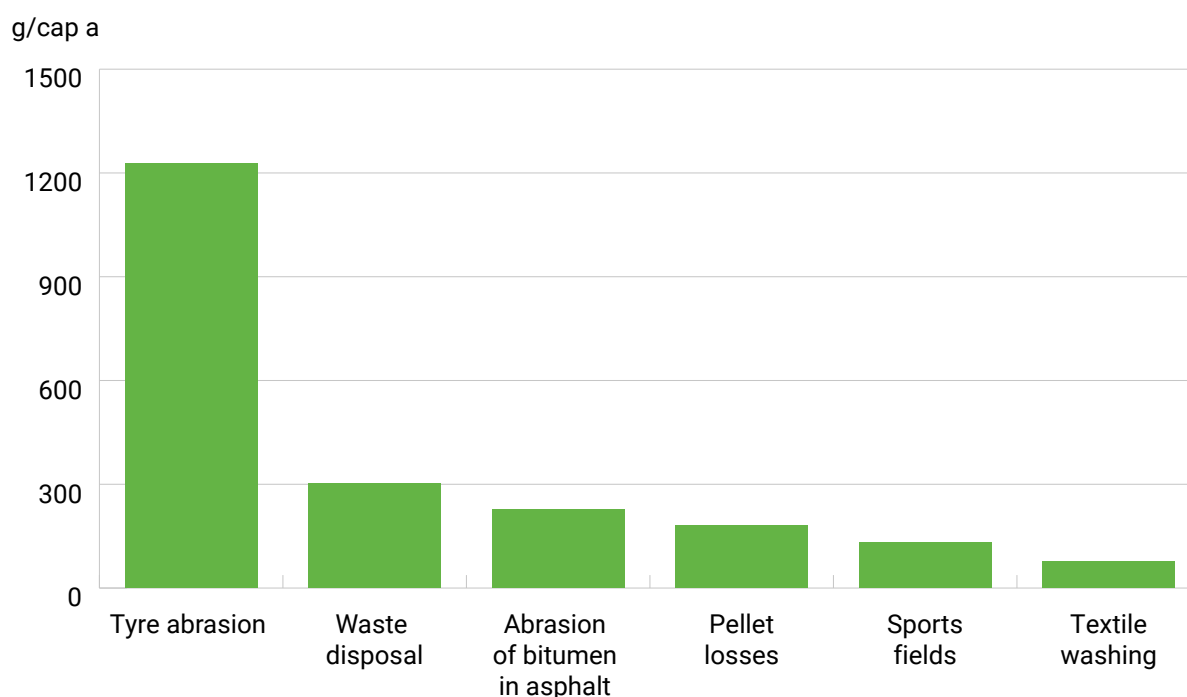


Figure 2: Sources of primary microplastics (selection): tyre abrasion, release during waste disposal, pellet losses, drift from sports fields and playgrounds, fibre abrasion during textile washing; in annual per capita amounts (g/cap a); [Bertling et al. 2018].

4 Microplastics

4.1 DEFINITION OF MICROPLASTICS

Microplastics are solid, insoluble, particulate and biologically non-degradable synthetic polymers ranging in size from less than 5 millimetres to 1 micrometre. Even smaller plastic particles (smaller than 1 micrometre) are referred to as nanoplastics.

Microplastics are divided into primary and secondary microplastics. Primary microplastics are particles that are already in the microplastic size range when they are used. These include, for example, particles used in the cosmetics and personal care industry [BUND 2019c], but also for the controlled release of nutrients in fertilisers. [Umweltbundesamt Österreich 2025].

Secondary microplastics are created when larger plastic parts break down through physical, biological and chemical degradation. This includes, for example, abrasion from car tyres or fibres from synthetic textiles that enter the wastewater or air during washing or drying, or the decomposition of plastic parts in the oceans through UV light and wave motion. There is still no binding definition for microplastics and nanoplastics [Hartmann et al. 2019].

4.2 WHY ARE MICROPLASTICS DANGEROUS?

Microplastics have a huge surface area due to their many small particles. Due to its surface properties, plastic acts like a magnet for many environmental chemicals and pathogens (microorganisms that can cause disease). These can accumulate on the plastic surface. For example, concentrations a hundred times higher than in seawater can be measured here. In addition, microplastics from tyre abrasion

pose a risk due to toxic constituents such as polycyclic aromatic hydrocarbons (PAHs) or the additive 6PPD, an antioxidant used in tyres.

The plastics are then absorbed by organisms along with the pollutants contained in the plastic and accumulated on the surface: microplastics have been detected in a variety of organisms that absorb them passively or ingest them with their food [Tekman et al. 2022]. These pollutants can be released in the gastrointestinal tract and affect the organism. However, microplastics and nanoplastics are also absorbed by humans via water, food, the skin or the respiratory tract. Abbasi calculated exposure via the skin with primary microplastics from cosmetics [Abbasi & Turner 2021]. The particles are widespread in the human body, even reaching the brain, placenta and breast milk [Winiarska et al. 2024]. Microplastics can accumulate via the food chain. The consequences have not yet been conclusively researched. However, it is becoming apparent that microplastics cause inflammatory reactions, and there are initial indications that they promote the formation of metastases and thromboses and that there may be a link to Parkinson's disease. The pollutants they contain cause annual health costs of 249 billion US dollars in the USA alone [Trasande et al. 2024].

The effects of microplastic intake on organisms are manifold: studies point to tissue changes or inflammatory reactions and toxicological effects, including internal injuries and deaths. Microorganisms such as zooplankton are an important food source for fish. These are in turn eaten by larger predatory fish. The non-degradable plastic and pollutants can accumulate in tissue and thus become part of the food chain. The smaller the plastic

particle, the greater the risk of ingestion and the number of animals that consume it. Once microplastics are in rivers and the sea, they cannot be removed. The state of the marine environment is worrying and the effects are difficult to estimate. The avoidable entry of microplastics must therefore be stopped consistently.

4.3 QUANTITIES AND ENTRY PATHS

According to data from the Fraunhofer Institute for Environmental, Safety and Energy Technology from 2018 [Bertling 2018], a total of around 446,000 tonnes of plastic enter the environment in Germany every year. Plastic particles smaller than 5 mm, at around 330,000 tonnes, account for around three times the amount of other plastic particles (larger than 5 mm, macroplastics). The largest proportion of microplastics is generated by abrasion from car tyres. Other sources include plastic from textiles, waste disposal, abrasion from bitumen and asphalt, emissions from sports fields and playgrounds (including artificial turf and riding arenas), emissions from construction sites, abrasion from shoe soles, plastic packaging and road markings, and synthetic fibres (especially from washing textiles).

Microplastics and nanoplastics also enter arable soils through agricultural applications and from there find their way into the human food chain [Boctor et al. 2025]. Plastic particles are not only found in soil and water, but also in the air. Monitoring studies have even detected nanoplastics in alpine summit regions and remote mountain lakes [Materić et al. 2021, Akdemir et al. 2025].

The entry of microplastics into the oceans is particularly problematic. A report by the International Union for Conservation of Nature (IUCN) estimates this at 1.5 million tonnes per year [Boucher & Friot 2017]. New research

findings indicate that the amount of nanoplastics in the oceans has been significantly underestimated. ten Hietbrink et al. found 1.5–32 mg/m³ in the water column during measurements in the North Atlantic, which adds up to 27 million tonnes in the North Atlantic alone, more than the estimated amount of macro- and microplastics [ten Hietbrink et al. 2025]. A significant proportion of microplastics in the oceans is caused by fishing. Researchers at the University of Plymouth found that new and one-year-old synthetic ropes can release around 20 microplastic fragments per metre into the sea – and that this number increases exponentially as the material ages [Napper et al. 2022]. Two-year-old ropes release 720 fragments per metre and ten-year-old ropes release 760 fragments per metre. According to the report, fishing vessels use about 220 metres of rope in a typical fishing operation. Based on a conservative 50-metre line, the researchers estimate that new ropes can release up to 2,000 microplastic fragments each time, while old ropes can reach values of up to 40,000 fragments.

The largest proportion of microplastic particles comes from washing synthetic textiles and from tyre abrasion during driving. Most of the releases into the oceans come from the use of products (49%) or the maintenance of products (28%). These plastics mainly enter the sea via road runoff (66%), sewage treatment plants (25%) and the wind (7%). The regional distribution of primary microplastic releases varies across the world's regions. All regions contribute significantly to releases. The largest regional releases are found in India and South Asia (18.3%) and North America (17.2%), closely followed by Europe and Central Asia (15.9%), China (15.8%) and East Asia and Oceania (15.0%). Releases are lower in South America (9.1%) and Africa and the Middle East (8.7%). In terms of per capita losses, India and

South Asia, China, Africa and the Middle East are below the global average (212 grams/year per capita). Large populations combined with a low proportion of the population connected to wastewater treatment systems, e.g. 6.2% in India and South Asia, lead to significant releases on a global scale. There are also significant releases in Europe and Central Asia as well as in North America, but for the opposite reason. In these regions, per capita plastic losses are higher than the global average.

4.4 STARTING POINTS FOR AVOIDING MICROPLASTICS

In addition to significantly reducing plastic use, the key in many cases lies in the responsible use and disposal of plastics. Product design plays an important role here, for example by providing products without added (primary) microplastics. Washing machines with suitable microplastic filters reduce the discharge of microplastics into wastewater. Curbing littering and conscious consumer behaviour have a direct positive impact on the microplastics problem. Reducing car traffic and driving slower or lighter cars also reduces tyre wear as a side effect. Regulations could also be used to manufacture more durable car tyres that would result in less tyre wear. At the operational level, the release of microplastics can be achieved through technical measures (e.g. filters) and special training for skilled workers. As part of the “Zero Pellet Loss” pact, for example, a reduction in raw material losses (transfer, transport, wastewater) has been achieved [Umweltbundesamt Österreich 2025].

5 Links to climate and biodiversity

The mass consumption of plastic is part of the triple planetary crisis declared by the UN [Villarrubia-Gómez 2024], which encompasses climate change, environmental pollution with harmful substances and biodiversity loss.

The production and disposal of plastic from fossil fuels contributes significantly to climate change (see Chapter 5.1), and the emission of plastic, the release of additives contained in it and its weathering into microplastics pollute ecosystems and have a negative impact on biodiversity (see Chapter 5.2). The longevity of plastic in particular makes it difficult to monitor and limit its impact on biodiversity, as it accumulates continuously in the environment and is almost impossible to recover. Reducing plastic production and implementing rigorous recycling while maintaining polymer quality can be part of the solution to the plastic problem. However, this requires the reduction or removal of additives in recycling to minimise unwanted pollutants (see Chapter 6).

5.1 PLASTIC AS A DRIVER OF CLIMATE CHANGE

Plastic is based on carbon, which comes mainly from fossil sources. Globally, in 2019, 93% of plastic was produced from natural gas, oil or coal (= primary plastic), 6% came from recycled plastic (= secondary plastic) and 0.6% from bio-based sources such as corn, sugar cane, wheat or other biomass residues [OECD 2023]. However, fossil fuels are not only used as raw materials in the production of plastic, but also as thermal energy sources, for example in steam production in steam crackers. Due to this dual role, plastic production accounts for one fifth of the total consumption of fossil fuels in the German chemical industry [BUND 2023a]. Worldwide, the production of plastic alone accounts for 5.3% of annual CO₂ emissions. At the current rate of growth, production

could cost up to 31% of the remaining CO₂ budget by 2050 [Karali et al. 2024]. Furthermore, the disposal of plastic and the production of additives contribute to further greenhouse gas emissions, meaning that plastic makes a significant contribution to climate change.

5.1.1 Climate-impacting emissions from plastic use

According to the OECD, the global use of plastic released 1.8 Gt (1,800,000,000 tonnes) of greenhouse gases (GHG) in 2020 [OECD 2023]. If plastic production continues to grow (business-as-usual scenario), this amount will increase by 50% to around 2.8 Gt by 2040 (see Figure 4). However, depending on the calculation method used, scientists are already estimating higher GHG emissions of up to 2.24 Gt, which could rise to 4.75 Gt (2.5% growth) or 6.78 Gt (4% growth) by 2050, depending on the growth forecast [Karali et al. 2024, Zhu et al. 2025]. The classification of these emissions depends heavily on future efforts to limit global warming, but the projected values would be between the current GHG emissions of Russia and the USA. In terms of GHG emissions, limiting global warming to 1.5°C would require production increases by 2050 to consume between 20 and 30% of the remaining GHG budget [Karali et al., 2024]. Production and conversion are particularly energy-intensive, accounting for approximately 90% of emissions, while proper and improper disposal account for only 10% (see Figure 3). Given the short-term usefulness of many plastic products and the high GHG emissions involved in their production, plastic production should be limited to essential uses in the short term and decoupled from fossil fuels in the long term.

A closer look at emissions from plastic production shows that approximately 20% are generated during raw material extraction, 29% during refining, 26% during monomer production, 8% during polymerisation and 17% during product manufacturing [Karali et al., 2024]. Energy consumption and greenhouse gas emissions during production dominate the life cycle analysis of plastics and argue in favour of material recycling of plastic waste (e.g. deposit systems, reuse or recycling) as a measure to minimise the environmental impact. Plastic recycling can be carried out in various ways to produce high-quality (high-quality recycling) or low-quality (downcycling) products that replace either primary plastic or other materials. A comparative study by the Swedish Environmental Research Institute (ivl) based on a typical European waste composition shows the advantages of high-quality material recycling in terms of greenhouse gas emissions [Ekvall et al., 2025]. However, recycling may lead to a change in quality and also to a deterioration in the quality of the recycled material, as the

chain length of the polymers is shortened, further additives are mixed in, foreign substances from previous use can be introduced, or, in the case of downcycling, the polymer types can even become mixed. Industry associations are therefore increasingly advocating chemical recycling, e.g. pyrolysis (see Chapter 8), in which the plastic is re-oiled. However, this process is very energy-intensive and releases approximately the same amount of greenhouse gases as the primary production of plastic [Quicker & Seitz, 2024]. In addition, projects are failing due to the mix of chemicals and are currently only scaling up in very few cases.

