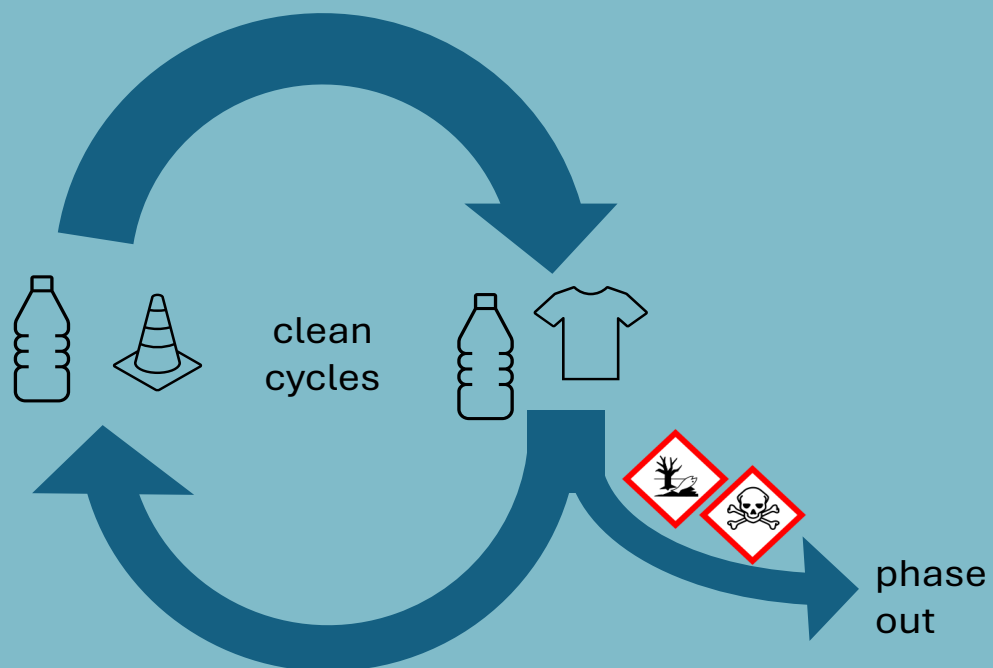


Clean Cycle Project Results

Commissioned by the Federal Office for the Environment (FOEN), the Federal Office of Public Health (FOPH) and the Office of Waste, Water, Energy and Air (AWEL) of the Canton of Zurich

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Klotz Magdalena (2023). "Design and Environmental Impact Assessment of a Circular Plastics Material Flow System". Doctoral thesis, ETH Zürich <https://doi.org/10.3929/ethz-b-000630291>

Wiesinger Helene (2024). "Investigating hazardous chemicals in plastics in a linear and circular economy". Doctoral thesis, ETH Zürich, <https://doi.org/10.3929/ethz-b-000673657>

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1 Plastics and their uses

1.1 What are plastics?

Plastics quietly accompany each step of our everyday lives. They form part of our mobile phones, tooth-brushes, T-shirts, water-bottles, yoghurt cups, bikes, furniture, toys and many more items. Plastics are truly ubiquitous materials that are used across diverse sectors. Globally, their production is around 460 million tonnes per year (in 2019) with a clear upward trend in recent decades (OECD, 2022).

“Plastics” are not one single type of material, but many types. These materials are mainly differentiated by their major component or “backbone”, the polymer. Polymers are in essence long chains of repeating monomer units. Typically, plastics may get their name from the monomer units that form the base polymer, for example, ethylene monomers are linked to form polyethylene (PE), styrene monomers form polystyrene (PS), and vinyl chloride monomers form polyvinyl chloride (PVC) (Kohlgruber, 2022). Besides the polymer, plastics contain additives, which modify and improve their specific properties, and other substances which are there non-intentionally (Figure 1). These non-intentionally added substances (NIASs) can end up in plastics during different life-cycle stages of plastics, including the manufacturing, use and recycling phases. NIASs can include contaminants, byproducts, or breakdown products of the polymer or the additives.

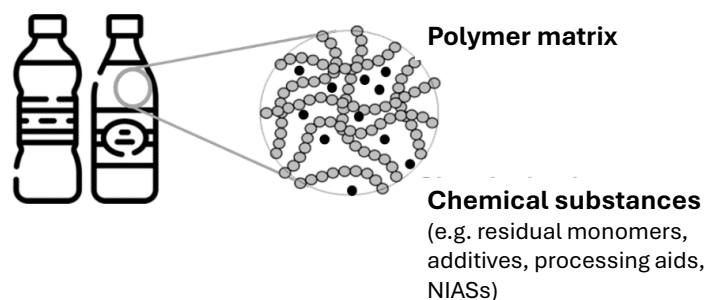


Figure 1: Composition of typical thermoplastic products. Polymers, long chains of repeating monomer units, form the “backbone” of the material. Additives can help to tune the properties of the material (e.g. color, strength, elasticity). Other substances such as processing aids, as well as non-intentionally added substances such as degradation products, contaminants, and side products can also be present in the plastics.

About 75% of all plastics produced are thermoplastics, meaning they melt when heated and can thus get a new shape. Thus, these thermoplastics can, in principle, be recycled mechanically at their end of life. The most widely used and most commonly known plastics such as PE, polypropylene (PP), PS, and PVC are all thermoplastics (OECD, 2022).

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1.2 Chemicals in plastics

1.2.1 Chemicals used in plastic production (PlasticMAP database)

The following section is a summary from Wiesinger, Wang, and Hellweg (2021).

More than 10'000 highly diverse chemicals have or may have been used in plastic production

Plastics are not just polymers. They contain a variety of chemical substances that are used in the production and processing, or that may be present non-intentionally (Section 1.1). 10'547 unique chemical substances (identified by their Chemical Abstracts Service Registry Numbers, CASRNs) have been reported for intentional use in the production and processing of plastics across 63 information sources from industry, science, and regulation. One-quarter of the identified substances (2'703 CASRNs) are not individual molecules, but are instead mixtures, polymers or so-called “UVCBs” – substances of unknown or variable composition, complex reaction products, or biological materials. The properties of these substances are often less studied due to their variable compositions. The remaining individual substances (7'844 CASRNs) are mostly organic substances in nature, with only 1'049 inorganic substances identified. There is a lot of diversity among the organic substances. They include, for example, various brominated substances or per- and polyfluoroalkyl substances (PFASs, the so-called “Forever Chemicals”) under “organohalogens”, or *ortho*-phthalates and bisphenols under “other aromatics” (see Figure 2 – right).

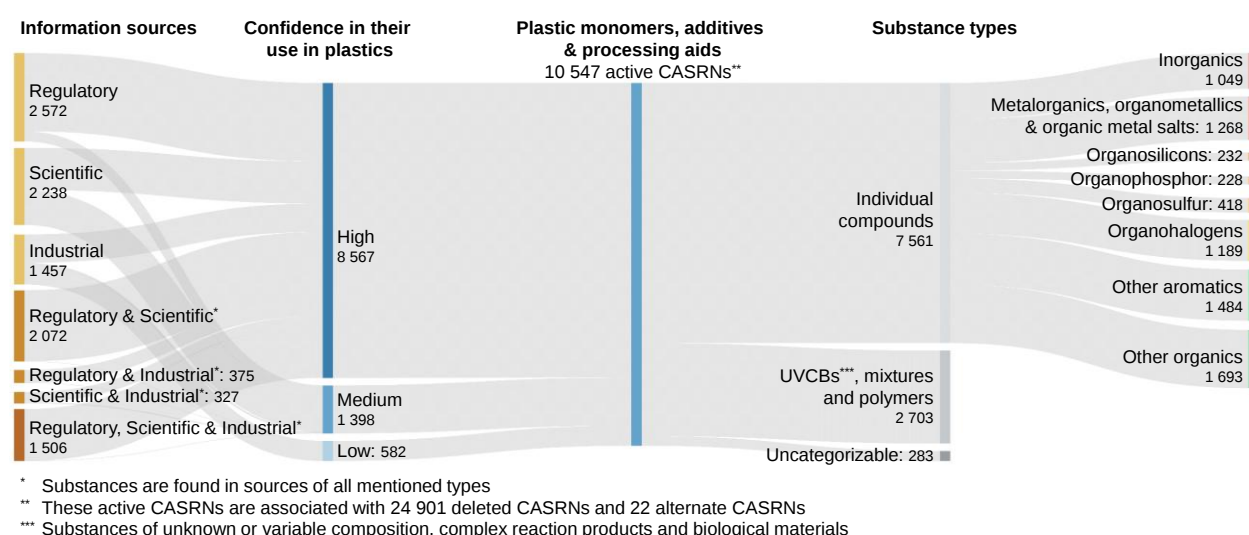


Figure 2: Substances that have or may have been used in the production and processing of plastics

Chemicals are used for different reasons in the production and processing of plastics, and they can be grouped into three main categories (see Figure 1)

- **Monomers:** These are the building blocks of plastics, which are linked together to form the polymer chains. The most important monomers for commercially relevant polymers include ethylene (CASRN: 74-85-1) for PE, propene (CASRN: 115-07-1) for PP, styrene (CASRN: 100-42-5) for PS, and vinyl chloride (VCM, CASRN: 75-01-4) for PVC.
- **Additives:** These help to maintain, enhance, and impart specific properties. For example, antioxidants help maintain the polymer matrix, plasticizers enhance flexibility, flame retardants impart fire resistance, and colorants impart color. Various other types of additives may be used, depending on the polymer type and desired functions of the plastic product.

- Processing aids: These substances enable or ease the plastic production and processing, such as polymerization catalysts (accelerating the reaction of monomer molecules to form polymers) or lubricants.

Information on the uses of specific chemicals is limited, but many of the identified chemicals can serve multiple roles in multiple plastic types, making it difficult to link them to specific plastic applications.

Approximately one-quarter of the identified substances are considered highly hazardous

Of the identified substances, 2'486 are classified as persistent, bioaccumulative, and/or toxic (see Table 1). These chemicals can cause severe toxic effects, with some that can additionally linger in the environment for extended periods and accumulate in living organisms (see Box 1). Notable examples include substances that promote the development of cancers (carcinogens) and/or disrupt hormone systems (endocrine disruptors, ED), and chemicals that are toxic to aquatic organisms. The majority of these hazardous chemicals in plastics are classified by regulators or the industry as CMRs (carcinogenic, mutagenic, or reproductive toxicants), substances that are toxic to specific target organs (STOT), or harmful to the aquatic environment (AqTox).