The incineration of plastic in waste incineration plants or cement kilns generates only a fraction of the greenhouse gas emissions of the entire life cycle and currently substitutes other, mostly fossil fuels. These emissions cannot be directly attributed to plastic, but they result from its use and amount to approximately 2 million tonnes of CO₂ equivalents per year [OECD, 2023].

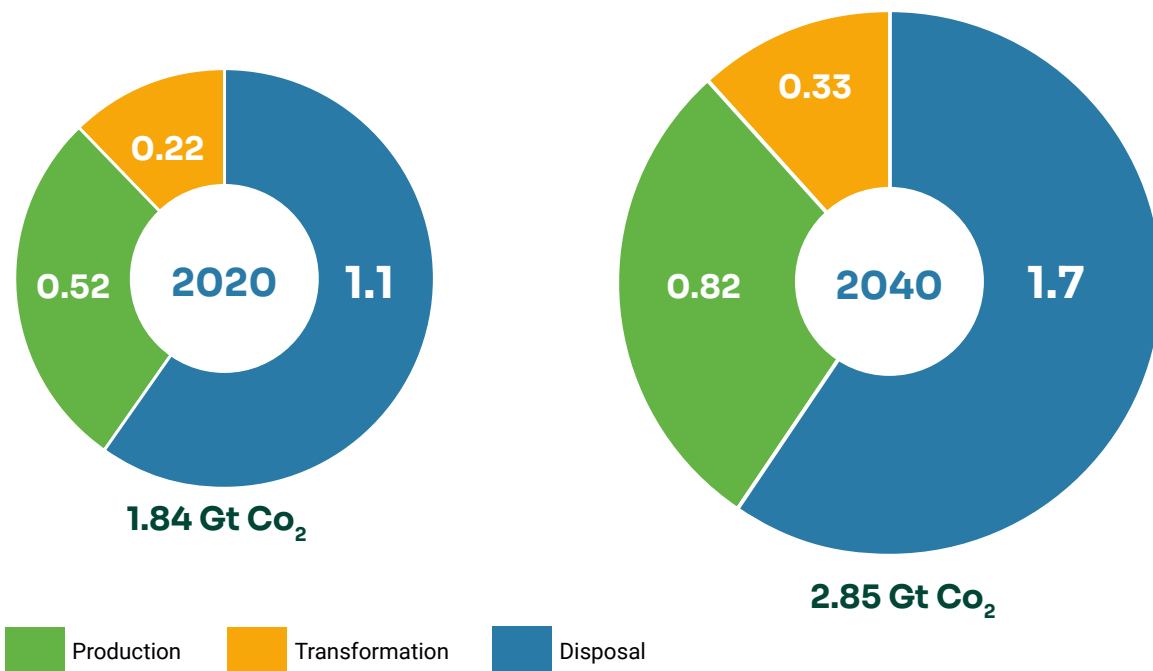


Figure 3. Annual greenhouse gas emissions from global plastic production and disposal and projections for 2040 assuming continued growth [OECD, 2024b]. Emissions of methane and nitrous oxide as carbon dioxide equivalents are included in the graph.

Considering the entire life cycle of plastic and all available recycling technologies, meaningful climate protection can only be achieved by significantly reducing plastic production. To this end, single-use packaging must be removed from the market as far as possible. Emissions from synthesis in particular clearly show that high-quality material reuse is the primary goal for unavoidable plastic waste.

5.1.2 Synthesis of additives as an additional source of emissions

Plastic production is not based solely on the use of monomers, but also on the use of catalysts, processing aids and, above all, additives (see also Chapter 6). According to a recent study, there are approximately 16,000 known additives, which are used in varying proportions depending on the product and function (e.g. antioxidants max. 3%, light/UV stabilisers max. 10%, flame retardants max. 28% and plasticisers max. 70%) [Wagner et al., 2024]. In 2024, around 20 million tonnes of additives were produced (see Chapter 6), which are subject to very different synthesis processes. For this reason, greenhouse gas emissions cannot be estimated on a flat-rate basis.

5.2 EFFECTS OF PLASTIC USE ON BIODIVERSITY AND HEALTH

Due to the large production volume and its careless handling, plastic has found its way into all ecosystems on this planet. It enters the soil via compost and sewage sludge, through precipitation into soils, rivers and seas, through wind into the atmosphere, and has now spread from the Himalayas to the Mariana Trench in the deep sea. Plastic is therefore everywhere, and almost all organisms on this planet have come into contact with plastic or carry it within them. Once released into the environment, it is almost unrecoverable, making it an existential threat to particularly exposed and vulnerable groups of organisms [MacLeod et al., 2021,

Thornton-Hampton et al., 2022]. The amount of plastics in the environment varies greatly, as wind, ocean currents and even animals transport plastic, creating local hotspots. Exposure to plastic does not automatically result in harm to living organisms, and the principle that the dose makes the poison does not automatically apply to plastic. This is because the effects of plastic are diverse and depend not only on the quantity, but also on the form, properties and chemical composition. This can lead to physical effects, such as animals becoming entangled in plastic strings or blockages in the gastrointestinal tract, health impairments due to the release of plastic chemicals (additives), or the creation of artificial habitats (e.g. through the colonisation of plastic surfaces as artificial reefs in the ocean). This has an impact on the diverse life forms on this planet (= biodiversity). The following chapter summarises the effects of plastics on the diverse life forms on this planet and shows that the effects of plastics can hardly be estimated due to its extreme longevity and heterogeneous distribution in the environment.

5.2.1 Plastic (surfaces) as a vector and habitat

As soon as a plastic surface is exposed to environmental influences, microorganisms and larger organisms (also known as “biofouling”) begin to colonise it. These organisms use the surface as a habitat and can reproduce there, protected from external influences [Rummel et al., 2017]. Genetic studies have shown that these microorganisms include human pathogens and that antibiotic resistance can accumulate there [Zadjelovic et al., 2023; Shruti et al., 2024]. Plastic in the environment can therefore serve as a vector for the spread of pathogens. In addition, plastic particle pollution represents a new habitat in which natural surfaces do not occur. This is particularly true for marine areas far from the continents, where

plastic can accumulate in so-called garbage patches in interaction with ocean currents. Studies have shown that many organisms that do not frequently occur in these marine areas are found on plastic [Bryant et al., 2016]. Plastic thus forms artificial floating reefs in these areas, which can persist for decades and have an impact on local biodiversity and material flows.

The ecological effect of plastic as a new habitat cannot be conclusively assessed and further research is needed. Nevertheless, it can be demonstrated by examples that plastic has an impact on biodiversity, for example when larger plastic objects are colonised by organisms such as crustaceans or other invertebrates, drift away with them and are spread beyond their natural habitat as alien species (neozoa) [Haram et al., 2021]. In addition, the availability of plastic surfaces in the ocean influences the behaviour of marine animals, as evidenced, for example, by the altered mating behaviour of the marine crab (*Planes minutus*). This species originally lives in social monogamy under the shells of loggerhead sea turtles (*Caretta caretta*) and is now even found in larger populations on drifting plastic [Pfaller & Gil, 2016].

5.2.2 It's all about size – the physical effects of plastic

Plastic can be mistakenly ingested with food or actively confused with it, which can lead to blockages (constipation) or injury to the gastrointestinal tract. In addition, a stomach full of plastic can impair food intake and thus the energy budget of an organism [Watts et al., 2015; Gardon et al., 2018]. There is no general critical plastic composition or size for ingestion with food, as microplastic particles are a problem for water fleas and mussels, plastic bags for sea turtles, and fishing nets, buckets or even car parts for sperm whales [Jacobsen et al.,

2010]. Confusion with natural food is not only due to the initial properties of the plastic, but also, and above all, to biofouling (see 5.2.1). Organisms on the plastic surface change the appearance and, above all, the smell of the plastic, making it more like a natural object. Animals with a keen sense of smell, such as seabirds (Procellariiformes, tube-nosed birds) such as albatrosses or storm petrels, often have plastic in their stomachs [Savoca et al., 2016; Pfaller et al., 2020].

In addition, plastic films, nets, containers, bags and lines are death traps for various creatures because they can become entangled in them. This is particularly true for birds that build nests, which bring plastic fibres from nets into their nests, creating a deadly hazard for themselves or their offspring (see Figure 4). Land mammals such as hedgehogs are also endangered by net-like plastic debris [Thrift et al., 2023]. But even in rivers, lakes and the oceans, ghost nets, longlines and fishing lines are a major problem, as marine animals such as fish, dolphins, whales and sea turtles can become entangled in them, cut off parts of their bodies or suffocate or starve to death [Butterworth et al., 2015]. Estimates suggest that 48,400 tonnes of plastic fishing gear are lost unintentionally in industrial fishing, although this figure is subject to considerable uncertainty [Kuczenski et al., 2021].

5.2.3 Uptake and effects of (micro) plastics in cells

Although swallowing or even inhaling plastic represents uptake into the body, protective barriers such as the epithelial cells of the lungs, stomach or intestines prevent further uptake into cells, tissue or the bloodstream. However, particle size also plays a decisive role here, as according to the European Food Safety Authority (EFSA), microplastics smaller than 150 µm can cross the intestinal barrier

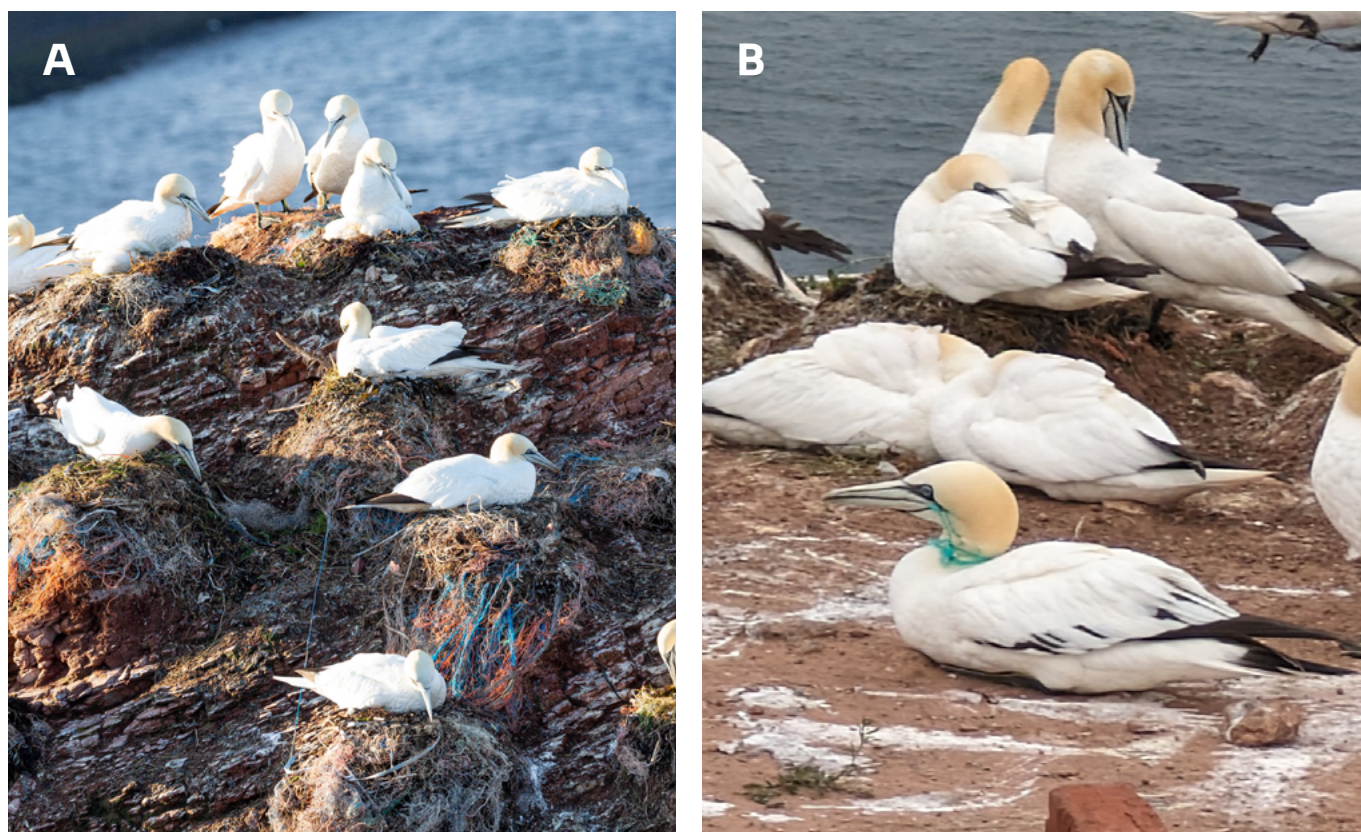


Figure 4: Plastic fragments from fishing entering the nests of northern gannets (*Morus bassanus*) on the island of Heligoland (source: Stefan Lips) and B) a northern gannet entangled in a fishing line (Source: Aaron Beck).

and those smaller than 10 μm can also penetrate cells. Various publications have observed microplastic particles in human organs, even in the brain [Amato-Lourenço et al. 2021, 2024]. However, quantifying microplastic particles in blood and organs is difficult and scientifically controversial [Obeng et al., 2025, Rauert et al., 2025, Xu et al., 2025a]. Further experiments by the Federal Institute for Risk Assessment (BfR) indicate that nano- and microplastics have an adverse effect on the epithelial and nerve cells of the intestine [Elfers et al., 2025]. Other studies have also demonstrated inflammatory reactions, oxidative stress, membrane damage or cell death in various cell types or model organs as a result of exposure to microplastics and nanoplastics [Wu et al., 2019; Yan et al., 2021, Stock et al., 2022; Donkers et al., 2022]. Scientific studies have also provided evidence that plastic may be involved in the development of diseases such as Parkinson's, thrombosis,

metastasis, breast cancer, stem cell damage and reduced sperm count.

As early as 1992, Jani et al. were able to show in feeding trials on rats that 3 μm polystyrene particles are distributed throughout the body and can be found, for example, in the lymph nodes and liver [Jani et al., 1992]. The EFSA also specifies a critical limit of 1.5 μm for the systemic distribution of particles in the body. The distribution of particles in the body raises further questions, as this can lead to accumulation in certain tissues or organs and thus to increased exposure of cells far away from the actual gastrointestinal epithelium. For example, an accumulation of microplastics in the brains of deceased individuals has recently been detected, exceeding the amounts found in the liver and kidneys [Nihart et al., 2025]. However, the question of whether microplastics cause permanent damage or disease in

the body still cannot be answered conclusively, because in addition to particle size, the type of polymer and the chemicals added to plastics as additives (see Chapter 6) also play an important and largely unexplored role.

Due to the constant presence of plastics in our everyday lives, humans are one of the species most exposed to microplastics. Estimates of unintentional daily intake vary and are subject to considerable variation depending on diet and lifestyle. A rough estimate yielded a daily intake of 883 particles, which corresponds to an approximate amount of plastic of 4 µg per week [Nor et al., 2021]. This is well below the amount of 0.1 to 5 g [Senathirajah et al., 2021], which has typically been compared to the amount of plastic in a credit card. Nevertheless, this exposure will continue to increase in the future if, according to current growth forecasts, more plastics come into circulation, plastic particles accumulate in food or the air, and food is increasingly packaged in plastic. Inhalation is a particularly important route of exposure, as according to Nor et al., the largest amounts of microplastics and nanoplastics enter the body via the air [Nor et al., 2021]. However, the extent to which self-cleaning processes in the respiratory tract, such as mucociliary transport, can remove the particles from the body and what health effects residual particles cause is currently the subject of research [Winiarska, et al. 2024; Gasperi, et al. 2018; Huang, et al. 2024]. However, increased exposure to plastic fibres in the air we breathe, which can occur in the workplace, for example, was already linked to lung diseases such as asthma and chronic bronchitis in 1975 [Pimentel, et al. 1975]. In the interests of preventive health protection for humans and the environment, it is necessary to curb the production and spread of microplastics by increasingly avoiding the use of plastics.

5.2.4 Release of plastic chemicals and their effects

Plastic contains chemicals that are added intentionally (=additives) or unintentionally, which evaporate from the plastic over time because they are not firmly bound in the polymer (see Chapter 6). These are distributed in the environment (such as water or air) and create complex chemical mixtures that can have harmful effects. Experiments with everyday plastic products have shown that the chemicals they contain can have an effect on algae [Tetu et al., 2019], crustaceans [Bejgarn et al., 2015; Linthner et al., 2012] and molluscs [Capolupo et al., 2020]. This is not surprising, as the list of possible plastic additives is long and includes at least 4,200 chemicals of concern that are hazardous to human health and the environment. Data is lacking for around 10,000 of the 16,000 chemicals associated with plastics [Wagner et al., 2024]. Among the known chemicals are bisphenol A and 4-nonylphenol, which are endocrine disruptors that can have effects on snails and fish even at environmentally relevant concentrations [Oehlmann et al., 2005, Hong et al., 2020]. These examples are representative of an entire group of substances that include structurally related chemicals such as tetrabromobisphenol A, bisphenol S, F and AF as substitutes and are often no less problematic [Reininger & Oehlmann, 2024]. Another serious example is the substance 6PPD, which has been used as an oxidation inhibitor in car tyres since 1970. Tyre abrasion, the oxidation of 6PPD to the quinone 6PPD-Q and the leaching of the substance and tyre abrasion into rivers caused local fish kills of silver salmon (*Oncorhynchus kisutch*) [Tian et al., 2022]. 6PPD-Q from car tyres is not only toxic to salmonids. Recent studies also show that it is highly effective against other aquatic and terrestrial animals such as nematodes [Jiang et al., 2024].

These examples illustrate the undesirable potential effects of plastic additives and thus also their potential impact on biodiversity. There is little conclusive evidence that plastic additives alone impair biodiversity. Rather, plastic chemicals and their transformation products contribute to biodiversity loss in combination with other chemicals and environmental factors such as climate change. Nevertheless, the studies highlight the urgent need for research into safe additives and the need to reduce the current diversity of additives in order to improve risk assessment for the protection of biodiversity.

6 Additives and accompanying substances as a key environmental problem

Chemical compounds are added to most plastics during manufacture and/or further processing in order to achieve the properties required for their intended uses. These additives can serve a wide variety of purposes. For example, pure PVC is hard and brittle. By adding so-called plasticisers, the PVC becomes softer, more elastic and more flexible as the mass fraction of the additive increases. Soft PVC consists of up to 50% added plasticiser. Plasticisers and three other important groups of additives are discussed in more detail in Section 6.1.

Due to the different types of plastics and their diverse uses, the variety of substances used as additives is enormous: Wiesinger et al. list more than 10,500 different chemicals that are used as additives, processing aids or monomers for the production of plastics [Wiesinger et al. 2021]. A United Nations study even iden-

tifies over 13,000 chemicals directly related to the production and use of plastics [UNEP 2023]. The latest study by Wagner et al. (2024) lists over 16,000 chemicals that are potentially used in or may be contained in plastic materials and products [Wagner et al. 2024]. More than 4,200 of these substances are of concern due to their persistence, bioaccumulation, mobility in the aquatic environment and/or their harmful effects on living organisms.

In line with the enormous and constantly increasing production volumes of plastics and the often (very) high mass fractions of additives in plastics (see above and 5.3), the production and use volumes of numerous additives are very high, ranging in the hundreds of thousands or millions of tonnes per year [Maes et al., 2023; Wiesinger et al., 2021]. The proportions attributable to global usage quantities (estimated for 2024) are shown in Figure 5.

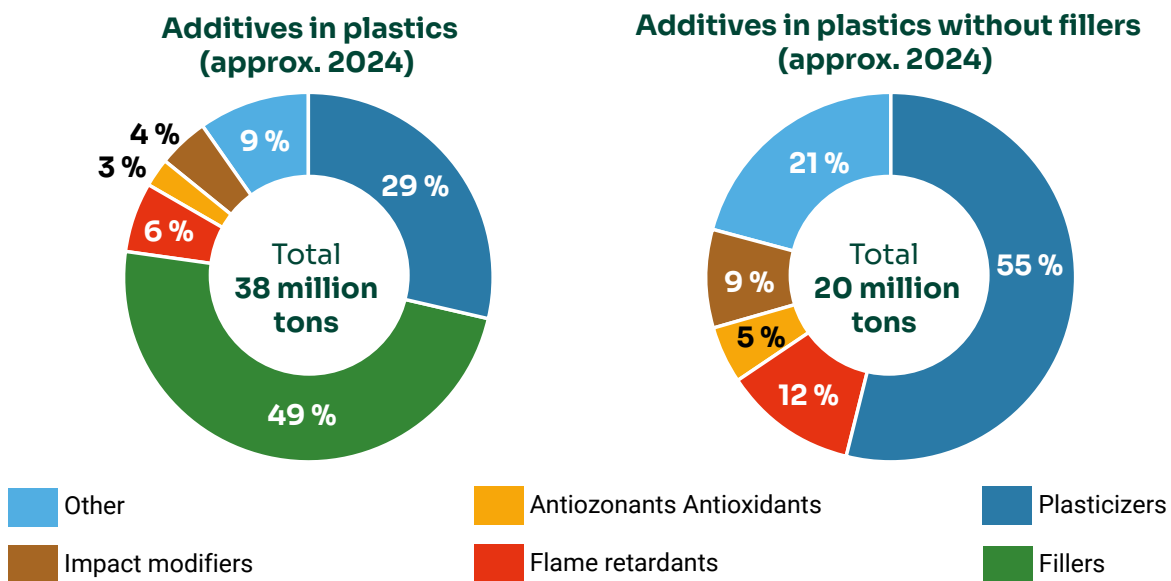


Figure 5: Main quantities of additives used in plastics, as of 2024 [Geyer et al. 2017; Aurisano et al. 2021; Maes et al. 2023; Maier, Schiller 2016; Ceresana 2024b; 2025; ChemAnalyst 2022; 2023; Pro Market Reports 2025; Statista Research Department 2023; U.S. National Library of Medicine 2025; Xu et al. 2022b]

In most cases, the substances added as additives are not chemically bound to or in the macromolecules of the plastic, but are only physically mixed with the polymer. The majority of additives are organic substances with a relatively low molar mass (up to about 1000 g/mol). Such substances can dissolve in liquids such as water when they come into contact with them. Examples include the technically intended long-term leaching of biocides from roofing membranes to prevent algae and moss formation due to rain, the dissolution of plasticisers from children's toys in saliva, and the transfer of plasticisers from packaging materials into fatty foods.

In contrast to macromolecules, numerous additives also have a certain tendency to transition from a solid or liquid state to a gaseous state. This tendency also exists in many semi-volatility organic compounds. This means that these substances can be released from the plastic materials into the surrounding air throughout the entire product life cycle, i.e. they can evaporate. This tendency is more pronounced the higher the additive content in the plastic, as this transport process, known as diffusion, depends on the difference in concentration between the additive and its surroundings. Higher temperature increase (e.g. heating of the plastic object by solar radiation or mechanical friction) accelerate volatilisation. The use of organic substances as additives in plastics without chemical bonding is therefore fundamentally an environmentally open application. Studies conducted on buildings exposed to polychlorinated biphenyls (PCBs), which were used as plasticisers and flame retardants in permanently elastic joint sealants and paints in the 1960s and 1970s, have determined an annual volatilisation rate of approximately 0.06%. For Germany, this means a continuous uncontrolled annual release of 7–12 tonnes of PCB into the air [Weber et al., 2015]. Numerous

other plastic additives are also found in the indoor air of buildings and in house dust [AGÖF 2007, 2013].

Additives that have volatilised from plastics can be transported over long distances by air, either in gaseous form or attached to fine dust particles or via microplastics and nanoplastics, and thus spread widely in the environment. Precipitation and atmospheric deposition in dry weather cause these substances to be introduced into ecosystems over large areas, including remote sites where they have never been used. The presence of semi-volatility brominated and chlorinated organic flame retardants (see 6.3.2) in the air and in deposits on the Zugspitze has been confirmed by a series of measurements [Umweltbundesamt Österreich 2021]. If such released and diffusely distributed additives are stable (persistent) in the environment, their accumulation in plants and soils as well as in suspended matter and sediments in water bodies and ultimately their biomagnification in animals and humans is the inevitable consequence.

The tendency towards leaching or volatilisation described above also applies to residual amounts of production and processing aids that are also present in unbound form in plastic products: for example, a per- or polyfluorinated alkyl substance (PFAS) must be added as an emulsifier in the manufacture of fluoropolymers. For the use of HFPO-DA in fluoropolymer production at a plant in the Netherlands, it was determined that approximately 0.5% of the emulsifier used is transferred to the products [Gebink & van Leeuwen 2020].

6.1 ADDITIVES RELEVANT TO THE ENVIRONMENT AND HEALTH

In terms of their relevance to the environment and health, plasticisers, flame retardants and stabilisers (antioxidants and UV light stabilis-

ers) are the most important plastic additives [Maier & Schiller 2016]. PVC stabilisers that have proven to be particularly toxic over time, such as cadmium, lead or organotin compounds, are now banned as additives in virgin PVC [EU 2025]. They make it difficult to recycle PVC products manufactured in the past, e.g. floor coverings, window frames or pipes. There are long-standing EU exemptions for cadmium and lead in recycled products [EU 2011a; 2023].

6.1.1 Plasticisers

According to DIN 55945, plasticisers are liquid or solid organic substances with low vapour pressure which, without chemical reaction, preferably through their solubility or swelling capacity, physically interact with high-polymer substances and can form a homogeneous material with them. Their function is to adapt the hardness of a polymer to the requirements of its use. Plasticisers are mostly colourless substances with low water solubility. [Römpf 1998]

Migration refers to the tendency of plasticisers to migrate towards the concentration gradient during prolonged contact with other materials, e.g. in food packaging and films. An increase in temperature increases the tendency to migrate.

The most important group of plasticisers are phthalates, diesters of phthalic acid (benzene-1,2-dicarboxylic acid). For decades, di(2-ethylhexyl)phthalate (DEHP) was the most important representative of this group in terms of quantity, especially for PVC. Due to their reproductive toxicity, DEHP and three other phthalates were classified as substances of very high concern in EU chemicals legislation in 2011 and have been subject to authorisation since 2015 [ECHA 2025c]. Since 2013, the European Chemicals Agency (ECHA) has also

classified a number of other phthalates (individual substances and mixtures) as substances of very high concern due to their reproductive toxicity and thus listed them as candidates for authorisation [ECHA 2025b]. Most of these phthalates have now become subject to authorisation.

Cyclohexane-1,2-dicarboxylic acid diisononyl ester (DINCH) and bis(2-ethylhexyl) terephthalate (DEHT) are used as DEHP substitutes in PVC for medical devices (e.g. infusion tubes), toys and food packaging. Based on current knowledge, these substances are considered to be largely harmless.

Other plasticisers used primarily for PVC include tris(2-ethylhexyl) trimellitate (CAS 3319-31-1), 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB, CAS 6846-50-0) and benzoic acid esters such as isononyl benzoate. Other plasticisers include dioctyl adipate (a diester of hexanedioic acid), epoxidised fatty acid esters (soya and cottonseed oils) and, in plastics for food packaging, citric acid esters such as acetyl tributyl citrate.

Another important group of plasticisers are **phosphoric acid esters**. They have a wide range of uses, including carpets, foams, wall paints, fibreglass wallpaper and floor sealants. In mattresses and upholstered furniture, they also act as flame retardants (see 6.3.2), with a mass fraction of 30% in the polymer usually required. Important representatives in terms of quantity are tris(2-chloropropyl) phosphate (TCPP), tri-iso-butyl phosphate (TiBP) and triphenyl phosphate (TPP). Some phosphoric acid esters are highly toxic; for example, TPP is neurotoxic. Almost all phosphoric acid esters are semi-volatile compounds. They are distributed over large areas via the air and enter ecosystems.

6.1.2 Flame retardants

Since most plastics consist entirely or predominantly of carbon and hydrogen (raw material base: petroleum), they are fundamentally combustible and ignite at relatively moderate temperatures when exposed to heat and flames. A flame retardant is a chemical that, when added to a combustible material, delays ignition and reduces the spread of flames when that material is exposed to fire. However, the addition of a flame retardant cannot make the plastic non-combustible. The flame retardants used can be divided into several groups according to their mechanism of action [Osterath 2015].