Table 1: Hazards of the identified chemicals used in plastic production

Hazard Type	Description	Number of chemicals	Percentage of plastic chemicals
Missing hazard data	No hazard data in the regulatory sources consulted	4'139	39.2 %
Hazardous substances	Fulfills one or more of the properties below	2'486	23.6 %
PBT	Persistent, bioaccumulative & toxic	22	0.2 %
vPvB	Very persistent & very bioaccumulative	35	0.3 %
CMR	Carcinogenic, mutagenic or toxic for reproduction	951	9.0 %
ED	Endocrine disruption	30	0.3 %
AqTox	Chronically aquatic toxicity	1'646	15.6 %
STOT_RE	Specific target organ toxicity, repeated exposure	891	8.4 %

Among these hazardous chemicals, some are especially concerning because they are produced in large amounts of more than 1'000 t/yr (1'254 substances), they are not adequately regulated (1'327 substances), or they are approved for use in food-contact plastics, which means they may migrate into food and pose a direct health risk to consumers (901 substances).

A significant challenge in addressing the safety of chemicals used in plastic production is the pervasive lack of public information and transparency regarding these substances. Despite advancements in scientific tools and methodologies, critical data necessary for assessing the risks associated with plastic-related chemicals remains incomplete or fragmented. For example, during the development of the PlasticMap, it is noted that a substantial portion of the identified 10'547 substances - 40% - lacks clarity about the specific industries in which they are employed, and 16% do not have details on the types of plastics in which they are used. Alarmingly, 39% of the identified chemicals have no hazard classifications in the public regulatory sources consulted. The fate of chemicals throughout the plastic life cycle - during production, use, and disposal - remains largely unclear, except for a few isolated cases. Given the widespread presence of potentially hazardous chemicals in everyday products, urgent coordinated action is needed. However, these information gaps complicate regulatory efforts to ensure chemical safety and significantly impede progress toward the adoption of safer alternatives in the plastic industry.



Chemical Hazard Classifications

The intrinsic properties of chemicals can render them hazardous to human health and/or the environment. The following properties are considered relevant for plastic chemicals in this project.

Persistence: Persistent chemicals are resistant to natural degradation and can accumulate in the environment. They can remain in ecosystems for decades or longer, posing long-term risks to humans, wildlife and ecosystems. Typical examples of persistent chemicals include the “*dirty dozen*” banned under the Stockholm Convention, or the “*Forever Chemicals*” PFASs.

Bioaccumulation: Bioaccumulative chemicals can build up in the tissues of living organisms with limited excretion. Over time, they can reach harmful levels, despite low environmental levels. Typical examples of bioaccumulative chemicals include the “*dirty dozen*” banned by the Stockholm convention, or many of the “*Forever Chemicals*” PFASs.

Toxicity: Toxic chemicals can cause harmful effects in living organisms, depending on the dose, the route of exposure, the duration of exposure, and so on. Acute toxicity refers to harmful effects that occur shortly after a single exposure to a toxic substance, often resulting in severe symptoms or death. Chronic toxicity refers to harmful effects that develop over a long period due to repeated or prolonged exposure to a toxic substance, typically at lower doses than that for acute toxicity.

- **Carcinogenicity, mutagenicity or reproductive toxicity (CMR):** Carcinogenic chemicals can cause or promote cancers. Mutagenic chemicals can alter the structure of DNA; these mutations can cause, typically negative, changes to an organism and any offspring. Reprotoxic chemicals can adversely affect both male and female fertility as well as offspring development. For example, certain *ortho*-phthalates and polycyclic aromatic hydrocarbons (PAHs) are known or suspected to cause cancer.
- **Endocrine disruption:** Chemicals such as bisphenol A (BPA) can interfere with hormone systems, potentially leading to reproductive and developmental issues.
- **Aquatic toxicity:** When plastics degrade or chemicals therein leach into water bodies, they can harm aquatic organisms.

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Wagner Martin, Monclús Laura, Arp Hans Peter H., Groh Ksenia J., Løseth Mari E., Muncke Jane, Wang Zhanyun, Wolf Raoul, Zimmermann Lisa (2024) [State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern](#)

1.2.2 Chemicals present in real-life plastic samples (LitChemPlast database)

The following section is a summary from Wiesinger, Shalin, Huang, Siegrist, Plinke, Hellweg and Wang (2024).

The composition of specific plastics is often unknown and requires chemical analysis

For specific plastic products or waste, the presence and concentrations of chemicals are typically unknown. This is caused by a general lack of communication along the supply/value chains, varied starting materials and practices in the initial production and processing, and unforeseeable changes during the use of plastics. The latter two factors do not only vary compositions of intentionally added substances such as additives and processing aids, but also impact the presence and levels of non-intentionally added substances (NIASs) such as impurities, byproducts, and degradation products. Thus, obtaining the chemical compositions of plastics typically requires a combination of various analytical techniques (for examples, see below). Numerous scientific studies have conducted such measurements. Through a careful manual curation, over 70'000 measurements from 372 studies between 1978 and 2021 are collected and compiled into an open database of chemicals measured in plastics - the LitChemPlast database.

Examples of chemical analysis techniques

Several methods exist to detect and quantify chemicals in plastics. While some of these methods are suitable for fast screening (particularly ATR-FTIR and XRF), others require elaborate and time-consuming sample preparation and analysis (e.g. GC-MS).

Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (ATR-FTIR): ATR-FTIR is a non-destructive analytical technique. It is a type of infrared spectroscopy that measures the absorption of infrared light by the surface of a sample. It can be used to determine the polymer type and the presence of other organic compositions such as plasticizers, stabilizers and antioxidants, for example *ortho*-phthalates. ATR-FTIR is straightforward to use and provides quick results, typically within minutes. Sample preparation is minimal, often just placing the sample on the ATR crystal sensor is sufficient.

X-Ray Fluorescence (XRF): XRF is a non-destructive analytical technique used to determine elements (e.g., metals, metalloids, bromine) in plastics. It works by exposing a sample to X-rays, causing the elements in the surface of a sample to emit secondary (fluorescent) X-rays that are characteristic of the elements present. XRF is relatively easy to perform and provides rapid results, often within minutes. It requires minimal sample preparation.

Gas Chromatography–Mass Spectrometry (GC-MS): GC-MS combines gas chromatography (GC) and mass spectrometry (MS) to separate and identify compounds in a sample. The liquid sample (typically in an organic solvent) is vaporized and passed through a chromatographic column, where it is separated into individual components. These components are then identified based on their mass spectra. GC-MS is complex. It requires extensive sample preparation, elaborate laboratory equipment, and is time consuming. GC-MS can be used to detect and quantify a wide range of organic chemicals in plastics.

Many chemicals other than those intentionally added can be present in plastic products

A striking finding is that many of the substances discovered in measurements have not been reported as monomers, additives or processing aids in the PlastChem database (Section 1.2.1). In total, of the 3'488 individual substances identified in the analytical measurements, only one-third are known for intentional use in the production of plastics. This suggests that many non-intentionally added substances are present in plastics, adding much complexity in understanding the chemical compositions of plastics along the supply/value chains, let alone assessing their hazards and risks. Moving forward, a thorough understanding and mitigation measures are essential.

Over 75% of the chemicals detected in plastics have been identified through non-targeted screening methods. In other words, they were found without prior knowledge of their occurrence, but by using high-end techniques that are designed to identify a wide range of chemicals, known and unknown. However, these methods also have limitations. For instance, quantification of substances remains difficult, and certain types of chemicals - such as very large molecules - cannot be detected with the techniques commonly used. In addition, it is challenging to perform the identification of such substances, requires time, high-end instruments, and specific expertise. Thus, the current knowledge of chemicals present in plastics is most likely only the tip of the iceberg. This means that many hazardous chemicals that may be present in plastics remain understudied and/or unidentified. To address this gap, upstream efforts from manufacturers may be more efficient than downstream detective work.

Only few substances are regularly and widely measured

Another challenge highlighted by the LitChemPlast database is the uneven focus of existing research (Figure 3). Some product groups or chemicals have received far more attention than others.

Particularly, chemicals that are well-known for being hazardous have been the focus of research so far. Among them are brominated flame retardants, which are added with the notion to reduce fire risks, *ortho*-phthalates, which are plasticizers used to make certain plastics more flexible, and metal(oids), which are used for a variety of functions. Many chemicals in these three groups are subject to regulation in various regions because of their known harmful effects on health and/or the environment.

Certain product groups, such as food packaging and electronic equipment, have been extensively studied due to regulatory requirements. Other categories that are just as widespread in everyday life - such as non-food consumer and industrial packaging - have received far less attention.

This lack of data and capacity to address the entire spectrum of chemicals and products in a timely manner, make it difficult to assess the full impact of chemicals in plastic products and creates significant knowledge gaps when it comes to ensuring their safe use and disposal. Future concerted efforts are needed to generate a comprehensive understanding of diverse chemicals in all products.

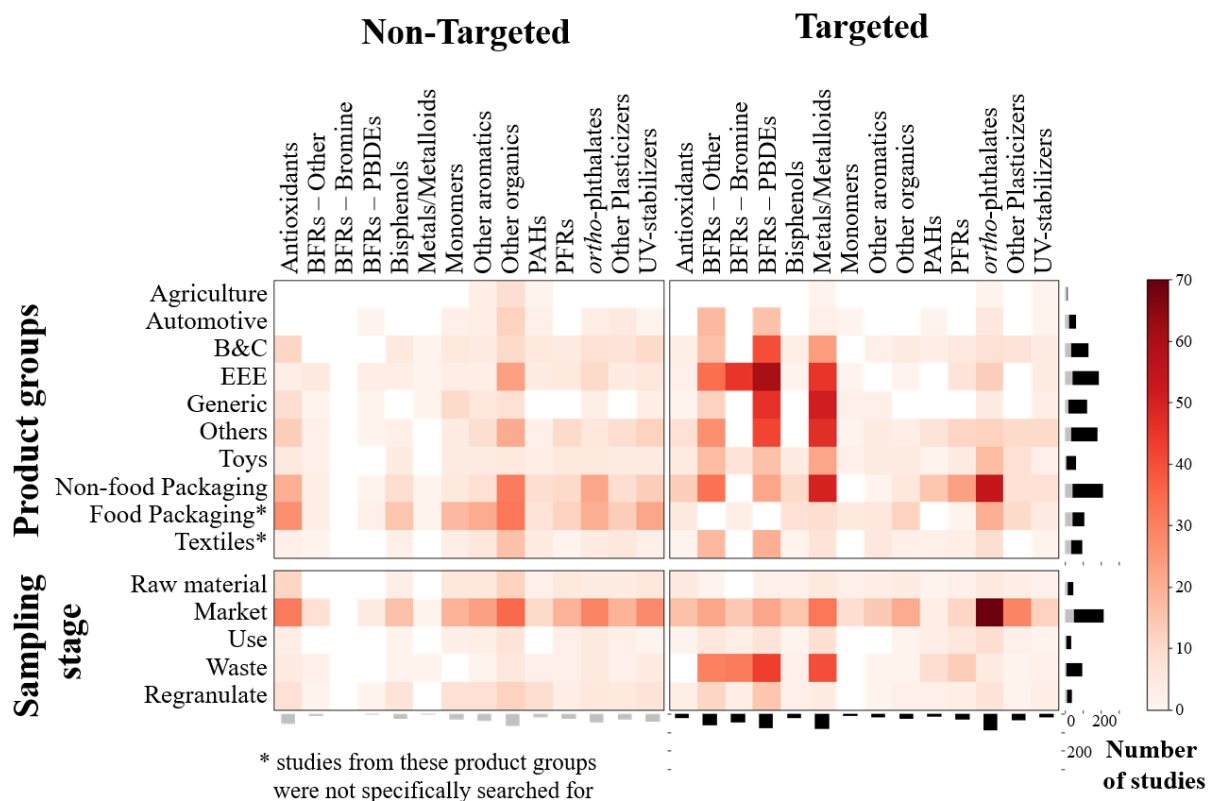


Figure 3: Number of targeted and non-targeted studies conducted per substance type, product (sub)category, and sampling stage. Targeted analyses detect/quantify pre-selected compounds, while non-targeted screenings aim to comprehensively identify known and unknown chemicals present in a sample. The light grey bars indicate the number of non-targeted studies and the dark grey bars the number of targeted studies. The substance grouping here is preliminary and highlights well-known groups, while less familiar ones are categorized as "Other aromatics" and "Other organics." BFRs = brominated flame retardants, PBDEs = polybrominated diphenyl ethers, PAHs = polycyclic aromatic hydrocarbons, PFRs = phosphorus flame retardants / plasticizers, UV = ultraviolet (light), B&C = building and construction, EEE = electrical and electronic equipment. (Wiesinger et al. 2024)

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1.3 Switzerland consumes one million tonnes of plastics per year, but recycles only 9% of its plastic waste

The following section is a summary from Klotz and Haupt (2022).

In Switzerland, about 1'000'000 tonnes of plastics are currently consumed each year (reference year 2017; Figure 4). Production of plastics from raw materials takes place almost exclusively abroad. Those plastics are then shaped into products, which happens domestically for about half of all products consumed in Switzerland.

Of the plastics consumed in Switzerland, one third is used in the packaging segment, followed by building and construction (25%) and textiles (10%). The most-used plastic types across all product segments are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinylchloride (PVC) and polyurethanes (PUR). In contrast, so-called technical plastics are used in smaller amounts in more demanding applications such as passenger vehicles or electrical devices.

Material flow analysis (MFA)

Material flow analysis is a method to quantify flows and stocks of a material between or in certain processes within defined temporal and spatial system boundaries (Brunner and Rechberger, 2004). For example, in the study presented here, consumption, waste and recycling amounts of plastics in Switzerland in 2017 were quantified.

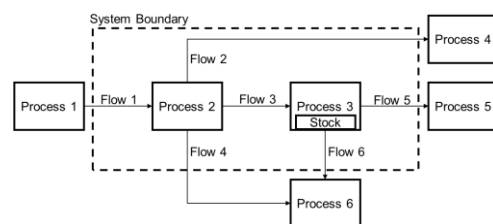


Figure based on Brunner and Rechberger (2004)

Some plastic products remain in use for several years, which is why the Swiss plastic waste amount is lower than the consumption amount. The waste corresponds to 780'000 tonnes per year and about 20% is separately collected for recycling. Some collections are plastic type- and product-specific (e.g., the PVC flooring collection) or only plastic type-specific (e.g., collection of different non-household films made of PE). Other collection systems target mixed plastic waste (e.g., household plastics consisting of different products and plastic types), while collections for composite products (e.g., bulky goods such as furniture or electrical equipment) even contain other materials than plastics. A relevant difference to other European countries is that in Switzerland household packaging waste is not yet collected on a national scale (so far, only regional collection systems exist). Instead, a focus has been put on well-recyclable PET drinking bottles as well as PE and PP bottles from consumer applications such as shampoo or milk bottles. PET drinking bottles feature high recycling rates of around 80%, achieved without a deposit-refund system, but with an extensive and dense network of waste collection points. However, there are ongoing initiatives to set up a national collection system for mixed plastic waste from households (Schweizerischer Bundesrat 2022). Certain product segments, such as electrical and electronic equipment, have take-back obligations. The resulting take-back schemes achieve high collection rates.

Of the separately collected plastic waste, less than half (43%) is recycled so far. On the one hand, this is due to a large variety of plastic types that are present in only small amounts in certain collection schemes and, therefore, not recycled. This is the case, for example, for certain plastics in vehicles or furniture. On the other hand, some plastics that are part of multi-material structures, such as window frames or electrical equipment, cannot be recycled because they cannot be separated from the other

materials. Material is also lost due to missorting: for example, sleeves made of a different material than the main product or external contamination can lead to misrecognition.

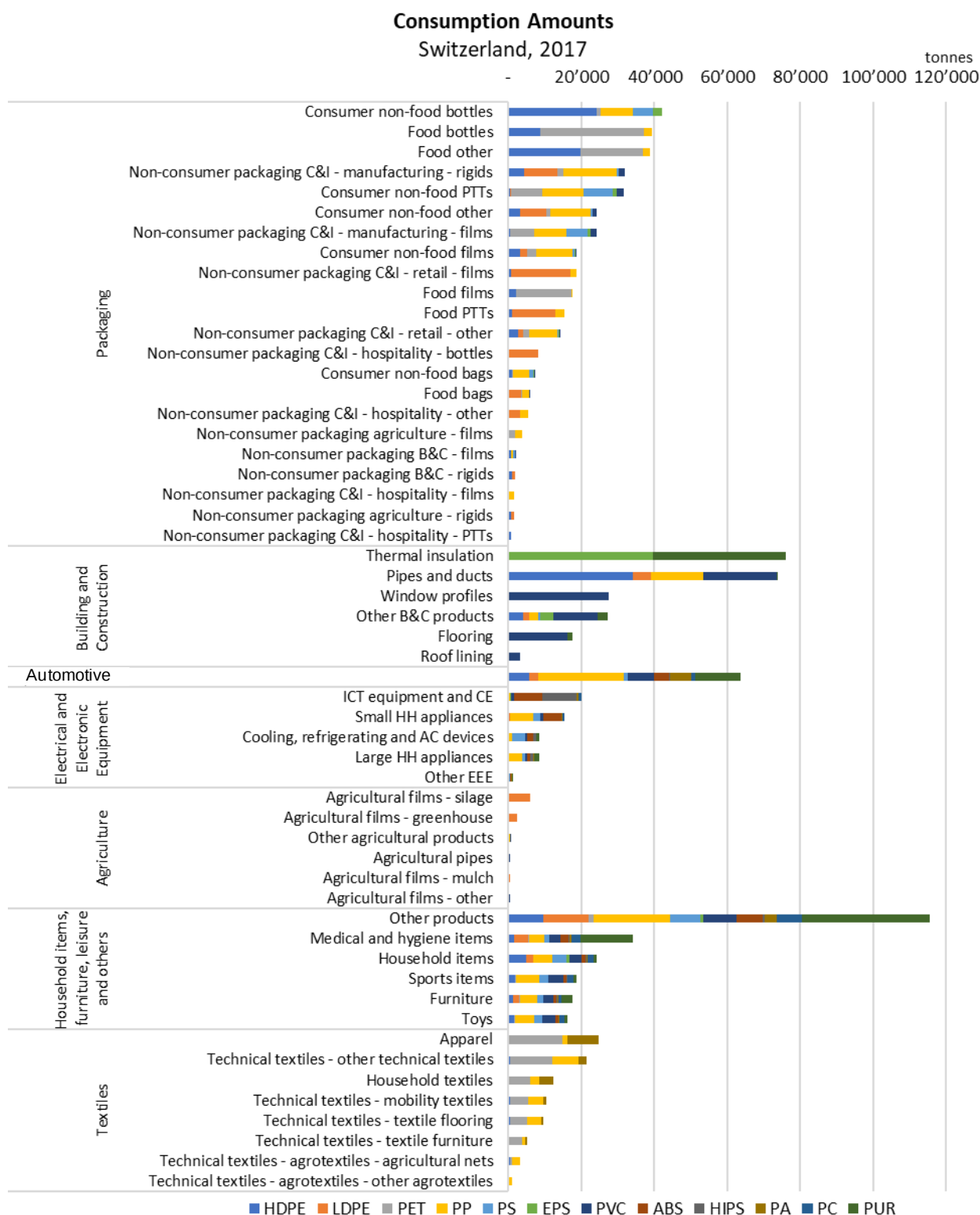


Figure 4: Consumption amounts of different product groups in Switzerland in 2017. AC: air conditioning, B&C: building and construction, C&I: commercial and industrial, CE: consumer electronics, EEE: electrical and electronic equipment, HH: household, ICT: information and communication technology, PTTs: pots, trays and tubs, HDPE: high-density polyethylene, LDPE: low-density polyethylene, PET: polyethylene terephthalate, PP: polypropylene, PS: polystyrene, PVC: polyvinyl chloride, ABS: acrylonitrile butadiene styrene, HIPS: high-impact polystyrene, PA: polyamide, PC: polycarbonate, PUR: polyurethane.

The resulting plastics recycling rate (the amount of recycled plastics produced in relation to the amount of plastic waste) for Switzerland is approximately 9%, which corresponds to approximately 72'000 tonnes of recycled, so-called secondary plastics. 38% of this secondary material comes from Swiss waste that has been recycled abroad, as Switzerland only has plastic recycling plants for certain packaging waste.