The flame-retardant effect of polybrominated and polychlorinated organic compounds is based on the termination of the radical chain reaction of combustion in the gas phase. When the plastic is heated, bromine or chlorine radicals are first released from the flame retardant. The splitting of carbon-hydrogen bonds in the polymer forms hydrogen bromide or hydrogen chloride molecules, which cause the radical chain reaction to break down. To enhance the effect of the halogenated flame retardant, antimony trioxide is added to the plastic in a ratio of approximately 1:3 to the flame retardant, so that the mass content of antimony trioxide in the polymer is often between 3 and 6%.

Aluminium trihydroxide and magnesium dihydroxide split off water in an endothermic reaction above approximately 200 °C. This cools the plastic material and delays ignition.

Diluting the plastic with a non-combustible substance reduces its flammability. This can be achieved in two different ways:

- a) Addition of inert inorganic fillers (e.g. talc)
- b) Separation of non-combustible gases from the flame retardant when heated:

- Separation of ammonia, nitrogen and CO₂ from melamine (2,4,6-triamino-s-triazine)
- Separation of ammonia from ammonium polyphosphate

All inorganic and organic phosphorus compounds act as flame retardants in oxygen-containing polymers by forming a protective layer through carbonisation. Phosphorus compounds are often used in combination with nitrogen-containing compounds as flame retardants. This strengthens the phosphorus bond in the polymer and forms cross-linked structures which promote carbonisation when heated. Phosphoric acid esters are used as flame retardants in electrical and electronic equipment as well as in mattresses and upholstered furniture (see 6.3.1).

The global market for flame retardants, estimated at 2.3 million tonnes in 2023, is divided into the following substance groups [ECHA 2023; Ceresana 2024a].

Aluminium trihydroxide	38 %
Organophosphorus compounds	17 %
Brominated and chlorinated substances	26 %
Antimony oxides	5 %
Other	14 %

Most brominated and chlorinated flame retardants, when used as additives, tend to volatilise and spread uncontrollably over long distances in the environment (see 6.2). As halogenated compounds, they are persistent in the environment, accumulate in living organisms and often exhibit significant chronic toxicity [Chen et al. 2023]. For this reason, the technical mixtures of penta- and octabromodiphenyl ethers were banned in 2009, hexabromocyclododecane (HBCD), used in expanded polystyrene for thermal insulation, was added to the Stockholm Convention on Persistent Organic Pollutants (POPs) in 2011, and decabromodiphenyl

ether was added in 2017 with the aim of global elimination [UNEP 2025]. For the same reason, short-chain chlorinated paraffins (SCCPs) were banned in the EU in 2015 and added to the Stockholm Convention in 2017. Even after 2017, almost all of the 13 technical chlorinated paraffin mixtures tested contained short-chain chlorinated paraffins (SCCPs) (> 600 mg/kg), three of which exceeded the maximum value of 1% set by the EU and the Stockholm Convention [Guida et al. 2023]. SCCPs have been replaced by medium-chain chlorinated paraffins (MCCPs), which have similarly problematic properties and are also often significantly contaminated with SCCPs. Their annual global production volume in 2020 was estimated at around 700,000 tonnes, mainly used as flame retardants and plasticisers in PVC, polyurethane and rubber products [Chen et al. 2022]. They enter Europe mainly through product imports, primarily from China. In 2021, the ECHA classified MCCP as substance of very high concern (SVHC) and therefore as a candidate for authorisation [ECHA 2025b]. In May 2025, it was decided to include it as a POP in the Stockholm Convention [UNEP 2025]. Long-chain chlorinated paraffins (LCCPs) are now also being used at high production growth rates (350,000 tonnes/year globally in 2024) [Promarket Reports 2025] and are increasingly found in the environment [Yuan et al. 2022]. Information on the toxicity of LCCPs is still scarce [Chen et al. 2023]. Due to their persistence and accumulation capacity, they, like all chlorinated paraffins, are also considered problematic additives.

There are some brominated compounds that are chemically bound into the polymer matrix and are therefore referred to as reactive flame retardants. For example, tetrabromobisphenol A (TBBPA) is sometimes incorporated into the macromolecules instead of bisphenol A in the manufacture of epoxy resins and poly-

carbonates. It is also the brominated flame retardant with the highest annual usage, at more than 150,000 tonnes. Unlike additives, the chemical bond prevents reactive flame retardants from volatilising. As a result, only a relatively small amount is released from materials into the environment, e.g. through hydrolysis and abrasion of small particles. However, TBBPA has now been classified as probably carcinogenic (category 1B) and was therefore listed as a substance of very high concern in the EU at the beginning of 2023 [ECHA 2025b].

6.1.3 Ageing inhibitors

The ageing of plastics and rubber refers to damage over long periods of time due to the influence of (UV) light, oxygen, ozone, temperature, moisture (including acidic or alkaline) and heavy metals. Ageing can be delayed or inhibited by adding stabilisers, which can be divided into antioxidants and UV light stabilisers. [Römpp 1998; Bonnet 2013]

Antioxidants

Primary antioxidants are radical scavengers that act by donating an electron or H atom to a radical, because free radicals occur during auto-oxidation. The following groups of substances are suitable as radical scavengers:

- Aromatic amines: e.g. p-phenylenediamine and alkyl compounds, alkylated diphenylamines
- Hydroquinones (1,4-dihydroxybenzenes)
- Brenzcatechins (1,2-dihydroxybenzenes)
- Phenols substituted with sterically hindered groups

An important example of the first group is N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD; CAS 793-24-8), which is added as an antioxidant in tyres and other rubber articles at a mass fraction of 0.4–2%. 6PPD protects the rubber from oxidation by ground-level ozone in the air and is itself

oxidised to 6PPD-quinone. 6PPD is used in large quantities in the EU, in the range of 10,000–100,000 tonnes per year. Tyre abrasion (around 100,000 tonnes per year in Germany) releases large quantities of 6PPD and 6PPD quinone into the environment. 6PPD quinone has been identified as the substance responsible for the widespread death of silver salmon during the spawning season on the west coast of the USA [Tian et al. 2020]. The example of 6PPD highlights a gap in the REACH chemicals regulation: it is not the highly toxic transformation product 6PPD-quinone that is assessed, but only the comparatively harmless starting product 6PPD.

An example of the group of sterically hindered phenols is BHT (3,5-di-tert-butyl-4-hydroxytoluene). In addition to its use in rubber products, it is also approved as an antioxidant in food (E321) and in pharmaceuticals and cosmetics.

Secondary antioxidants are peroxide scavengers. They prevent the onset of oxidation by removing an oxidative catalyst. The following groups of substances are used for this purpose:

Organic sulphides, polysulphides, dithiocarbamates, phosphonates and organophosphites (e.g. tris-(4-nonylphenol) phosphite in polystyrene and PVC, triphenyl phosphite in paints and polymers).

Primary and secondary antioxidants enhance each other's effects. Primary antioxidants are not very effective against oxidation caused by UV light.

UV light protectors

The absorption of solar UV radiation in the wavelength range of 280–400 nm is one of the main causes of polymer degradation. Sunlight can cause discolouration, cracking and embrittlement in plastics, among other things. This

process is known as photo-oxidative degradation. All technical polymers contain UV-absorbing impurities such as catalyst residues or solvents. The chain reaction responsible for the degradation of polymers is triggered by the absorption of UV radiation. The polymer chain is split into two radicals, which can form peroxy radicals with molecular oxygen. Under the influence of energy, the peroxy radical abstracts a hydrogen atom from the polymer chain, forming a hydroperoxide and an alkyl radical. The alkyl radical can react again with oxygen to form a peroxy radical. The hydroperoxide decomposes into an alkoxy radical and a hydroxyl radical. This radical chain reaction is only terminated when two radicals react with each other.

There are basically three ways to prevent the photo-oxidative degradation of polymers with additives:

- UV absorbers
- Radical scavengers/peroxide decomposers (see antioxidants)
- UV quenchers

UV absorbers prevent photo-oxidative degradation by filtering out the UV radiation from sunlight and converting the energy into heat. Examples are 2-hydroxybenzophenone and 2-hydroxyphenylbenzotriazole derivatives. The latter have a high absorption maximum in the ultraviolet wavelength range of 300–400 nm. However, at least some of these substances are persistent and bioaccumulative in the environment, so that four substances (UV-320, UV-327, UV-328 and UV-350) were classified as substances of very high concern in the EU Chemicals Regulation of 2014 and 2015 and are therefore subject to authorisation since 2023 [ECHA 2025c].

Sterically hindered amines are mainly used as radical scavengers/peroxide decomposers,

which intercept the reactive photo-oxidation products. UV quenchers can destroy the excited states of the chromophores and convert the energy into harmless heat or light. Organic nickel compounds are among the most important representatives of this class.

6.2 REDUCING THE USE OF PROBLEMATIC FLAME RETARDANTS

Since the diffuse release of additives from plastic materials during the product life cycle cannot be prevented and most polybrominated and polychlorinated organic compounds are (potentially) persistent in the environment, options for replacing or avoiding them are described here [Beard 2002; Troitzsch 2011; Maier, Schiller 2016].

6.2.1 Polymeric brominated flame retardants

Macromolecules cannot volatilise and are therefore only released into the environment in small quantities. Furthermore, macromolecules are generally hardly bioavailable. Polymeric brominated flame retardants require significantly less antimony trioxide as a synergist than other systems. Brominated polystyrenes are used as flame retardants in polyamides. PolyFR is a block copolymer made from polystyrene and brominated polybutadiene. It is used in polystyrene foams (EPS, XPS) for thermal insulation composite systems as a substitute for the additive flame retardant hexabromocyclododecane (HBCD), which has been banned in the EU since 2018.

6.2.2 Polymeric organic phosphorus compounds

Reactive phosphorus(III) polyols can be used in place of technical pentabromodiphenyl ether (pentaBDE), which has been banned in the EU since 2004, for polyurethane flexible foams (upholstered furniture, mattresses). Polyphosphonate homopolymers, e.g. for linear poly-

ters (PET, PBT), thermoplastic polyurethane (TPU) and polylactic acid (PLA). A block copolymer of polyphosphonate and polycarbonate is used as a flame retardant in polycarbonates.

6.2.3 Inorganic phosphorus compounds

Metal phosphinates (titanium, zinc, iron, aluminium) can be used in polyamides, polyesters, epoxy resins and PU resins. Melamine polyphosphate (MPP) and ammonium polyphosphate (APP) act as flame retardants by first releasing ammonia at temperatures above 250 °C and then forming a charred surface layer at higher temperatures (see 6.3.2).

6.2.4 Inorganic hydroxides

Aluminium trihydroxide (ATH) and magnesium dihydroxide (MDH) can replace halogenated organic flame retardants in the electrical and electronics sectors, for example. They make up to 60% of the polymer by mass.

6.2.5 Inherently flame-retardant polymers

When heated, oxygen-containing plastics undergo dehydration through water abstraction, forming a protective layer on the surface through carbonisation. This corresponds to the mode of action of phosphorus compounds (see above), which is why such plastics do not require the addition of a flame retardant. Such inherently flame-retardant polymers are:

- Aromatic polyamides (aramids) which are used in the electrical and electronics industries and for special textiles. (Aliphatic polyamides, on the other hand, show only slight carbonisation.)
- Polyarylsulphones (PPSU), polyarylethersulphones (PES), polyarylethers (PAE), polyaryletherketones (PAEK),
- Polyphenylene sulphides (PPS) are also self-extinguishing.

Compared to common mass-produced plastics, these polymers are relatively expensive, which is why they are mostly found in special applications.

6.2.6 Non-combustible and other insulation materials for buildings

Non-combustible mineral wool (rock wool, glass wool) is an almost equally inexpensive and effective alternative to flame-retardant expanded polystyrene for thermal insulation of building facades and can be used for most applications. Another alternative is thermal insulation materials made from wood or hemp fibres [Gutex 2025, Pavatex 2022, Thermo-Hanf 2021]. The developer of the ecological alternative using hemp received the German Environmental Award in 2013 [DBU 2013].

6.3 DEFICITS IN THE REGULATION OF ADDITIVES

Decabromodiphenyl ethane (DBDPE) has been used since the 1990s as an additive flame retardant to replace decabromodiphenyl ether (DecaBDE), which was classified as a substance of very high concern in the EU at the end of 2012 due to its persistence, among other things [ECHA 2025b] and its use is subject to extensive restrictions. However, despite its semivolatility, DBDPE is widespread in the environment, similar to DecaBDE. In Bavaria, for example, the substance is found in the air not only in urban areas but also on the Zugspitze [Umweltbundesamt Österreich 2021]; its entry into alpine forest ecosystems through atmospheric deposition has already been detected in soil samples (litter and humus layers) from the Berchtesgaden National Park in 2009 [Körner 2023]. This is clearly a case of *regrettable substitution*, as these two highly brominated, structurally closely related aromatic compounds show no significant difference in terms of persistence. There is currently no EU regulation for DBDPE.

Unfortunately, there are a number of other examples where a chemical regulated in the EU due to its persistence and bioaccumulation (and toxicity) has been replaced by manufacturers with a structurally related substance with similar problematic properties. This has happened several times within the PFAS group of substances. For example, perfluorooctanoic acid (PFOA), which was used for decades as an emulsifier in fluoropolymer production, has been replaced by the polyfluorinated oxocarboxylic acids DONA and HFPO-DA (see 6.2). However, these substitutes are just as persistent and escape from production facilities that are not completely sealed into the environment via exhaust air and wastewater, where they can be detected in the air, precipitation, soil, and ground and surface water, among other places [LfU 2013, LfU 2025, Gebbink, van Leeuwen 2020].

The approach of considering and regulating each individual chemical, as previously provided for in the EU chemicals legislation REACH, has therefore proven to be lengthy and ineffective in terms of environmental and health protection. Since persistence is the key critical property of organic chemicals that can enter the environment during their production, use and disposal phases, there is a need to further develop REACH. For numerous polybrominated and polychlorinated organic compounds, which are used, among other things, as flame retardants for plastics, there is a large number of published studies that confirm their presence in various environmental media and thus their persistence [Covaci et al. 2011; Vorkamp & Rigét 2014]. In this case, regulation of both groups of substances as a whole would be necessary instead of further regulation of individual substances in order to achieve real progress in substance-related environmental and health protection.