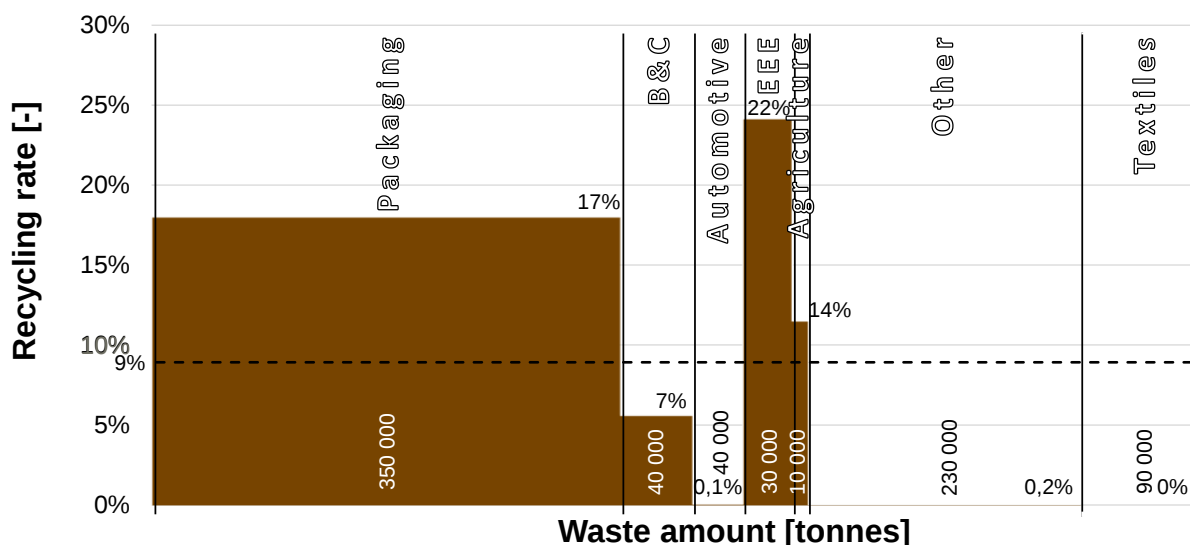


Figure 5: Plastic waste amounts and recycling rates for different product segments in Switzerland in 2017

The biggest share of recycled plastics from Swiss waste comes from PET drinking bottles. Large recycling amounts also come from non-consumer packaging films such as pallet wrapping, information and communication technology equipment and consumer electronics, as well as rigid packaging used in industry. After PET, the plastic type with the second largest recycling amount is PE, stemming from caps of PET drinking bottles and consumer bottles (e.g. shampoo or milk bottles) as well as non-consumer films, followed by PP and ABS. While the largest absolute amount of secondary material stems from the packaging segment, the highest recycling rate is achieved for plastics in electrical and electronic equipment (Figure 5).

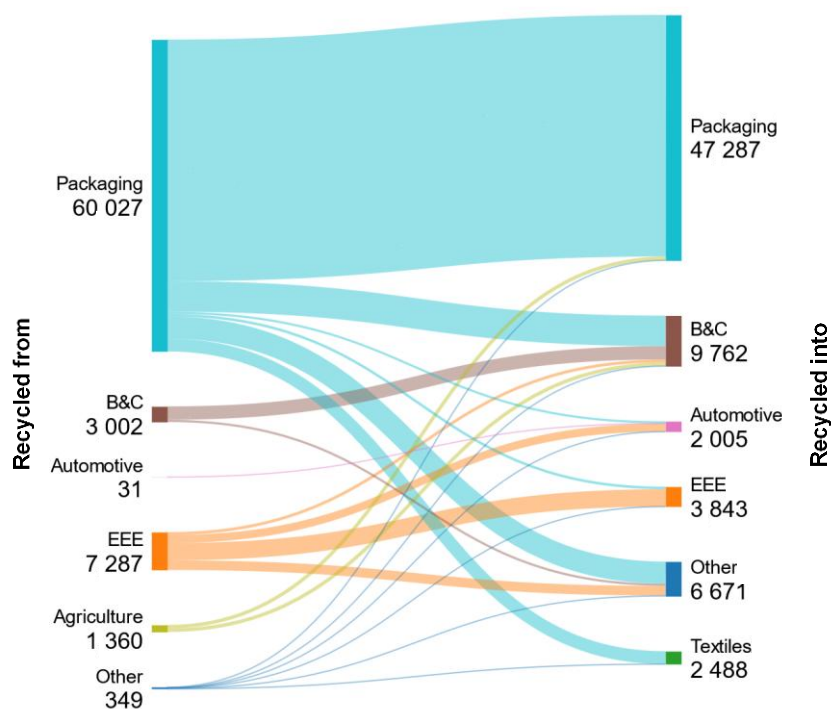


Figure 6: Utilization of secondary plastics from Swiss waste in 2017. Unit: tonnes.

Most of the secondary material is used in packaging items, due to closed-loop recycling of PET bottles (Figure 6). A disproportionally large amount of secondary plastics is used in building and construction applications and products with lower technical requirements such as flower pots (“Other” in Figure 6). In any case, most product segments take up a share of secondary material.

Besides recycling, reuse also preserves the value of Swiss plastic products. The main products that are reused are passenger vehicles and textiles, with most reuse taking place abroad.

83% of all arising plastic waste is neither recycled nor reused but burned in waste-to-energy (WTE) plants, producing electricity and heat. This plastic may stem from mixed household waste, the burnable fraction of building demolition waste, automotive shredder residue or waste collections of bulky goods such as furniture parts. A share of the sorting and recycling residues is also incinerated in WTE plants. 2% of the total plastic waste serves as substitute for coal as an energy source in clinker production for cement. In cement kilns, no non-separately collected plastic waste, but only sorting and recycling residues of separately collected plastic waste are allowed to be processed.

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2 Recycling can reduce the environmental impacts of plastics

2.1 Plastics have a multitude of environmental and health impacts

Plastics impact the environment in different ways. An important effect is their contribution to global warming. The production of plastics is currently responsible for 4–5% of all global greenhouse gas emissions, with an increasing trend (Cabernard et al. 2021; Zheng and Suh 2019).

Another relevant impact of plastics concerns human health. Detrimental health impacts may be related to chemicals present in plastics (Section 1.2). Large data gaps exist concerning the use, exposure pathways and hazardous properties of these chemicals, hindering the quantification of related health effects.

A further prominent negative consequence of plastics is macro- or microplastic pollution, caused by factors such as improper waste management, littering, textile fibers release, or rubber tire abrasion (Kawecki and Nowack 2019; Sieber, Kawecki, and Nowack 2020). Plastic waste accumulates in the (marine) environment (Nayanathara Thathsarani Pilapitiya and Ratnayake 2024). These plastics in the environment may have different impacts. Animals can die as a consequence of being trapped by macroplastics such as fishing nets, or the ingestion of microplastics could lead to toxic effects along the food chain (Bio Intelligence Service, AEA Technology, and Institute for European Environmental Policy 2011). These effects have so far not been holistically understood and assessed to be quantifiable within a life cycle assessment framework.

The most important plastic feedstocks are oil and gas (Kulprathipanja et al. 2021). About 5% of all oil and gas consumed are used for plastics production (Hopewell, Dvorak, and Kosior 2009; Kaiser 2021). A share of plastics is produced from coal, with very high associated environmental impacts (Cabernard et al. 2021). The consumption of fossil resources as fuels is likely to decrease drastically in the coming decades due to the implementation of climate change mitigation measures. Consequently, many stakeholders have considered plastic production as a manner to continue the extraction of fossil resources.

Life cycle assessment (LCA)

Life cycle assessment is a method to quantify environmental impacts of a product or system, considering all life cycle stages from production to waste treatment (International Organization for Standardization 2022). Resource consumption and emissions as well as the resulting environmental impacts are quantified. In the Clean Cycle project, the climate change impact of the Swiss plastics consumption, considering material production and waste treatment, was quantified for different recycling scenarios.



Figure based on PRé Sustainability (2024)

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2.2 Scenarios of increased plastic recycling could halve the carbon footprint of the plastics economy

Different measures exist that may lower the climate footprint of plastics. They include the use of renewable energy for material production, the use of bio-based materials, the application of circular economy strategies such as consumption reduction, reuse or repair, or carbon capture at the waste incineration (combined with carbon storage or utilization). To ensure that implemented measures actually bring ecological benefits, it is important to consider all their effects, e.g., land-use-related impacts for bio-based plastics.

Recycling is one circular economy strategy and one way to reduce the climate impact of plastics by avoiding virgin material production as well as end-of-life incineration. Proper recycling practices can also prevent plastics from ending up in the environment. When increasing recycling, it must, however, be safeguarded that this does not lead to additional negative environmental or health impacts (Section 3).

Recycling as part of a circular economy (CE)

A circular economy aims to retain the value of products and materials by preventing or managing waste (Potting et al. 2017; Wiprächtiger et al. 2021). To be sustainable, a circular economy should lead to reduced environmental impacts compared to a linear value chain, based on quantification with LCA (Haupt and Hellweg 2019).

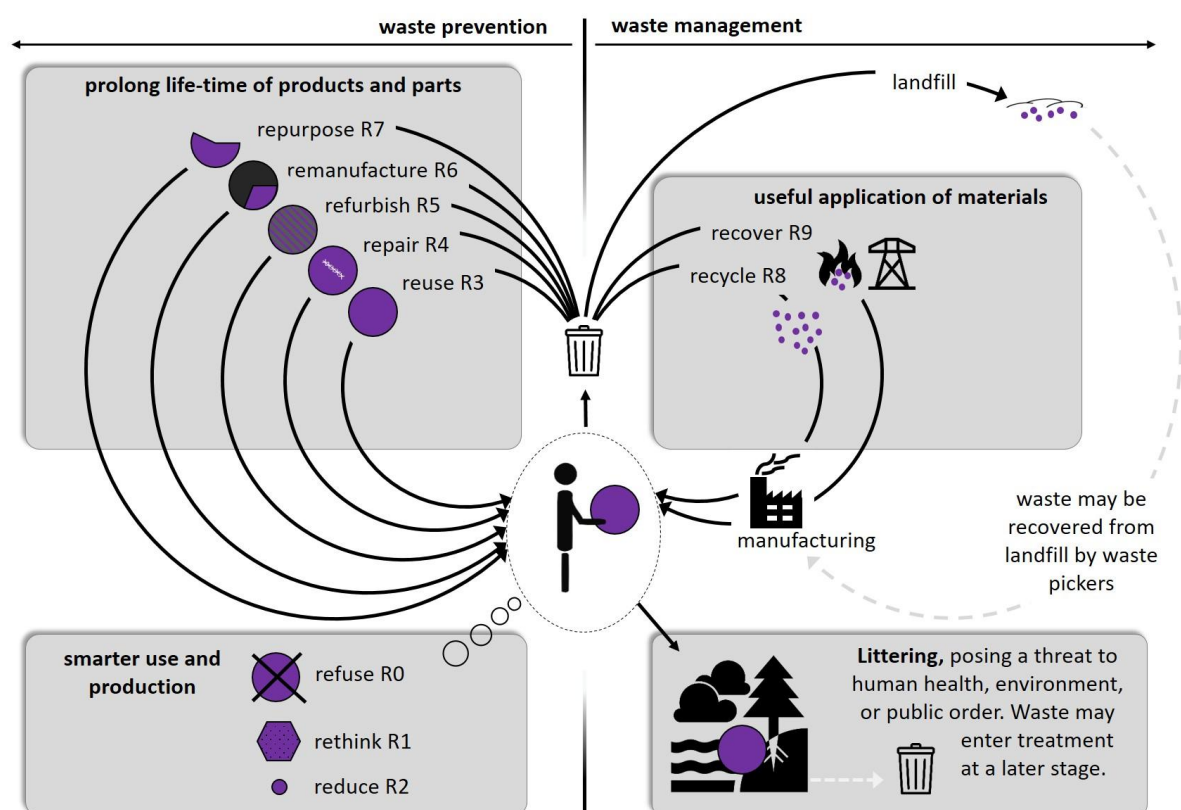


Figure from Wiprächtiger et al. (2021). The first three circularity strategies (R0-R2) increase circularity and prevent waste through improved design and production, while strategies R3–R7 aim to retain the value of products and strategies R8-R9 the value of materials.