In fact, in March 2023, the ECHA published its strategy for regulating flame retardants. It identifies brominated aromatic flame retardants as candidates for an EU-wide restriction because these substances are generally persistent in the environment [ECHA 2023]. A corresponding restriction proposal, which could also include some non-aromatic brominated flame retardants, is planned for 2025.

The substance 6PPD is added to rubber compounds for vehicle tyres to prevent the oxidative destruction of the tyre matrix by ozone in the air. In this process, 6PPD itself is oxidised by ozone to 6PPD-quinone in order to fulfil its desired function (see 6.3.3, section on antioxidants). However, this by-product, which is extremely toxic to silver salmon [Tian et al. 2020; 2022] and is produced in significant quantities when used as intended, does not have to be tested and evaluated for potentially hazardous properties under current chemical legislation. This gap in the EU chemicals legislation REACH must be closed.

The import of consumer goods and other consumer-related products from non-EU countries is currently largely exempt from official controls for harmful substances when ordered online. In 2024, BUND had 15 party items from online retailers tested for harmful substances on a random basis. In more than half of the products, legal limits for harmful and banned additives such as DEHP, other phthalate plasticisers and short-chain chlorinated paraffins were exceeded, in some cases drastically [BUND 2024]. Effective control in this area is virtually impossible due to the huge number of products sold online. However, the analytical capacities of market surveillance authorities are completely inadequate. A comprehensive ban on harmful substances in products, which does not yet exist in the EU chemicals legislation REACH, is urgently needed.

6.4 REQUIREMENTS FOR RECYCLING

Material recycling is problematic for plastics with a high proportion of additives, as hazardous substances can easily be transferred to consumer goods. Behnisch et al. found high levels of brominated flame retardants and brominated dioxins/furans in 48 samples of consumer products and toys from four continents that were made of black plastic [Behnisch et al. 2023].

Material recycling works best with simple plastics that contain no or only low levels of additives or only unproblematic substances. However, a number of additives such as antioxidants and UV light stabilisers are necessary to make plastic products as durable as possible; increasing the concentration of these additives extends the service life of the products. One example is the addition of the antioxidant 6PPD (see 6.3.3) to protect the rubber in vehicle tyres from oxidative degradation by ozone in the air. On the other hand, many inorganic additives can also interfere with material recycling. There is a certain demand for plastics that are highly complex and highly adapted and contain many additives. These will be almost impossible to recycle [Neubauer, 2023]. All other plastics, if necessary, should be designed so that they can be collected separately and recycled mechanically. The lack of declaration of additives and their diversity often hinders or prevents the material recycling of plastics (see Chapter 7). High-quality material recycling can only be achieved if the variety of additives in mass-produced plastics is significantly reduced [Steinhäuser & Große Ophoff 2025]. A mandatory, transparent positive list of permitted additives would protect against unforeseen hazards and quality losses in recycled plastics.

HEALTH RISKS POSED BY ADDITIVES

Over 16,000 chemicals are used in plastics or plastic products or may be contained in them. More than 4,200 of these chemicals are considered hazardous due to their properties, and there is no data available for 10,000 of them [Wagner et al. 2024].

Given the large number of chemicals in our everyday lives and other environmental factors, it is not easy to establish a direct link between a disease and chemicals as the trigger. However, for decades we have seen a massive increase in diseases caused by disruptions to our hormone system, such as breast and testicular cancer. The number of sperm in semen has been declining for years, falling by 51% on average worldwide between 1973 and 2018. This is leading to increasing infertility in men [Levine et al. 2022]. This massive increase in hormone-related diseases has led the World Health Organisation (WHO) to conclude that increasing chemical exposure must have an impact [WHO 2012].

Plastic additives can evaporate from products and enter the body through skin contact, indoor air or indirectly via house dust.

One example is phthalates, which are used as plasticisers, especially in PVC (see 6.3.1). Products made of PVC include children's toys, plastic tablecloths and vinyl flooring. As they can cause infertility in boys and men, the use of

some phthalates has been restricted in the EU [ECHA 2025a, Entry 51]. This restriction came late, as studies on the hormonal effects of phthalates have been available since the 1990s [Gray jr. 2000] and phthalates are already found in the bodies of almost all Germans. The fourth German Environmental Health Study in 2009 (GerES IV) found that all phthalate metabolites tested were detectable in almost all urine samples (N=599). Children had three to five times higher concentrations than adults analysed during the same period. Some children even exceeded the Human Biomonitoring Value I (HBM I) of 500 µg/l in urine for the sum of the metabolites 5OH-MEHP and 5oxo-MEHP, which indicates that health effects in these individuals cannot be ruled out with sufficient certainty [Becker et al. 2009]. Soft PVC cannot be produced without plasticisers, as it would otherwise become brittle; additives can account for over 50% of the material. Following the restriction of the four phthalates, other plasticisers such as DINCH and bis(2-ethylhexyl)terephthalate (DEHT) are now frequently used (see 6.3.1). The question remains as to whether these less well-studied substitutes have similar negative effects.

The situation is similar with bisphenols. In addition to its use as a starting material for polycarbonate, a transparent plastic used in measuring cups and beverage bottles until 2024, bisphenol A is also a building block for epoxy resins, which are used, among other things, as baked-on coatings for the interior of food cans. Bisphenol A was

also used for a long time as a coupling component for writing in thermal paper for cash register receipts. Bisphenols also impair fertility and the endocrine system. Here, too, it took many years for regulation to be introduced [Beronius et al. 2010]. For a long time, BPA was only banned in baby bottles (2011) and then in cash register receipts and other thermal paper [ECHA 2025a, Entry 66]. In 2023, the EU Food Safety Authority EFSA recognised a higher risk from BPA and reduced the previously applicable limit for the so-called tolerable daily intake (TDI) by a factor of 20,000, from 4 micrograms to 0.2 nanograms per kilogram of body weight per day. This was followed at the end of 2024 by a ban on BPA in food contact materials. In France, such a BPA ban has been in force since January 2015. The ban on food contact materials applies to bisphenol A and bisphenol S. However, studies have long indicated that other bisphenols used as alternatives also have hormonal effects [Reininger & Oehlmann 2024]. These cases show that, on the one hand, the regulation of harmful substances under the REACH chemicals legislation is very slow and often only individual chemicals are banned, which shifts the problem to similarly problematic chemicals. Many researchers therefore advocate regulating entire groups of (harmful) chemicals. In addition, the high health costs associated with plastic materials must be considered. It is estimated that in the United States alone, chemicals in plastics cause health costs of \$22.4 billion every year [Trasande et al. 2024].

FOOD CONTACT MATERIALS

Chemicals from food contact materials (FCM) can migrate into packaged foods and be ingested by humans. Plastic packaging in particular contains a wide variety of chemicals. More than 14,000 chemicals from food contact materials are listed in databases, of which approximately 12,000 are intentionally added and approximately 2,000 are not intentionally added, such as residual monomers, degradation and breakdown products. Many of these chemicals can migrate into food and contribute to chemical exposure in humans [Geueke et al., 2024; Muncke et al., 2025]. In order to systematically collect data on chemicals that can be extracted from food contact materials or migrate into food or food simulants¹, an international working group has created a database [Groh et al., 2021]. This database contains 12,285 chemicals and is publicly accessible. Plastic is the most frequently investigated material, with 1,975 analytically detected chemicals [Geueke et al., 2023]. This reflects the high chemical complexity and widespread use of plastics in food packaging. In biomonitoring studies using human blood or umbilical cord blood, numerous chemicals from food contact materials have been detected [Wang et al., 2021]. The most common were phthalates and their metabolites, the antioxidants tert.-butyl hydroxytoluene (E 321) and 2,6-di-tert-butylphenol, as well as decamethylcyclopentasiloxane and dodecamethylcyclohexasiloxane, bisphenols and per- and poly-fluorinated alkyl compounds (PFAS)

¹ Model substances used in migration tests instead of food.

[Muncke et al., 2023]. The presence of PFAS in food contact materials is particularly concerning because this group of chemicals, which comprises several thousand substances, cannot be broken down and therefore spreads in increasing concentrations across the globe [Brunn et al., 2023]. Many members of this group are chronically toxic at very low concentrations. Paper and compostable containers in particular, but also several plastic materials used for food packaging, are coated with PFAS, with fluorotelomer alcohols, phosphoric acid esters and side-chain fluorinated polymers being particularly common [Barhoumi et al., 2022, Schwartz-Narbonne et al., 2023]. The OECD published a report identifying alternatives to PFAS in food packaging [OECD 2020]. The use of some of these substances in food contact materials is now banned or severely restricted in the EU. For example, some bisphenols and bisphenol derivatives have been banned in food contact materials in the EU since December 2024 [European Commission, 2024b]. Although the chemicals can also enter the human body through other routes of exposure, food contact materials clearly play a significant role. It is alarming that of the 235 chemicals detected in biomonitoring from food contact materials, 100 are chemicals of concern – carcinogenic, mutagenic, reprotoxic and endocrine disruptors or specific organ toxicity. A systematic analysis of 470 studies on chemicals in plastic packaging shows that 1,086 of the 1,346 chemicals analysed could migrate into food under certain conditions. This

means that, according to the studies, 81% of the chemicals can be absorbed by humans (exposure) [Geueke et al. 2023]. The usual assessment of toxicity based on single-substance-specific data is insufficient here, as the harmful effect results from the interaction of numerous components [Muncke et al., 2023]. For example, many eluates from plastic packaging show higher in vitro toxicity than the data for the individual substances would suggest [Zimmermann et al., 2021].

In the EU, food contact materials are governed by Regulation 1935/2004 [EU 2004]. According to this, new additives require authorisation. Data must be submitted to the European Food Safety Authority (EFSA), which must verify the transfer to food through migration tests [EFSA 2021]. Currently, approximately 1,000 chemicals from food contact materials are listed [EU 2011b], but for many of these substances there are no generally available analytical methods, which makes monitoring difficult [Muncke et al., 2023]. A special category is “active and intelligent” chemicals from food contact materials, which are subject to Regulation 450/2009 [EU 2009]. These interact with the packaged food by indicating that it has spoiled or by keeping it fresh for longer. Such chemicals are unnecessary and avoidable and do not make a meaningful contribution to reducing food waste.

Recycled plastic is rarely suitable as a food contact material because harmful substances can accumulate in the plastic during the recycling process and

fragments of the polymer and transformation products may be present.

Bioplastics (biodegradable plastics and plastics made from biological raw materials) and other plant-based materials are often touted as sustainable alternatives to conventional plastics. However, these can also contain hazardous chemicals and exhibit similar toxicological profiles to conventional plastics [Zimmermann et al., 2020].

The concentrations of chemicals from food contact materials are particularly high in ultra-processed foods (UPF), whose market share is growing [Yates et al., 2024, Muncke et al., 2025]. Highly processed foods are often sold in small packages. During preparation, they come into contact with plastic in many different ways. Epidemiological studies show higher chemical exposure in population groups that eat a diet consisting mainly of highly processed foods [Lane et al. 2024].

It is clear that legal provisions are not sufficient to adequately protect the population from the intake of chemicals from food contact materials that are harmful to health. Zimmermann et al. point out that 388 chemicals from food contact materials meet the criteria set out in the EU's "Chemicals Strategy for Sustainability" [European Commission 2020]. Many of these chemicals have been proven to migrate into food [Zimmermann et al., 2022]. Where food packaging is necessary, there are safe products on the market that do not contain any known hazardous chem-

icals or at least do not transfer them into food. Manufacturers must disclose the chemical composition and processing steps of their plastic products. As a minimum requirement, food contact materials should not contain any hazardous or untested chemicals.

7 Recycling of plastics

7.1 POSSIBILITIES AND LIMITATIONS OF MATERIAL RECYCLING

Plastic waste fractions that can no longer be mechanically recycled are mostly used to generate energy in cement plants, power stations and waste incineration plants. In 2023, 34 per cent of the plastic waste collected, sorted and pre-treated (post-consumer waste and post-industrial waste) in Germany was reused as recycled material. Less than 1% of waste was sent to landfill, less than 4% was sent abroad for material recycling and over 60% was thermally recovered in waste incineration plants or as a substitute fuel, for example in cement kilns. The share of recycled material from post-consumer waste in total plastics processing was 12.8 per cent [Jepsen et al., 2020]. The use of recycled material from post-consumer waste has increased in all areas of application, for example in construction, packaging, agriculture, horticulture and forestry, and in the automotive sector [Conversio 2024].

The material recycling of plastic waste is limited by various factors. In general, most plastics are only recyclable to a limited extent: a loss of quality and material is unavoidable both during the use phase and during recycling. Recycling has physical, technical, economic and logistical limitations.

Physical and technical limitations include material wear, thermodynamics, colour sorting, odour and contamination. Plastics lose quality (downcycling) and material (dissipation) with each recycling cycle. Furthermore, polymers and additives can no longer be separated purely thermodynamically. Other losses are functional, such as tyre abrasion. In addition, recycling requires energy to process materials – often more than new production. The mechanical, chemical and physical properties

of the recycled materials are decisive for their use. The quality of recycled materials is influenced by ageing processes (e.g. as a result of UV radiation, moisture or temperature), the recycling process itself (mechanical and thermal stress) or so-called mixing damage (imperfect separation processes or compounding of the starting materials) [Quicker & Seitz 2024]. Unknown additives and foreign substances (IAS and NIAS) added to plastics are found in the recycled material.

Mixed or coated materials (e.g. mixed plastics or plastics with other materials such as paper) are difficult and often impossible to recycle and are therefore incinerated. Plastics such as epoxy resins and other thermosets (e.g. polyurethane) cannot be recycled according to the current state of technology.

Economic constraints include high costs, lack of demand, lack of subsidies and incentives such as quotas. Recycling is often more expensive than production from new raw materials. Many recycled materials are of lower quality and have few buyers. Without political support, recycling is often not economically viable.

Logistical and social challenges include inadequate separation, global waste streams and a lack of infrastructure. Consumers often separate waste incorrectly, making recycling impossible or inefficient. Poor packaging design, a lack of collection infrastructure (including separation into food and non-food items) and a lack of knowledge are the reasons for this. According to the Basel Convention, mixed plastic waste may no longer be exported, yet German plastic waste still ends up in countries such as Turkey. There are no suitable recycling facilities there and fires break out in illegal dumps. Germany, once a pioneer in the

circular economy, now ranks only in the middle [Eurostat 2021]. There is consensus that, although Germany has steadily optimised waste disposal, it has not focused enough on developing systems in which waste is recovered as raw materials for the local economy, which is mostly based on fossil raw materials, especially in the plastics and chemicals sectors.

The EU Commission is also aware that dependence on fossil fuels and raw materials and the lack of a circular economy infrastructure are Europe's greatest economic weaknesses [European Commission 2024b]. A circular economy could close this gap, but key investments in the necessary infrastructure, especially for the first stages of the waste hierarchy such as plastic avoidance, reuse and mechanical recycling, are lacking, as are design specifications that regulate the diversity, transparency and safety of the chemicals used. However, expanding recycling infrastructure could lead to lock-in processes [Syberg 2022] that prevent resources from being focused on more effective regulatory levers such as plastic avoidance and reuse (deposit systems) [Wang et al. 2023], which are also less harmful to the climate.

Plastics contain chemicals (additives) that can interfere with recycling or be released during the process. Not only substances of very high concern (SVHC) are critical, but also less toxic contaminants such as carbon black, which interferes with infrared detection in sorting plants. All plasticisers impair the extrusion of secondary plastics.

In Germany, the following plastic-containing fractions are collected separately: packaging and plastic fractions via household recycling collection and from businesses ("yellow bin"), construction and demolition waste, which is usually already separated into fractions, bulky

waste, end-of-life vehicles and waste electrical and electronic equipment. There is often a considerable gap between the state of the art and industrial practice. It is clear that the practice of plastics recycling lies primarily in the implementation of existing technology and in different product design, rather than in the development of further technical innovations [Quicker & Seitz 2024).

Improved collection and sorting are necessary because high-quality recycling depends on clean separation by type. Separation by polymer type is often not sufficient. Additives (and impurities) are problematic because they can mask the physical or chemical properties used for detection and sorting, making it impossible to separate even the plastic types cleanly. Therefore, the following potential improvements to sorting should be pursued and implemented: use of markers and digital watermarks, sorting by product form in conjunction with artificial intelligence-supported image recognition, flotation processes where appropriate, and the use of additional detectors or sensors. The digital product passport must take the requirements of the recycling industry into account. In the context of further processing after separation of plastic waste into plastic fractions, the following issues should be considered: improvement of cleaning performance, reduction of energy and water consumption in washing, and processing in line with requirements.

New technologies that combine laser technology, spectroscopy and digitalisation will significantly improve the possibilities for mechanical recycling in the future. An exemplary technology works as follows: First, the plastics or other materials such as metals are broken down into small pieces (flakes). These flakes are then irradiated with a laser and the reflected light emissions are measured. Digital spectroscopic

analysis can identify the type of plastic or metal alloy in a fraction of a second. The sorting is then carried out by air jets, which transport each individual flake into the appropriate container. Hundreds of thousands of flakes can be identified and sorted per second. The lasers can also vaporise surface contamination or coatings using a short, high-energy pulse, which is then followed by the measurement pulse for the cleaned area of the flake. These processes are already proven and established in the recycling of disposable PET bottles. They are able to accurately separate the PET from the PVC in bottle caps. In addition, spectroscopy also detects contaminated plastic, for example if waste oil has been stored in such a bottle, and can reliably remove this contaminated plastic. The recycled PET obtained is once again of food grade quality and can be used to manufacture new bottles. [Spilok 2015, Unisensor 2025]

Recycling alone cannot solve the complex multi-crisis (biodiversity, resources/pollution, climate). Avoiding and reusing plastics is more effective and conserves resources, so all existing avoidance measures must first be exhausted. Even high-quality material recycling has its limits: technical, infrastructural, economic and physical. There is great potential in product design (design for recycling) and in the design of systems, in the expansion of the collection, sorting and processing infrastructure for high-quality mechanical recycling, and in limiting the use of certain plastics and additive groups, as well as in transparency regarding ingredients. Only when this potential has been exploited (through stricter regulation and/or financial incentives) can thermochemical processes be useful in certain sectors and for certain products. In order to operate in a truly resource-efficient manner in line with the EU's circular economy [European Parliament 2023], interdisciplinary approaches, accurate

analyses and systemic changes as well as infrastructure development are necessary to effectively reduce primary resource consumption and environmental impact. The circular economy is not a "magic key" to a sustainable economy that enables "green growth". Reducing material flows through sufficiency is necessary to achieve environmental goals. For decades, corporations such as ExxonMobil and their associations have been promoting recycling as a solution, even though they knew that mechanical recycling is not technically and economically feasible on a large scale. Internally, an Exxon employee admitted as early as 1994: "We are committed to the activities, but not committed to the results" [Allen et al. 2024]. Misleading marketing campaigns served primarily to avoid regulations and secure sales of single-use plastics. By presenting recycling as the solution, production growth could continue unhindered.

As there are indications that industry associations have long been making false promises about the recyclability of plastics against their better judgement, California has initiated legal proceedings against Exxon [Allen et al. 2024].

7.2 THE SENSE AND NONSENSE OF CHEMICAL RECYCLING (FOR SYNTHETIC RAW MATERIALS)

Chemical recycling processes are believed to have the potential to recycle plastic waste that is currently used for energy in cement kilns or waste incineration plants. In addition to opening up new material flows for the circular economy, another advantage is the possibility of removing pollutants ("detoxification") from the cycle.

The processes summarised under the term "chemical recycling" vary greatly in terms of the input materials, technology, auxiliary energy and use of auxiliary materials, quality of the

products produced and the effort required for further material use.

The German Federal Environment Agency [Quicker & Seitz 2024] considers these processes in technically mature, energy-integrated and optimised plants to be a potentially positive contribution to the circular economy – but only if the potential of mechanical recycling (in particular through product design, collection, sorting and preparation) has been exhausted and only for certain sectors and products.

The data on chemical recycling is patchy. System boundaries are often not specified, and data on chemicals or pollutants in particular is missing or not published.

According to the German Federal Environment Agency [Quicker & Seitz 2024], chemical recycling is defined as follows: “Process chains in which polymers are completely or partially broken down into their constituent parts, which are then used as materials to produce new polymers or other substances. No energy is recovered (apart from by-products).” This definition includes solvent-based processes, which have detoxification potential. For example, brominated flame retardants are successfully separated from polystyrene in the CreaSolv process, while the Vinyloop process has not succeeded in removing phthalate plasticisers from PVC [Altnau & Hamann 2024, VINYLOOP 2001, 2018].

Thermochemical processes (liquefaction, pyrolysis, gasification) were analysed by Quicker and Seitz, particularly with regard to energy consumption and greenhouse gas emissions [Quicker & Seitz 2024]. They conclude that mechanical recycling is more energy-efficient. However, thermochemical processes can significantly reduce greenhouse gas emissions compared to energy recovery by combustion.

However, the data available must be evaluated differently. More reliable statements can be made about the approaches of liquefaction and pyrolysis, while there are still major gaps in knowledge in the area of gasification.

The benefit basket method applied by Quicker & Seitz, clearly showed that thermochemical processes are clearly inferior to mechanical recycling and only moderately inferior to recovery in cement kilns. However, some of the processes offer possibilities for removing pollutants from the recyclates, but no reliable, independent studies are available on this.

The hydrocarbon yields of liquefaction are approx. 80% and those of pyrolysis approx. 70%.

The pollutants and heteroatoms contained in the input material are transferred to the hydrocarbon fractions in relevant proportions and must be removed before further treatment. The sources of impurities in polyolefins are fillers, colourants, coatings and other additives. The oils must be treated by washing, distillation, filtering, adsorption and hydrogenation to remove or hydrogenate metals, ash, chlorine, nitrogen, oxygen and other impurities, as well as the high proportion of unsaturated compounds [Quicker & Seitz 2024]. In order to use the resulting oils in steam crackers for plastics production, they must meet quality criteria defined by the operators.

The three processes – gasification, pyrolysis and liquefaction – may require water-intensive cleaning processes, in particular through the use of wet scrubbers, which leads to high water consumption and possible water contamination by pollutants such as halogens, tars and nitrogen compounds. Gasification is particularly complex and sensitive to pollutants in the raw gas. Specific figures on consumption and pollution are not currently available.

While pyrolysis and gasification of plastic waste are carried out without added reactants, other chemical recycling processes need solvents or other substances for depolymerisation. The most important processes are solvolysis, liquefaction and hydrothermal liquefaction.

Solvolysis, i.e. the decomposition of polymers into oligomers or monomers, is primarily used for so-called condensation polymers, which are broken down “step by step” into monomers [Maisels et al., 2021]. The most important examples are polyurethane (PU(R)), polyethylene terephthalate (PET) and polyamide (PA). Solvolysis uses adapted solvents or reagents, which give rise to the various names for the respective processes, e.g. glycolysis – ethylene glycol, aminolysis – ethylene amine, methanolysis – methanol, hydrolysis – water. In this respect, solvolysis is a much more selective recycling process than pyrolysis.

PU recycling is used for mattress and upholstery foams. This results in polyols that can be repolymerised. PET recycling mostly involves packaging material from the food industry and fibres. The end products are monomeric compounds such as terephthalic acid and ethylene glycol. Glycolysis or methanolysis are usually used for both polymer groups, PU and PET. Polyamide from technical and textile applications and fishing nets can be recycled via aminolysis, for example [Maisels et al. 2021].

Liquefaction is carried out with the aid of a starting oil. The plastic waste is decomposed directly thermally or catalytically in a stirred tank reactor. The main product is a liquid hydrocarbon mixture. Until now, liquefaction processes have in rare cases been used from plastic waste. Mainly diesel oil is produced by this method. Liquefaction is considered a promising process for recycling selected

plastics and plastic-rich waste mixtures. However, further research and development work is needed. Liquefaction processes are not “omnivorous”. Plastics from the polyolefin group, primarily PE and PP, are suitable for these processes.

In hydrothermal liquefaction, plastic waste is broken down under high pressure with the addition of supercritical water and a catalyst to produce products similar to those obtained in pyrolysis (naphtha, light oil). However, industrial waxes and bitumen are hardly produced in this process.

In 2024, approximately 100,000 tonnes/year were recycled in Europe using the above-mentioned processes; in 2025, this figure was expected to rise to 1.2 million tonnes, but this was not achieved. According to the C4C study [VCI & VDI 2023], 2.23 million tonnes could be chemically recycled in Germany in 2045 (and 3.16 million tonnes mechanically). The rest must be used for energy recovery.

Experts from politics and science doubt the relevance of chemical recycling processes. It is predicted that by 2040, only around 3% of all plastic waste worldwide will be recycled in this way (15.4 million tonnes) [Nordic Council of Ministers 2023]. The UBA also predicts that pyrolysis oil will only cover 5–12% of the input for steam crackers in Germany in the future [Umweltbundesamt 2025b]. Zero Waste Europe states that even after 50 years of development, these pyrolysis is not a sustainable or effective solution [Veillard 2024]. In particular, pyrolysis is expensive, inefficient and requires large quantities of fossil raw materials. In a report, UNEP points out that these processes theoretically clean polymers, but it remains unclear whether harmful substances remain in the output [UNEP 2023]. Emissions (air, water, solid residues) must also be taken into ac-

count. This is also pointed out by other studies on pyrolysis, which mention emissions of nitrogen oxides, ammonia and dioxins, among other relevant emissions [Sphera Solutions 2022, Pivato et al., 2024]. UNEP concludes that chemical recycling processes should be scaled up with caution in the future and that further work is needed to assess their actual potential (costs, yield, greenhouse gas emissions and health impacts) [UNEP 2023]. The Center for Climate Integrity [Allen et al., 2024] also criticises the promises made under the label “advanced recycling” in a report, stating: The oil and plastics industries are promoting these processes as a breakthrough solution for plastic waste. However, internal documents and experts show that these methods have been known for decades, are technically limited and hardly practicable from an economic point of view. It is known internally that the quality and quantity of raw materials are often insufficient and that mixed plastic waste cannot be used effectively. Furthermore, fuels are often produced instead of new plastics [Allen et al. 2024].

8 Scenarios for reducing material flows

8.1 STATUS OF PLASTIC PRODUCTION AND PLASTIC WASTE

Plastic production has grown significantly in recent decades. Global production was 234 million tonnes in 2000 and rose to 460 million tonnes by 2019 [OECD, 2022a]. Plastic waste grew from 156 million tonnes to 353 million tonnes over the same period. China is the main producer, accounting for 32%; the EU produces 14% of the plastic manufactured worldwide, with a slight export surplus [PlasticEurope 2024]. In Germany, production amounted to 21.1 million tonnes in 2021, of which 17.7 million tonnes were produced from fossil raw materials and 1.65 million tonnes from recycled materials. The share of bioplastics was very low (approx. 1%) [Umweltbundesamt 2025a, Conversio 2022]. In 2021, 14 million tonnes were processed, of which approx. 58% were polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC). The most important areas of application for plastics are packaging (31.2%), construction (26.3%), automobiles (8.8%) and electrical/electronics (6.4%). Looking at the use of recycled materials, packaging (28%) and construction (40%) also dominate, but agriculture (12%) is also significant [Umweltbundesamt 2025a]. This suggests that recycled materials are often used in low-value applications (“downcycling”).

The amount of waste generated in Germany is significantly lower than the amount produced: while it was 2.8 million tonnes in 1994, the amount of waste rose to 5.67 million tonnes in 2021, the vast majority of which was post-consumer waste (5.44 million tonnes), which is also responsible for the sharp increase [Umweltbundesamt 2025a, Conversio 2022]. The useful life of plastics and plastic products

varies considerably. While packaging usually ends up in the waste stream after less than one year, lifespans of up to 50 years are not uncommon in the construction sector, for example [Plastics Europe 2022]. In 2016, 38 kg of plastic waste was generated per person per year in Germany [Heinrich Böll Stiftung 2019]. In contrast, plastic consumption per person and year in the EU was 187 kg in 2020 [Pottinger et al., 2024]. The recycling rate in the EU is 35%, although since 2019, according to an implementing decision by the EU Commission, the calculation is no longer based on the quantity of plastic waste delivered, but on the significantly lower quantity of shredded and washed plastic parts that are fed into the plant. Further quantities are lost there, so that the amount of recyclate obtained is even lower.