For plastics recycling, different technologies can be applied. The currently almost exclusively practiced method is so-called mechanical recycling, which reshapes plastic waste via a melting process (Sections 2.2.1, 2.2.2). Besides, the plastic material compound may also be dissolved with a solvent which disentangles the polymer chains. This keeps the chains themselves intact, similar to mechanical recycling. It is also possible to break and recompose the polymer chains (chemical recycling, Section 2.2.3).

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2.2.1 Low quality of recycled plastics inhibits achieving ecological benefits with high recycling rates

The following section is a summary from Klotz, Haupt, and Hellweg (2022).

Increasing recycling rates while maintaining a high quality of recycled plastics is not a simple task. One big challenge is the diversity of plastics. Not only are there different plastic types, also one specific plastic type may feature different polymer chain configurations and contain various combinations of chemical additives (Section 1.2). To recycle all of these individual plastics separately would be logistically difficult, therefore, recycled plastics are commonly a blend of different plastics. As a consequence, they often have less targeted properties and are only utilizable in products with low technical or aesthetic requirements.

From an environmental perspective it does not matter in which products secondary plastics are utilized, as long as the same quantity of primary material is substituted. However, the restricted use of recycled plastics to lower-demanding products becomes an issue when recycling is to be increased. This is because the demand for products that are suitable to take up secondary plastics as they are today is limited, meaning that a situation with supply surplus of secondary plastics may occur. In such a situation, no benefits of avoided primary plastics production would arise for the share of secondary plastics that cannot be utilized and substitute primary plastics due to their low quality. Instead, for example, these low-quality secondary plastics may be used for manufacturing additional low-demanding products, leading to increased consumption, or substitute only low-impact materials like wood, resulting in reduced savings of environmental impacts. Such a situation is to be expected in Switzerland if we increase recycling by merely collecting more waste without providing for other changes to the production and recycling system. In other European countries with similar product portfolios and recycling processes as in Switzerland, it may already be the case that secondary plastics are partly used for producing additional products that would otherwise not be consumed. Some countries may also rely on exporting surplus secondary plastics.

The limited usability of today's secondary plastics implies that we need to qualitatively change our production and recycling practices in case we want to achieve ecological benefits with high recycling

rates. In addition, recycling rates should ideally not be calculated based on the production amount of secondary material (or even the input amount of waste into recycling processes), but rather based on utilized secondary material.

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Klotz Magdalena, Haupt Melanie, and Hellweg Stefanie. 2022. "Limited Utilization Options for Secondary Plastics May Restrict Their Circularity." *Waste Management* 141:251–70., <https://doi.org/10.1016/j.wasman.2022.01.002>

Read more

Klotz Magdalena (2022). "Plastic recycling shouldn't be an end in itself". *ETH Zukunftsblog*. <https://ethz.ch/en/news-and-events/eth-news/news/2022/02/plastic-recycling-shouldnt-be-an-end-in-itself.html>

2.2.2 System changes needed to increase mechanical plastic recycling, but certain barriers remain

The following section is a summary from Klotz, Haupt, and Hellweg (2023).

Various measures can be undertaken to increase recycling in the future, while ensuring that produced secondary plastics can substitute primary materials (Figure 7). Aligning product design and establishing more specific sorting processes can reduce the mixing of different plastics during recycling, which increases the share of secondary plastics that can be used in the same product type as the one they originated from. This increases the total amount of usable secondary plastics. A more specific waste sorting may be implemented by using product marking (with the principle of QR codes) that links to relevant information such as composition or former use. Sorting waste based on measurable material characteristics seems challenging: for instance, testing waste for all included chemicals seems not practicable (Section 4). Avoiding multi-material structures and reducing plastic type diversity can reduce sorting and recycling losses caused by the inseparability of materials or by a presence of plastic types in too small amounts for efficient recovery. Increasing the collection of waste streams that are feasible to collect and suitable for recycling would allow to realize the full potential of mechanical recycling.

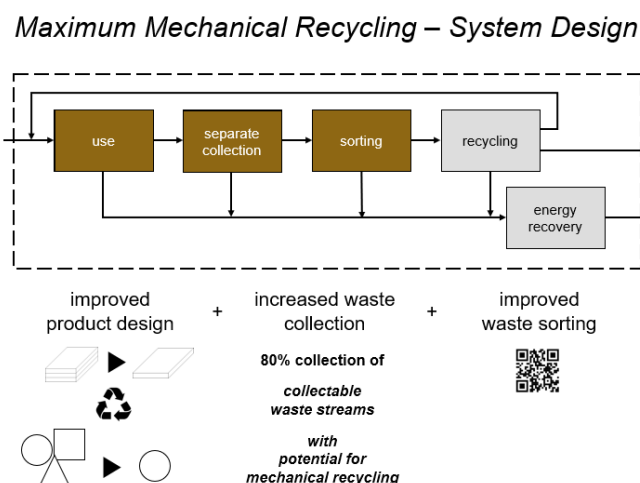


Figure 7: System design for maximum mechanical recycling involving measures related to the use, separate collection and waste sorting stages. The assessed time horizon was the year 2040.

All the mentioned severe changes to the recycling system combined, however, still seem to be only able to achieve a mechanical recycling rate of about 30% in the year 2040 across all plastic types and product groups, when all secondary material produced shall be able to substitute for primary plastics (Figure 8). Why do all those combined measures not result in a higher recycling rate? The most important reason for waste not being recycled is waste not being collectable. This includes, for instance, a share of pipes in buildings that are difficult to dismantle or separate from demolished buildings rubble. We assumed that generally only a collection rate of 80% is achievable, with the remaining 20% of waste not being available for recycling. The second most relevant reason is that waste streams are too diverse to be separated to a degree that would allow for establishing a collection and recycling system for individual plastics. Another very important factor inhibiting recycling is the contamination of waste with additives that are by now known to be hazardous, such as in expanded polystyrene (EPS) insulation (Section 3), or with external substances such as germs on medical items or sewage pipes, hazardous chemicals on their packaging or soil on agricultural films. Certain losses also occur during the sorting and recycling processes.

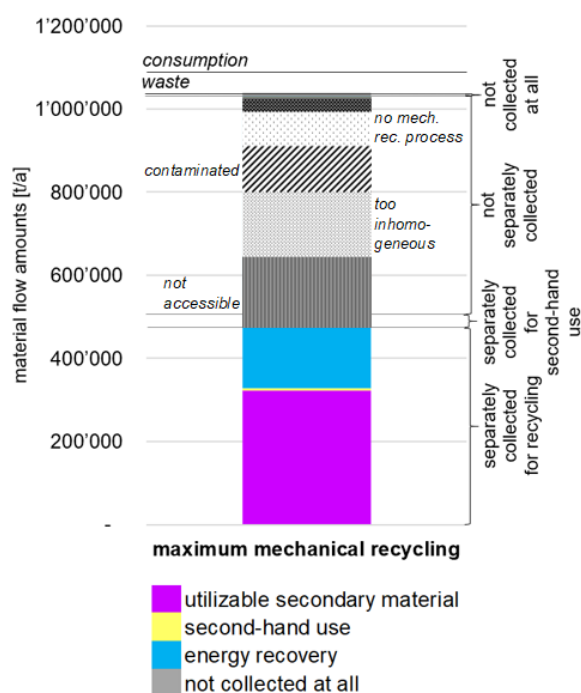


Figure 8: Secondary material amounts and losses in a maximum mechanical recycling scenario for Switzerland in 2040

Many barriers for mechanical recycling are strongly linked to the chemicals used in plastics. These chemicals play a crucial role in plastics diversity and may inhibit recycling if they were used in the past but are now restricted as is the case for EPS insulation or PVC flooring (Section 3). Plastic additives may also impair the mechanical recycling process itself, e.g., by contributing to polymer degradation.

Despite the limited material quantities that appear to be mechanically recyclable, such a recycling may considerably reduce the plastics' carbon footprint by one quarter.

In an optimized mechanical recycling scenario as described above, three quarters of the secondary plastics may be utilized in packaging products. Still, the building and construction segment would take up a part of the secondary plastics stemming from packaging and other product segments, as is already the case today (Figure 6).

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2.2.3 Chemical and solvent-based recycling may complement mechanical recycling in the future

The following section is a summary from Klotz, Oberschelp, Salah, Subal, and Hellweg (2024).

The challenges of mechanical recycling (Section 2.2.2) may be partly overcome by chemical or by solvent-based recycling, allowing for an additional share of plastic waste to be recycled (Figure 9). Due to the potential capability of these processes to either remove additives or de- and recombine the polymer chains, they are theoretically able to restore virgin plastic properties for mixed waste streams. Common chemical recycling technologies that are applicable for different plastic types are gasification, pyrolysis, and depolymerization. These processes decompose the polymer chains by means of heat, pressure, reactants and/or catalysts. Solvent-based recycling processes keep the polymer chains to a large degree intact, while they disentangle them by means of solvents, commonly separating them from additives. While gasification and pyrolysis are able to treat a mix of different plastic types, depolymerization and dissolution are plastic type-specific.

However, most chemical and solvent-based plastic recycling processes are not in operation on an industrial scale today. Therefore, the potentially treatable waste amounts, as well as the performance and the related achievable environmental benefits are highly uncertain.