Plastics that are not recycled are incinerated in Germany or used as substitute fuel in cement kilns (“energy recovery”). Incineration plays a lesser role in the EU: 25% is landfilled. Outside the EU, plastic waste is usually not incinerated but landfilled, provided that it is collected and disposed of properly and not burned in unregulated open fires, buried (“mismanagement”) or thrown away and released (“leakage”) into the environment (rivers, seas, etc.) Some reports estimate that, particularly in countries with poorly developed waste management systems, the proportion of waste that is disposed of in an unregulated manner and enters the environment is as high as 32% [World Economic Forum et al. 2016].

Although countries in the Global South do not generally have the same level of waste management as industrialised countries, both per capita plastic consumption and waste gener-

ation are significantly lower than in industrialised countries.

8.2 THE “BUSINESS AS USUAL” SCENARIO

In 2022, the OECD published a Global Plastics Outlook [OECD 2022a]. It presents scenarios for how global production, waste generation and the presence of plastics in the environment will develop by 2060, based on the reference year 2019. The “baseline scenario” describes the development if there are no significant changes to the existing political framework conditions. According to this scenario

- production will increase from 460 million tonnes to 1,260 million tonnes (2.7 times) by 2060, of which only 143 million tonnes will be secondary plastic.
- of 1,014 million tonnes of plastic waste, which is a threefold increase, 507 million tonnes will be landfilled and 179 million tonnes incinerated. 153 million tonnes will be mismanaged – a slight improvement in percentage terms compared to 2019, but a significant increase in absolute terms. Of this, 38 million tonnes end up in the terrestrial or aquatic environment.
- this development increases the amount of plastic in the aquatic environment to 493 million tonnes – 145 million tonnes of which end up in the ocean – where it gradually breaks down into microplastics.
- plastic production and use contributed 3.4% (equivalent to 1.8 billion tonnes of CO₂eq) to greenhouse gas emissions in 2019. For 2060, 4.3 billion tonnes of CO₂eq are calculated in the baseline scenario.

In an update from 2024, the OECD forecasts slightly lower growth rates until 2040 [OECD 2024b]. In addition, the OECD specifies the current development of plastic waste in a working paper [OECD 2024a]. According to this, exports of plastic waste to non-OECD countries have

declined significantly following a change to the Basel Convention (2022: 6.3 million tonnes compared to 2017: 12.4 million tonnes), with a large proportion of waste exports continuing to go to Southeast Asian countries.

Other projections for the future cite slightly different figures. In their baseline scenario, Pottinger et al. expect plastic consumption to reach 749 million tonnes (86% of which will be primary plastic) and 121 million tonnes of improperly treated waste by 2050 [Pottinger et al. 2024]. Lau et al. expect the amount of plastic entering the oceans to increase to 29 million tonnes by 2040 [Lau et al. 2020, The Pew Charitable Trusts 2020].

8.3 ALTERNATIVE SCENARIOS FOR LESS PRODUCTION, WASTE AND ENVIRONMENTAL INPUTS

The OECD is developing two scenarios to reduce plastic pollution. Three sets of measures are being used with varying degrees of stringency [OECD 2022a and 2022b]:

- a. Reducing plastic production and use through a tax on plastic use and increasing the lifespan of plastic products (recyclable design, durability, reparability)
- b. Increasing the recycling rate by building capacity, promoting secondary products and extending producer responsibility
- c. Preventing improperly treated plastic waste from entering the waste stream by investing in waste collection and treatment and sorting at source.

The “Regional Action Scenario” levies a tax on plastic use of US\$750 per tonne (US\$1,000 for single-use plastics). The use of secondary plastics is promoted, increasing the recycling rate to 40% (globally). Improved waste management reduces improper disposal into the environment. However, the effectiveness of the measures remains limited: instead of tripling

production and waste generation, a doubling is expected.

In the “Global Ambition Scenario”, the tax is twice as high and the recycling rate is to reach 60%, resulting in a market share of secondary plastics of 40%. Primary plastic consumption and waste generation would be 33% lower. This still means an increase in plastic production from 460 million tonnes (2019) to 827 million tonnes (2060), but the authors are confident that these quantities can be managed. The approach relies on advanced recycling and cleaning technologies, can no longer be implemented through regional actions and requires a global approach with international cooperation [OECD 2022 a and 2022 b].

The Pew Charitable Trusts has developed a “System Change Scenario” to break the plastic wave and reduce marine litter by 78% compared to the baseline scenario. This is expected to reduce plastic consumption by 30%. Eight measures are to be implemented [The Pew Charitable Trusts 2020, Lau et al. 2020]:

- a. Reducing plastic production and use, with a particular focus on avoiding plastic in the packaging sector
- b. Substitution of plastic with paper and compostable materials
- c. Changing product design to increase the proportion of recyclable plastic to up to 54%
- d. Increasing the proportion of waste collected in low-income countries to 90% (in cities) and 50% (in rural areas)
- e. Doubling mechanical recycling capacity to 86 million tonnes in 2040
- f. Develop chemical plastic-to-plastic recycling to a capacity of 13 million tonnes in 2040
- g. Establishment of safe landfills and incineration plants for the 23% of non-recyclable plastic

- h. Reduction of plastic waste exports by 90% by 2040.

These measures are to be implemented through a mix of government regulations, controls and incentives, extended producer responsibility and market-based instruments (e.g. taxes, levies and certificate trading for recycling).

However, microplastics entering the oceans, particularly from tyre abrasion and textile fibres, pose a particular problem. In the business-as-usual scenario, 3 million tonnes of microplastics are expected to enter the oceans in 2040.

Further measures to prevent an increase in plastic production and use

In its study “The New Plastics Economy”, the Ellen McArthur Foundation highlights the need to significantly increase circularity, particularly in plastic packaging [Ellen McArthur 2016]. It proposes creating a market for secondary plastics by expanding recycling, reusable packaging and incentives to prefer circular products. This requires extensive standardisation in the packaging sector with uniform labelling, restriction to a few types of plastic without hazardous substances, i.e. greater transparency regarding the composition and specification of the plastics used – ideally on a global scale. Large-scale pilot plants should be used to develop and test innovations for standardising design, sorting and recycling systems. Another challenge is the development of multi-layer films that can be easily separated.

In its latest study from 2024, the OECD emphasises that an ambitious global package of measures is needed to effectively reduce plastic material flows [OECD 2024 b]. Regional measures in industrialised countries are not enough, nor is limiting action to waste man-

agement. A determined policy to limit plastic production and consumption, high recycling rates, the expansion of an effective waste collection and sorting system, and internationally harmonised eco-design standards for plastic applications are necessary. The macroeconomic costs are manageable but require international cooperation on financing due to the higher percentage burden on countries in the global South. The study also addresses other aspects such as the risks of microplastics, the avoidance of chemicals of concern and the need to remediate environmental damage.

In Europe, the EU has taken a number of measures to tackle the plastic problem. Recycling measures have been developed and promoted, circularity has been pursued, some unnecessary plastic products have been removed from the market and public awareness of the plastic problem has been raised [European Commission 2018, EEA 2020]. Progress has been made compared to other regions of the world. Overall, however, some measures, such as the ban on certain plastic uses in the Single Use Directive, are very fragmented and unlikely to bring about a reversal of the trend.

Pottinger et al. calculated the effectiveness of global measures on consumption, waste quantities, greenhouse gas emissions and unregulated waste disposal [Pottinger et al. 2024]. They considered the following approaches:

- a. Used plastic contains at least 40% secondary plastic
- b. Plastic production is frozen at 2020 levels (cap)
- c. US\$ 50 billion is invested in the collection and treatment of plastic waste (primarily in countries in the Global South)
- d. US\$100 billion is invested in recycling capacities and technologies

- e. The recycling rate of collected waste is at least 40% (based on the amount of plastic waste collected)
- f. A tax will be levied on packaging plastic
- g. The use of packaging plastic will be restricted or banned
- h. Reuse of packaging plastic (e.g. deposit bottles)

A combination of measures a, b, c and f would achieve a very effective reduction. Instead of 121 million tonnes of unregulated plastic waste, only 11 million tonnes would be generated in 2050. Greenhouse gas emissions would fall from 3.35 Gt CO₂eq to 2.09 Gt CO₂eq.

8.4 EFFECTIVE REDUCTION OF PLASTIC CONSUMPTION

An effective reduction in plastic consumption, the amount of plastic waste and the amount of waste entering the environment irregularly can only be achieved through global measures. Small-scale measures such as bans and restrictions on individual uses of plastic are not very effective. The most sensible approach appears to be a combination of sector-specific caps on plastic production [Erdle & Erikson, 2023], commitment to a minimum level of recycled plastic, a tax on the use of (packaging) plastic and investment in effective waste management, especially in countries in the Global South. A market for secondary plastic can support the achievement of high recycling rates. However, many issues remain unresolved, e.g.: how will production limits be distributed among countries and companies? How can the use of secondary plastic be increased without downcycling if the variety of plastics and their contents are not regulated, at least in mass applications? Who will collect the tax and how will the tax revenue be distributed to benefit countries in the Global South, which still need to invest in setting up effective waste management systems?

9 Recommendations and demands

BUND is calling for a radical shift in thinking on the subject of plastic. This requires sustainable material flow management for plastics (see section 9.1), consistent policy (see section 9.2), a global plastics agreement (see section 9.3) and the promotion of research and education (section 9.4).

9.1 FOR SUSTAINABLE MATERIAL FLOW MANAGEMENT OF PLASTICS

Plastics should only be used if they offer concrete benefits for the environment and society as a whole. The current large number of applications with little or no social benefit should be avoided as far as possible. The question of the necessity of the application or product should therefore always be asked (sufficiency²) [IKHAPP 2024, INEBB 2018]. Furthermore, natural (non-chemical) alternatives, such as wood instead of plastic or natural fibres instead of synthetic fibres in textiles, should always be preferred without the use of harmful chemical additives and without jeopardising food security through their cultivation [Helm et al., 2025].

Essential plastic products should be designed so that they can be reused. If this is not possible, material recycling of plastics should be clearly preferred over other methods. For material recycling, return and take-back obligations, possibly with deposits, as well as service models could be considered as substitutes for (single-use) plastic applications.

The basic framework conditions for a limited number of standard plastics with few environmentally compatible additives for essential applications with large volume flows should be defined according to scientific criteria. The aim is to ensure that these standard plastics

can be sorted properly after use and recycled. These standard plastics should be reviewed regularly so that they can be further developed through innovation and optimised from an environmental perspective.

Environmentally open applications of plastics, such as mulch films or plastics as “soil improvers”, should be minimised or further developed in such a way that releases into the environment are avoided.

Particular attention must be paid to the environmental damage caused by microplastics and nanoplastics. Primary microplastics must therefore be banned. For secondary microplastics, such as plastic abrasion resulting from the decomposition or use of plastic products (especially tyre abrasion), ways of minimising their release into the environment must be found as a matter of urgency.

Another problem is posed by liquid and water-soluble plastics that are released directly into the environment. The use of liquid or water-soluble plastics, especially hydrogels, should be minimised.

The pollution of indoor air by plastics or their constituents (e.g. synthetic textiles, furniture, floor coverings) should be minimised. High standards of freedom from harmful substances and comprehensive knowledge of their composition are required, especially for plastics in contact with food or children.

Plastics should be tested for their effects on various biosystems. In addition to aquatic systems, soil, air and effects on humans and/or animals should also be tested (leaching and evaporation). Such impact tests can also

2 https://www.nachhaltigkeit.info/artikel/suffizienz_2034.htm

detect the effects of ingredients that are not yet known.

Problematic ingredients and substance groups should be banned. Such bans must also be implemented promptly via the REACH processes. Exceptions should only be made for necessary applications with high societal benefits (essential uses) [Scientists Coalition, 2024]. Such exceptions should be temporary and reviewed regularly to ensure that the search for sustainable, safe alternatives for such applications continues.

9.2 RECOMMENDATIONS FOR POLICYMAKERS

International and national legislation should establish regulations that restrict the use of plastics in short-lived applications that are potentially environmentally harmful. Appropriate legal regulations (e.g. in a resource conservation law or a plastics law) at national and European level should include:

- Short-lived plastics require approval. For all plastics whose period of use by consumers is less than one year, the benefits of the application must be demonstrated to an independent approval authority, alternatives must be examined and, if the application proves to be appropriate, a concept for material recycling and the absence of problematic substances (see below) must be submitted. If the manufacturer cannot (or does not want to) meet the above requirements, they must pay a plastic levy with a steering effect. The levy depends on the degree of non-compliance with the above requirements.
- The material recycling concept for these short-lived plastics is the responsibility of the manufacturer (extended producer responsibility). They must ensure that the plastic is reused after its useful life or sent for material recycling and then recycled appropriately. For their own production, they must strive to use the highest possible amount of recycled plastic in accordance with the state of the art [Betz et al., 2022].
- Composting, thermal recycling, pyrolysis and similar processes are significantly worse than material recycling processes in terms of both energy consumption and resource conservation. These processes should therefore only be used if existing prevention measures have been exhausted and material recycling has been proven impossible. Investments must be made in advanced sorting processes that enable the production of single-type fractions of plastics. This can be financed through a plastics levy (see above). Plastics should not contain any problematic substances. All “Substances of Very High Concern” (SVHC) are prohibited in plastic products for consumers. The list of prohibited substances in plastics should be expanded to include substances that can cause environmental and health problems and should be replaced quickly. The SIN list³ can serve as a basis for this [ChemSec 2025]. Entire groups of substances will be banned if there is a risk of one pollutant being replaced by a similar pollutant.
- In the case of mass-produced plastics, the number of additives used must be significantly reduced in order to enable high-quality material recycling, e.g. by creating a transparent positive list.
- Non-recyclable residual fractions must be disposed of in an environmentally compatible manner. Where possible, the substances contained in plastics should be recycled. The

³ The SIN List is a list of hazardous chemicals used in a wide range of articles, products and manufacturing processes around the world. The abbreviation SIN – Substitute It Now – means that these chemicals should be eliminated as quickly as possible because they pose a risk to human health and the environment. The SIN List is compiled by the non-profit organisation ChemSec in close collaboration with scientists and technical experts, as well as an advisory committee of leading environmental, health and consumer organisations.

transfer of pollutants must be avoided as far as possible.