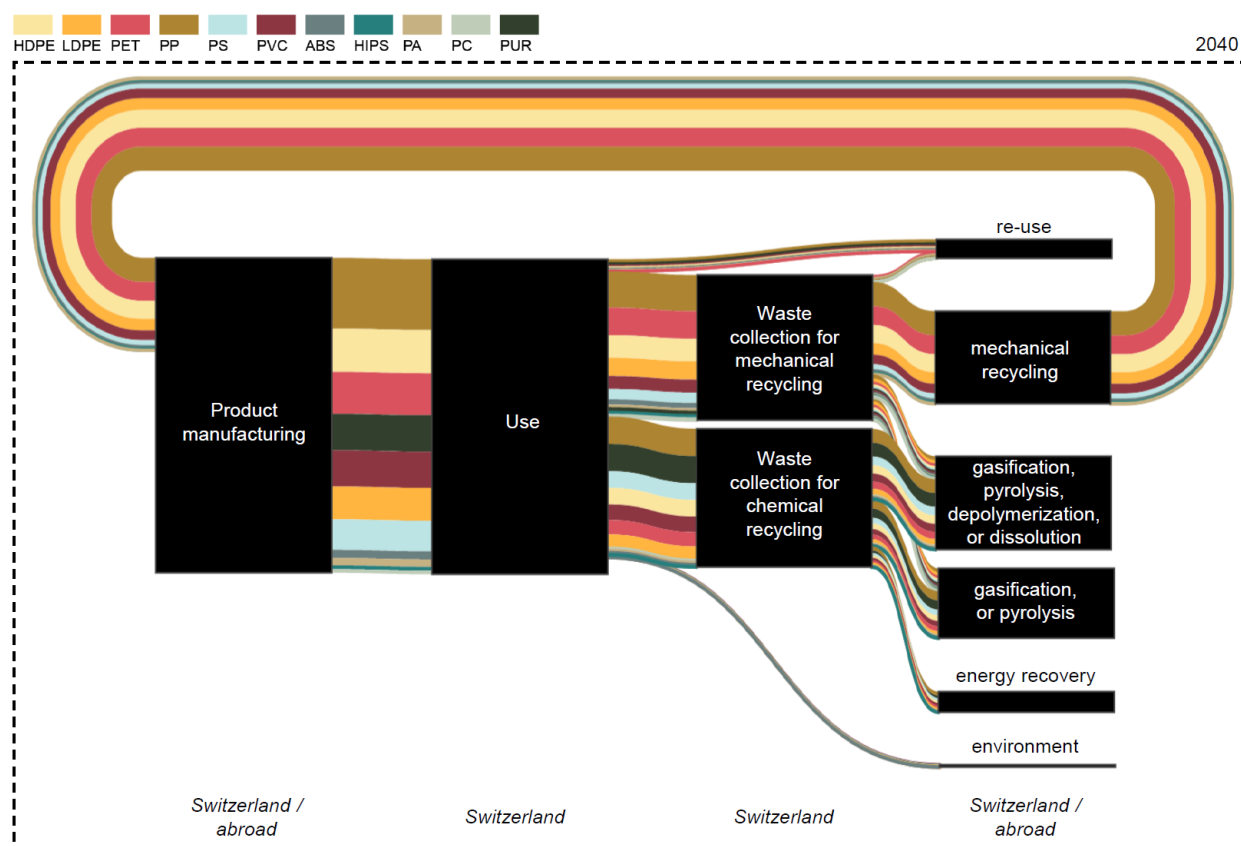


Figure 9: Material flows in a maximum plastic recycling scenario for Switzerland in 2040. The products of chemical and solvent-based recycling may be used for the production of plastics or other chemicals. Implementation of this scenario would require drastic system changes regarding mechanical recycling, while the waste amounts treatable by chemical and solvent-based recycling are highly uncertain, as industrial plants for these processes are very rare today.

Mechanical recycling should be prioritized, as it is able to achieve the highest environmental benefits of all plastic waste treatment methods (Laurent et al. 2014; Meys et al. 2020; Schwarz et al. 2021). Employing chemical and solvent-based processes complementary to mechanical recycling may provide further benefits. The potential additional impact reduction of chemical and solvent-based

recycling, however, strongly depends on process choice and exact process performance achievable on industrial scale, for instance, on product composition achieved or reactor heat transfer efficiency (Figure 10). Therefore, even if high waste amounts are chemically recycled, the related environmental benefits may be limited.

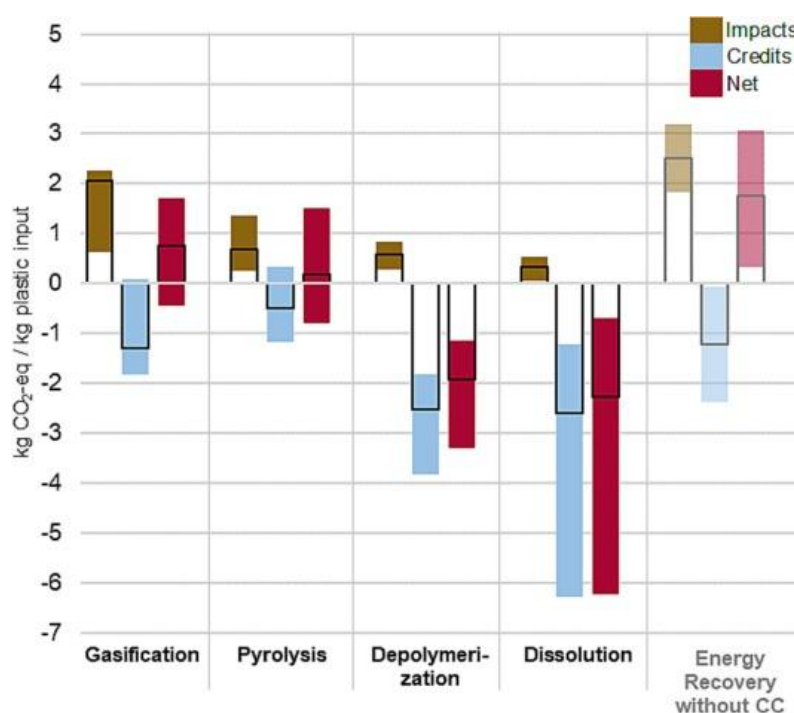


Figure 10: Ranges of potential climate change impacts of different chemical recycling processes, per amount of plastic waste treated. Credits result from avoided impacts, e.g. due to the avoided production of pyrolysis products such as ethylene or benzene by alternative processes. The framed bars show the impacts for each process type based on intermediate process performance and the filled bars show the potential impact range from minimum to maximum plausible assumptions for process parameter values. For comparison, the impacts of energy recovery are given, for different fossil shares in the substituted energy mix and energy efficiencies. CC: carbon capture.

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3 Chemicals can impact mechanical and chemical recycling

3.1 “Clean Cycle” strategy

Some chemicals in plastics negatively affect recycling by hindering certain process steps, influencing polymer degradation, increasing environmental and occupational exposure, and impacting the quality and safety of recycled plastics (Wang and Praetorius, 2022). Additives such as carbon black can hinder sorting technologies. Many metal salts can accelerate polymer degradation or poison catalysts required for chemical recycling (Day et al. 1995). The heat and high surface area during recycling may increase the release of hazardous chemicals (Hahladakis et al. 2018). The mixing of plastics with different compositions can result in undesirable qualities such as off-colors or odors. Legacy substances in older plastics (cross-temporal recycling) or hazardous substances in specific products (cross-sectoral recycling) may pollute recycled materials (Wiesinger et al. 2024). This may lead to human exposure to toxic chemicals in recycled products even after the phase-out of such chemicals in primary materials. Therefore, the environmental benefits achieved through recycling may be at tradeoff with increased risks of human exposure to legacy toxic chemicals contained in recycled products. One strategy to avoid the negative consequences is that only “clean” materials should be recycled. This “Clean Cycle” strategy (the adapted form is shown in Figure 14) was established by Kral et al. (2013) and requires (a) that impurities and dissipative material losses are directed to safe final sinks and (b) that an optimum mix of primary and clean secondary material is used to keep the material cycle alive.

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3.2 What is known regarding recycled plastics (LitChemPlast)

The following section is a summary from Wiesinger, Shalin, Huang, Siegrist, Plinke, Hellweg and Wang (2024).

Recycling is often promoted as a key solution to reducing plastic waste and creating a more sustainable, circular economy. However, recycling plastics can introduce new challenges, particularly when it comes to managing chemical contamination. Existing measurement data reveals that recycled plastics tend to have higher concentrations of hazardous chemicals compared to virgin (newly produced) plastics. This is especially concerning for legacy chemicals, which are substances that were commonly used in the past but have since been banned or restricted due to their harmful effects. For example, brominated flame retardants that are now restricted or banned in many regions still appear in high concentrations in recycled plastics, particularly those used in electronics, toys, and household items (see Figure 11).

The issue of chemical contamination in recycled plastics arises because when old plastics are recycled, the chemicals they contain are not removed during the process. This means that banned substances from products made decades ago can end up in new products today. This is especially problematic for products that have a long lifespan, such as building materials, where cross-temporal recycling can reintroduce substances that are no longer considered safe in modern products. Additionally, cross-sectoral recycling, where plastics from one industry are repurposed for use in another, can lead to chemicals being used in contexts where they are not needed or where their risks are greater. For instance, brominated flame retardants from recycled electronics have been found in children's toys, where the risk of exposure is much higher (Fatunsin et al., 2020).

The complexity of plastic recycling is further complicated by the wide variety of plastics in use today. Each plastic product, even those of the same type, may have a unique chemical composition, and some plastics are inherently more difficult to recycle than others. For example, multilayer packaging, which combines different types of plastics in a single product, is particularly challenging to recycle, especially in avoiding contamination. Furthermore, the additives used in plastics, such as stabilizers and plasticizers, can accumulate over multiple recycling cycles, thereby increasing the risk of harmful exposure.