- The targets of the Paris Climate Agreement must be met. At the latest from the date on which the residual greenhouse gas emissions budget specified therein is reached, plastics will only be permitted if they are produced exclusively from non-fossil raw material sources (Defossilisation).
 - All (mass) plastic products should be assessed for their environmental impact according to independent, science-based criteria (life cycle assessment). As almost all plastics are persistent, a hazard assessment should be carried out (rather than a risk assessment; see [BUND 2023b]).
 - The production, use and placing on the market of primary microplastics shall be prohibited. Procedures shall be developed and requirements set to minimise the generation of secondary microplastics.
 - Improved collection and sorting of plastics is necessary, and potential for improving sorting must be expanded in order to produce high-quality recyclates.
 - Only after the potential in product design, reuse and the expansion of the collection, sorting and processing infrastructure for high-quality mechanical recycling has been exhausted thermochemical processes can be a useful substitute in certain sectors and for certain products.
 - For short-lived products such as packaging, chemical recycling is too resource- and energy-intensive and should not be used.
 - The use of liquid or water-soluble plastics that do not harden when used properly (polymer dispersions in paints and coatings) is minimised, especially in applications that are open to the environment (hydrogels).
 - All of the above criteria also apply to “bio” plastics, whose potential as a solution is frequently overestimated. For “bio” plastics, the specific requirements set out in the BUND background paper on “bio” plastics must also be taken into account.⁴
 - In view of the enormous and growing quantities of polymers to which humans and the environment are exposed, polymers must meet the same legal requirements as other chemical substances. In the course of the REACH revision, a registration requirement must therefore be introduced for all polymers (for production or import in quantities exceeding one tonne), particularly with regard to their pollutant potential (including microplastics and nanoplastics).
 - Additives in plastics must be declared. High-quality material recycling can only be achieved if the variety of additives in mass-produced plastics is significantly reduced. A mandatory, transparent positive list of permitted additives would protect against unforeseen hazards and quality losses in recycled plastics.
 - When assessing chemicals used as additives, it must be checked whether they form transformation products with other substances in the environment as intended. These transformation products must be identified, investigated and evaluated.
 - As part of the EU process to restrict PFAS, strict criteria must be applied to the granting of exemptions, including for polymeric PFAS. Polymeric PFAS should be banned in consumer applications as a matter of principle.
 - A central body at European level (e.g. ECHA) should be tasked with the following:
 - Monitoring the use of plastics
 - Maintaining a register of plastic ingredients
 - Maintaining a list of substances prohibited in plastics
 - Establishing recycling routes and quotas for plastics based on ecological criteria
- Data on plastics throughout their life cycle should be disclosed and made accessible.

⁴ <https://www.bund.net/service/publikationen/detail/publication/bio-kunststoffe/>

This applies to the entire production process and, in particular, to all additives and ingredients. This data should be made available in a plastics register in the form of a database.

9.3 NEED FOR A GLOBAL PLASTICS AGREEMENT

Every year, over 460 million tonnes of plastic are produced worldwide. If plastic production continues to grow as it has done so far, this amount will almost triple by 2060. This threatens ecological, social and economic sustainability. Studies show that recycling and effective waste management alone are not enough to overcome the crisis. Scientific calculations show that a drastic reduction in plastic production is the most effective solution.

For a global plastics agreement to be effective, it must contain clear targets and binding measures. Scientists are calling for the following key points [IKHAPP 2024]:

- A holistic goal: The agreement must cover the entire life cycle of plastics. Its goal must be to protect the environment and human health and end plastic pollution by 2040.
- Reduction of plastic production: Ambitious, legally binding targets are needed to reduce plastic production. Incentives should be created to reduce not only plastic itself, but also the chemicals it contains.
- Ban on hazardous chemicals: Many plastic additives are harmful. They must be regulated at a global level. Currently, very few of these chemicals are controlled by international environmental agreements.
- Measures against microplastics and nanoplastics: These tiny plastic particles are particularly problematic. They account for about a quarter of all plastic pollution in the environment and cannot be removed from the environment. Their production must therefore be minimised throughout the entire plastic life cycle.
- Ban on non-essential plastic products: Plastic products and chemicals that are not absolutely necessary should be phased out. Exceptions should only apply to plastics that are essential for health, safety and the functioning of society – and for which there are currently no sustainable alternatives.
- Safety and sustainability standards: Clear, internationally uniform, science-based criteria are needed for plastics, substitutes and new technologies. Comprehensive testing must be carried out before market introduction.
- Prioritising avoidance and reuse: The waste hierarchy must be adhered to. This means that plastic waste should first be avoided, then reused and only disposed of as a last resort. Waste management systems must be made safer and more environmentally friendly. Binding minimum recycling quotas should be introduced to this end.
- Transparency and control: Companies must disclose which plastic chemicals, materials and products they use. The entire supply chain must be monitored. This requires clear rules with measurable indicators.
- Financial support and cooperation: Developing countries and particularly affected communities must be supported. This requires a special financing mechanism, technical cooperation and trade agreements that enable the transition to less plastic. Adequate financing is needed to implement the plastics agreement and the necessary processes, e.g. a tax on plastic production and/or use. Financing should be based on the polluter pays principle.
- Independent scientific advice: A neutral group of experts should monitor progress and make recommendations. Clear mechanisms must be established to prevent conflicts of interest. (In coordination with the tasks of other bodies and institutions.)

An effective plastics agreement requires ambitious measures and enforcement mech-

anisms. Only by drastically reducing plastic production and hazardous chemicals can the global plastics crisis be contained. Science has provided the facts – now it is up to politicians and industry to act.

STATUS OF NEGOTIATIONS FOR AN INTERNATIONAL PLASTICS AGREEMENT

The fifth round of negotiations of the UN Intergovernmental Negotiating Committee (INC-5.1) for an international plastics agreement took place in November/December 2024 in Busan, South Korea, but ended without a final agreement. The main points of contention were whether the agreement should include binding limits on global plastic production, regulations on chemical composition, and what financing mechanisms should be put in place for the measures agreed upon. More than 100 countries, including the EU, Mexico, Panama and Rwanda, supported such limits. In contrast, oil-producing countries such as Saudi Arabia, Russia, Iran and India rejected them and instead advocated limiting measures to efficient waste management.

Another round of negotiations (INC-5.2) in August 2025 also ended without result. The aim was to reach a globally binding agreement that takes into account the entire life cycle of plastics, regulates harmful chemicals, and ensures sustainable financing [UNEP 2024]. An urgently needed plastics agreement has thus been postponed or even jeopardized altogether.

Environmental organisations criticised the failure to reach an agreement and accused some countries of conducting the negotiations with the intention of preventing an effective agreement from being reached. Civil society organisations welcome the intention to continue negotiations so as not to rush into weak agreements under time pressure.

9.4 RECOMMENDATIONS WITH REGARD TO RESEARCH AND EDUCATION POLICY

Much of the scientific knowledge on the pollution and overload of the Earth with plastics is the result of research conducted over the past decades. Numerous questions remain unanswered and many connections are still unknown. There is a clear need for further research to develop a sustainable materials policy for plastics, which should be taken into account in particular in government research programmes. It is also necessary to anchor sustainable chemistry and material flow management in university courses and in education and training.

Research recommendations:

- Strengthening the independence of research. Scientific research into the material risks of plastics must not be dependent on funding from industry. Conflicts of interest must be avoided. Funds from the plastic levy imposed on manufacturers should also be used to finance independent research in this area.
- A research focus should be established on how to prevent or reduce the entry of plastics into the environment and how to transform chemical production towards a sustainable materials policy.

- A research focus on the material contamination of existing and new plastics with pollutants from additives and other plastic chemicals should be developed. The aim should be to minimise additives and, where necessary, to develop environmentally friendly alternatives and to eliminate problematic substances from the recycling of plastics.
- A research focus on the standardisation of plastics in mass applications, on appropriate material recycling processes and on adapted logistics structures for the return of the corresponding waste must be established.
- Schoolbook publishers should give more space to the sustainable use of plastics in new editions.

Recommendations for education:

- The subjects “sustainable chemistry” and “environmentally friendly product development” must be incorporated into at least the chemistry, process engineering and engineering (textiles, mechanical engineering, paper, etc.) degree programmes, and appropriate teaching materials must be developed.
- The topics of life cycle analysis, material flow management and recycling management must be included in the curriculum of all engineering courses and natural science subjects.
- Training and further education programmes for the responsible, sustainable use of plastics, materials and products must be expanded.
- Educational programmes for schools and further education institutions on the sustainable use of plastics should be developed and expanded.
- Technically sound information on the sustainability assessment of plastics, compiled and reviewed by independent experts, should be made available.
- Access to information on the sustainability of plastics for consumers and associations should be improved. Manufacturers must provide the relevant information in a verifiable manner.

10 Glossary

Bioplastics

Plastics made from biological, non-fossil raw materials (plants, microorganisms). Sometimes also used for biodegradable plastics.

Chemical recycling

A process for recovering raw materials from plastic waste through chemical conversion (e.g. depolymerisation, pyrolysis). This produces oils that are similar to fossil raw materials used in the manufacture of plastics, but often contain impurities that can be problematic for production.

ECHA (European Chemicals Agency)

European authority responsible for implementing the REACH chemicals regulation. Assesses the risks of chemicals, including those contained in plastics.

EEA (European Environment Agency)

European authority responsible for assessing the state of the environment.

EFSA (European Food Safety Authority)

European authority for food safety. Assesses plant protection products, food and feed additives, and food contact materials.

Elastomer

Soft plastics with high elasticity that return to their original shape after deformation. Due to their cross-linking, they are difficult to recycle.

Endocrine substances

Chemicals that can disrupt the hormonal systems of humans and animals. Found in plastics as additives, e.g. several plasticisers or flame retardants.

Exposure

Concentration of a substance in an environmental medium (water, soil, air – environmental exposure) or concentration/dose of a substance absorbed, e.g. through the air we breathe or food – human exposure.

In vitro toxicity

Toxicity to cell cultures

In vivo toxicity

Toxicity to living organisms

Food contact materials

Substances in packaging materials for food

Mechanical recycling

Physical process for recycling plastics by shredding, washing, sorting and reprocessing without changing the chemical structure.

Microorganisms

Microscopic organisms consisting of one or a few cells (e.g. bacteria, archaea, fungi, algae).

Microplastics

Plastic particles smaller than 5 mm. Secondary microplastics are created through abrasion, decomposition or deliberate production. They spread in the environment and enter food chains.

Monomer

A single molecule that is linked to form polymers through chemical reactions.

Mulch films

Thin plastic films used in agriculture to cover the ground. Problematic because plastic residues remain in the soil and are not disposed of properly.

Nanoplastics

Very small plastic particles measuring less than 100 nm. Formed by further decomposition of microplastics.

NIAS

NIAS = non-intentionally added substances. Reaction and degradation products can arise during the manufacture and use of plastic items. These are unintentionally contained in the respective article.

PA (polyamide)

Thermoplastic with high strength, e.g. in textiles. Can emit microplastics, especially when washing clothes.

PAM (polyacrylamide)

Polymer with a wide range of applications, e.g. in sewage treatment plants. Degradation products such as acrylamide are considered toxic and potentially carcinogenic.

Pathogens

Disease-causing microorganisms that can attach themselves to microplastic particles, increasing their spread and transmissibility.

PBAT (polybutylene adipate terephthalate)

A fossil-based plastic that is slow to biodegrade. Used in compostable plastic bags, for example, but only decomposes under industrial conditions.

PE (polyethylene)

One of the most commonly used plastics worldwide. Very persistent in the environment due to its chemical stability.

Persistence

Property of substances to remain stable in the environment over long periods of time. Persistent plastics do not decompose completely, but form microplastics and nanoplastics.

PFAS (per- and polyfluorinated alkyl substances)

Fluorinated synthetic chemicals with mostly water-, grease- and dirt-repellent properties. Very persistent in the environment and toxic to humans and the environment.

PLA (polylactic acid)

Bio-based and potentially biodegradable plastic. However, actual degradability is highly dependent on environmental conditions and is only possible under industrial conditions over long periods of time. Composting plants in Germany do not accept PLA plastics.

Polymer

Macromolecule consisting of many repeating monomer units. All plastics are polymers.

PP (polypropylene)

Lightweight thermoplastic with a wide range of applications (e.g. packaging, textiles). Very persistent in the environment due to its chemical stability.

PS (polystyrene)

Brittle thermoplastic, often used as foam (styrofoam) or for packaging. Easily breaks down into small particles and contributes significantly to microplastic pollution.

PVC (polyvinyl chloride)

Soft or hard plastic with high chemical resistance. Often contains problematic additives such as plasticisers or stabilisers.

Pyrolysis

Thermal process for the chemical decomposition of plastics at high temperatures in the absence of oxygen. This produces pyrolysis oil, pyrolysis gas and pyrolysis char in varying compositions.

Solvolysis

Chemical recycling process in which solvents are used to depolymerise plastics. Enables selective recovery of monomers.

Thermoplastic

Plastic that melts and becomes malleable when heated. Unlike thermosets, thermoplastics can be recycled mechanically.

Thermoset

Plastics that cannot be reshaped after curing. Due to their chemical structure, they are difficult to recycle and often remain in the environment for a long time.

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Bund für Umwelt und Naturschutz Deutschland e.V. (BUND)

Bundesgeschäftsstelle | Kaiserin-Augusta-Allee 5 | 10553 Berlin

Phone +49 30 27586-40 | Fax +49 30 27586-440 | bund@bund.net

www.bund.net

BUND (Friends of the Earth Germany) Federal Working Group on Environmental Chemicals / Toxicology

Authors:

Gottfried Arnold, Eva Bittmann, Hubertus Brunn, Markus Große Ophoff, Janine Korduan, Wolfgang Körner, Stefan Lips, Gerd Rippen, Klaus Steinhäuser

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