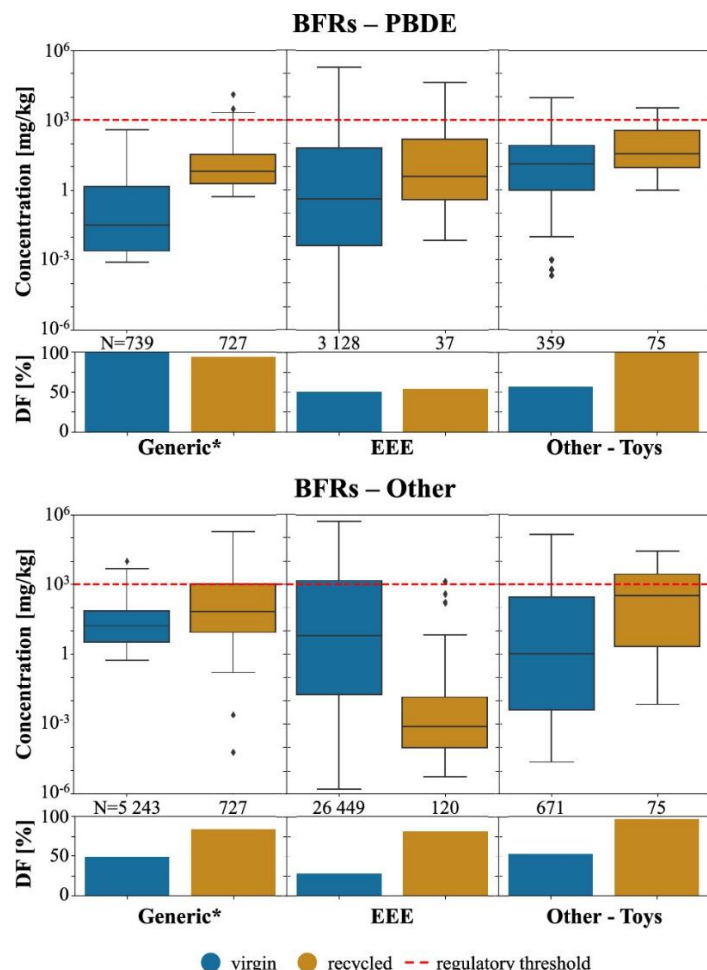


Figure 11. Comparison between recycled and virgin plastics for different product categories and substances in terms of the detection frequencies (DF) and concentration distributions (box plot). Only brominated flame retardants (BFRs; Polybrominated diphenyl ethers (PBDEs)) and selected product categories are displayed, as these are the only combinations for which sufficient measurements are recorded (>20 samples per group). The red line signifies a commonly used regulatory threshold of 1000 mg kg⁻¹ as a benchmark. * “Generic” encompasses products that lacked a specific description, e.g., those samples described as “raw material”, “plastic”, or “waste”. EEE: electrical and electronic equipment.

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3.3 Testing strategies for chemicals in plastics and Swiss case studies

The following section is based on own (unpublished) measurements conducted during the Clean Cycle project.

To implement a “Clean Cycle” strategy, it is crucial to understand the chemical composition of plastics that are or will be recycled (i.e., the sources of recyclates), and of the products that consume recycled materials (i.e., the sinks of recyclates). The chemical composition of plastic products and wastes is typically not known, and requires analytical measurements (Section 1.2.2). However, too many plastic products exist and too many chemicals are potentially present to conduct thorough analyses of all product-chemical combinations. Thus, a strategic approach to testing is needed. Building upon the lessons learned under the Clean Cycle Project, a selection strategy of relevant plastic products and chemicals to test is proposed and summarized in Table 2.

Table 2: Selection and testing strategies of relevant plastic products and chemicals in plastics for safeguarding plastic recycling while minimizing exposure to hazardous chemicals.

Selection strategies of products for testing	
- those associated with open-loop recycling (for observing “cross-sectoral” and “cross-temporal” contamination)	
Sources of recyclates to be potentially prioritized (products that are or will be recycled)	Sinks of recyclates to be potentially prioritized (products that consume recyclates)
- are (or will be) commonly recycled - are available in large quantities - known to contain hazardous substances, and/or - have a long lifespan (to observe “cross-temporal” recycling)	- commonly consumed recyclates, and/or - have high exposure potential
Test strategies of chemicals in plastics	
Uncover unknown contaminants: Use effect-based methods (e.g., <i>in-vitro</i> bioassays) and/or non-targeted analyses to reveal unknown toxicological effects and/or chemicals	Screen for expected contaminants: Contaminants that either are known to be present (from the literature, or previous screening), or have been widely used in plastics and known to be hazardous (e.g., those that have been regulated): Use quick screening tools (e.g., XRF for metal(loid)s), and targeted analyses for specific chemicals

To test the selection and testing strategies, within the Clean Cycle Project, several plastic product sectors were identified based on the above criteria and screened for toxic metals and *ortho*-phthalates. These include consumer and food packaging, hospitality packaging, building materials, and furniture (Table 3). From these sampling campaigns outlined in Table 3, the detection of *ortho*-phthalates in plastics varies significantly across product groups and polymer types, with detection frequencies ranging from 0% to 36%. These chemicals are most commonly found in building and construction (B&C) products, especially PVC flooring, where they were historically used as plasticizers at concentrations up to 65% by weight. Detailed analysis of PVC flooring shows that these substances remain prevalent (see Section 3.4 below).

In addition to phthalates, various metals and metalloids were detected across product samples, including vanadium, chromium, titanium, iron, barium, chlorine, and zinc, with the average detection frequencies across the sample product categories ranging from 46–73%. Concentrations of these elements vary widely, even within the same product category. For example, titanium concentrations in hospitality packaging range from 0.005% to 21% by weight.

Toxic metals and metalloids such as chromium, lead, cadmium, arsenic, and nickel were detected in 766 samples (covering 72% of the samples screened, noting XRF is a sensitive method with low limit of detection). Among them, 16 samples have levels of these toxic elements surpassing a common regulatory threshold of 0.1 weight% (except for cadmium, a regulatory threshold of 0.01 weight% was used), i.e., with a detection frequency of 1.5% of the samples screened. Most of these samples contain lead (n = 12) and originate from old products or those made from recycled materials, especially in the PVC-based B&C products and waste office furniture. This shows some levels of concern over legacy contamination in recycled materials and products with long lifespans for further

analysis. At the same time, it shows the effectiveness of XRF as a potential screening method to better control the input of recycling.

Table 3: Selected case studies from the Clean Cycle Project. Plastics from these sectors were sampled and screened with ATR-FTIR and XRF spectroscopy to determine their polymer type, the presence of ortho-phthalates and metal(loid)s.

Sector	Consumption amounts in CH [kt/year]	Current recycling rate in CH	Type of recycling	Product lifespan	Exposure potential	Sampling location and size
Packaging – Consumer & Food	226	low	Recyclates to other sectors →	short	high	Denner, <i>n</i> =4012 (119 screened using XRF and 1602 screened using ATR-FTIR)
Packaging – Hospitality	32	low	Recyclates to other sectors →	short	medium	SVG, <i>n</i> =540 (all screened using XRF and ATR-FTIR)
B & C – Waste	43	medium	Partially open-loop recycling	long	medium	Sortag, <i>n</i> =25 (all screened using XRF and ATR-FTIR)
B & C – Flooring	18	high	Closed-loop recycling ↻	long	medium	Retailers, <i>n</i> =204 (all screened using XRF and ATR-FTIR)
Furniture	17	medium	→ Recyclates from others	medium	medium	IKEA, Neumann, <i>n</i> =107 (all screened using XRF, but no ATR-FTIR)
Furniture – Waste	17	medium	→ Recyclates from others	medium	medium	ETH furniture waste, <i>n</i> =42 (all screened using XRF, but no ATR-FTIR)

PVC flooring was considered particularly interesting because it was found to contain hazardous substances, has a long lifespan, is commonly recycled, and plays a significant role in indoor exposure. Recent changes in its composition, due to the phase-out of regulated substances such as *ortho*-phthalates, cadmium, and lead, make it an ideal case study to observe recycling impacts. Consequently, PVC flooring was selected for further in-depth analysis, including chemical screening and bioassays assessing biological effects (see Section 3.4 below).

3.4 Swiss PVC flooring contains legacy pollutants suggesting mismanaged recycling

The following section is a summary from Wiesinger, Bleuler, Christen, Favreau, Hellweg, Langer, Pasquettaz, Schönborn, Wang (2024).

For our case study on PVC floorings, we analyzed 151 new products collected from the Swiss market in 2021/22 using ATR infrared spectroscopy (ATR-FTIR), X-ray fluorescence spectroscopy (XRF), gas chromatography-mass spectrometry (GC-MS), and *in vitro* bioassays. Although the products were new from the market, 16 % of the samples contained banned chemicals with more than 0.1% by weight, mainly lead and bis(2-ethylhexyl)phthalate (DEHP, CASRN: 117-81-7). A further 35% of the samples may be potentially harmful as they triggered certain level of toxicities in the bioassays or contained other *ortho*-phthalates or other hazardous metal(loid)s than those already regulated (Figure 12).

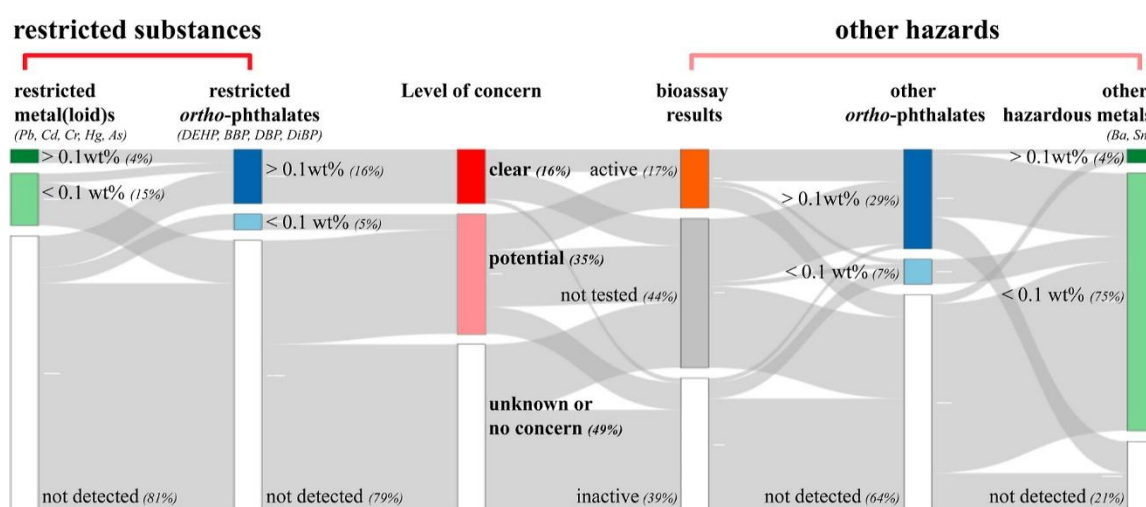


Figure 12: Percentage of samples with a reason for clear or potential concern. DEHP: di(2-ethylhexyl) phthalate (CASRN: 117-81-7); BBP: benzyl butyl phthalate (CASRN: 85-68-7); DBP: di-n-butyl phthalate (CASRN: 84-74-2); DiBP: diisobutyl phthalate (CASRN: 84-69-5).

Flooring samples typically contained one major plasticizer, either the *ortho*-phthalates - diisononyl phthalate (DiNP) or diisodecyl phthalate (DiDP) - or an alternative plasticizer, such as bis(2-ethylhexyl) terephthalate (DEHT, CASRN: 6422-86-2) or 1,2-cyclohexane dicarboxylic acid diisononyl ester (DINCH, CASRN: 166412-78-8). Moreover, most samples contained zinc, tin, and/or barium, suggesting the wide use of novel heat-stabilization systems, instead of the legacy cadmium or lead stabilization. Furthermore, nearly 400 organic substances were tentatively identified in the flooring samples using non-targeted suspect screening.

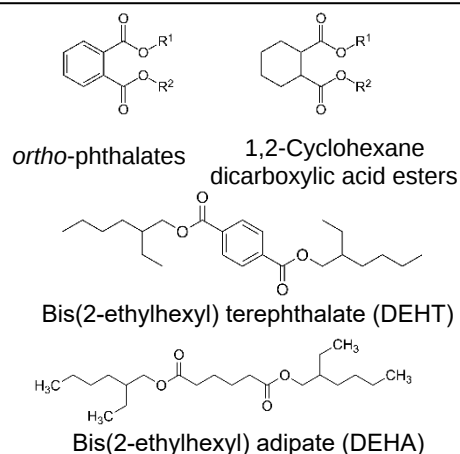
The measured DEHP concentrations were mostly below the typical concentrations for plasticizers in flexible PVC (5-50% by weight), and in almost all samples contained additional (main) plasticizers besides DEHP. This indicates that the presence of banned chemicals is mainly related to the use of recycled PVC in new floor coverings.

This case study shows that recycling of old materials containing now banned chemicals, without sufficient controls prior to recycling, can lead to cross-temporal contamination of the recyclates. The contaminated material still in use therefore poses a problem for the current and future recycling systems.

Chemicals in PVC

Plasticizers: These chemicals are added to make plastics softer and more flexible, commonly used in items such as flooring, cables, and packaging. Historically, *ortho*-phthalates were the most widely used plasticizers, but several of them have been linked to severe health risks, such as endocrine disruptions, cancer, and developmental issues in children. Due to these concerns, *ortho*-phthalates are being phased-out and replaced with alternatives, such as terephthalates and adipates, although some of these still lack comprehensive data to conclude their safety.

Heat Stabilizers: PVC needs heat stabilizers to prevent it from degrading during processing and when exposed to heat or sunlight. Previous stabilizers were based on hazardous metals such as cadmium and lead, which have been replaced with new systems based on organotin, barium, and zinc–calcium. However, these alternatives can still pose health risks. For example, organotin can disrupt the endocrine system, and barium exposure can affect the kidneys and nervous system.



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Read more

Wiesinger Helene (2024) "Recycling plastic is not a quick fix". *ETH Zukunftsblog*. <https://ethz.ch/en/news-and-events/eth-news/news/2024/03/blog-recycling-plastic-is-not-a-quick-fix.html>

3.5 Increasing the recycling of PVC flooring requires phthalate removal for ensuring consumer safety

The following section is a summary from Klotz, Schmidt, Wiesinger, Laner, Wang, Hellweg (2024).

PVC flooring is widely used in buildings and, due to its long lifespan, contains legacy plasticizers like DEHP, which were employed in the past and have been phased-out in the meantime due to their harmful effects. These legacy additives are still present in old floorings and continue to enter the recycling stream, as indicated by our measurement results (Section 3.4).

The effect of certain recycling scenarios on future additive concentrations in floorings can be investigated with dynamic substance flow analysis (SFA). We assessed the case of plasticizers in PVC flooring for Switzerland, modelling the consumption, waste, and recycling flows of the two *ortho*-phthalates DEHP, DiNP, and the alternative plasticizer DEHT from 1950 to 2100. The results indicate that, if recycling is considerably increased without specific removal measures, DEHP levels in PVC flooring on the market will remain above legal limits for decades, posing health risks due to prolonged exposure (Figure 13). This is because recycling keeps the hazardous DEHP in the loop. It also leads to dilution and a substance distribution throughout the system, making it even harder to recognize and remove concerning substances.

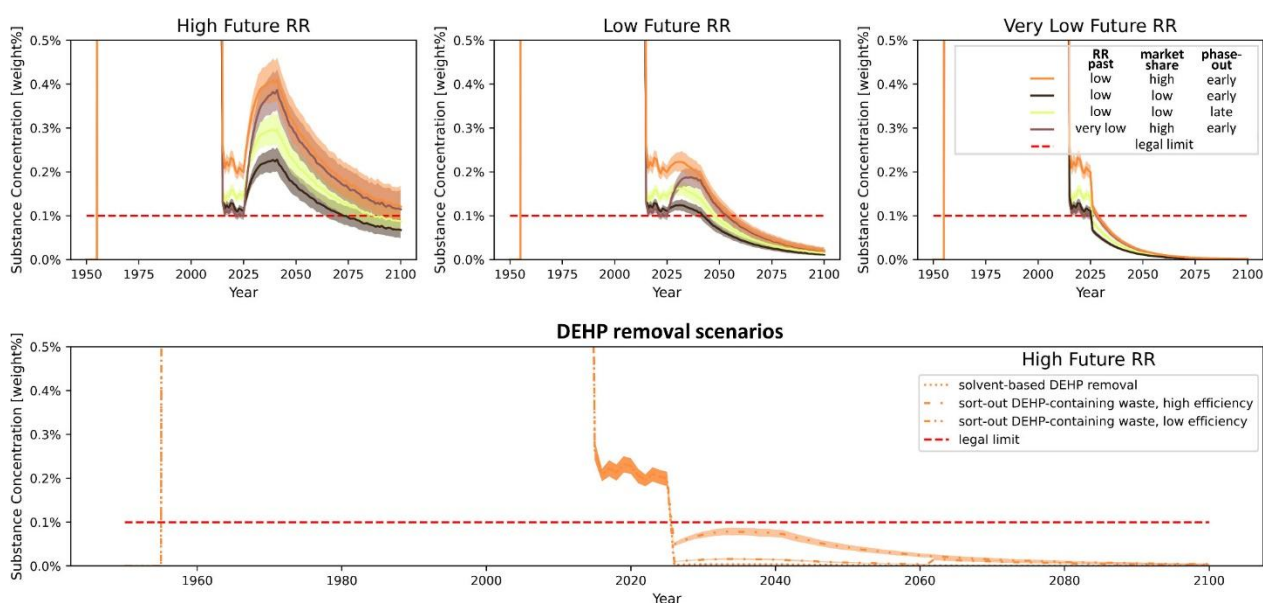


Figure 13. Future DEHP concentrations in PVC flooring in the case of different future recycling rates (RR) for selected plausible model scenarios. The DEHP concentrations are expected to remain above the legal limit (0.1%) for decades to come for business-as-usual and increased recycling scenarios. Two options for DEHP removal are modelled: (1) sort-out of contaminated waste and (2) direct DEHP removal by solvent-based-recycling. Immediate implementation of DEHP removal measures can help achieve both increased recycling and compliance with the legal DEHP limit. RR: recycling rate.

The recycling of PVC flooring can only marginally be increased if the concentration of the plasticizer DEHP in products must remain within legal limits. However, there are effective strategies to increase recycling while keeping DEHP levels low: (1) sort-out of contaminated waste using available analytical detection methods or (2) solvent-based recycling processes like CreaSolv to separate contaminants from the polymer.

While these contaminant removal methods offer promising solutions for handling legacy substances, they require significant effort and resources, and they may not be possible for all types of

contaminated wastes. Sort-out requires previous knowledge of the relevant hazardous substances and sufficiently fast and sensitive detection methods for each of them. Solvent-based recycling needs to yet prove to be viable at large scale.

The recycling challenges posed by hazardous additives found in plastic waste and the potential solutions are not unique to PVC or specific to Switzerland. Given the generally very limited knowledge about the identity and properties of additives used in plastics, these challenges could potentially apply to a wide range of plastic products. Other materials like paper and wood are affected by similar contamination concerns (Pivnenko et al., 2016, Faraca et al., 2019), and comparable remedies have been proposed. Many European countries likely face comparable difficulties in recycling PVC flooring wastes, as shown by a comparison with substance flow analysis results from Germany.

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Klotz Magdalena, Schmidt Sarah, Wiesinger Helene, Laner David, Wang Zhanyun, Hellweg Stefanie, “Increasing the Recycling of PVC Flooring Requires Phthalate Removal for Ensuring Consumers’ Safety: A Cross-Checked Substance Flow Analysis of Plasticizers for Switzerland”, *Environmental Science & Technology*, vol. 58, pp. 18686–18700, (2024), <https://doi.org/10.1021/acs.est.4c04164>

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4 Summary, discussion points & ways forward

4.1 Recycling can lower environmental impacts of plastics, but also lead to negative health effects

To increase plastic recycling is a commonly agreed goal, but not a simple task. The diversity of plastic products regarding polymer types and chemicals contained is immense. Therefore, large sorting efforts are required for high-quality recycling. The diversity of the product system with cross-sectoral recycling streams also makes it difficult to ensure that polluted waste is not recycled into exposure-relevant products.

Nevertheless, several options exist that may allow for a considerable increase in plastic recycling. Plastic waste collection for recycling may be extended by making it more financially advantageous and convenient. Technologies for improved waste sorting - for maintaining the specific properties of mechanically recycled plastics - are under development. Aligned product design, which can also avoid blending waste plastics with different properties during recycling, is aspired by manufacturers. In addition, chemical and solvent-based recycling technologies for challenging waste streams are experiencing a development boom at the moment. All mentioned efforts combined may halve the plastics carbon footprint. At the same time, the required system changes are drastic.

Recycling, however, poses the risk of keeping dangerous chemical substances in the loop (Figure 14). Plastic waste may contain chemicals that were allowed for use in the past and later banned, which through recycling can be conferred to new products - in case of open-loop recycling potentially even to products with higher exposure potential than for the original product. Many different chemicals are used in plastic products, while knowledge about them is usually not available to recyclers and testing methods are effortful or not available. This makes it difficult to decide on the recycling potential of waste and has led to hazardous substances being recycled into products where they may lead to negative health effects. In Switzerland, for instance, such a substance transfer likely occurred for the case of legacy phthalates in PVC flooring.

Increasing plastic recycling can reduce negative impacts of plastics, yet it is complex and requires addressing contamination issues to ensure safety.

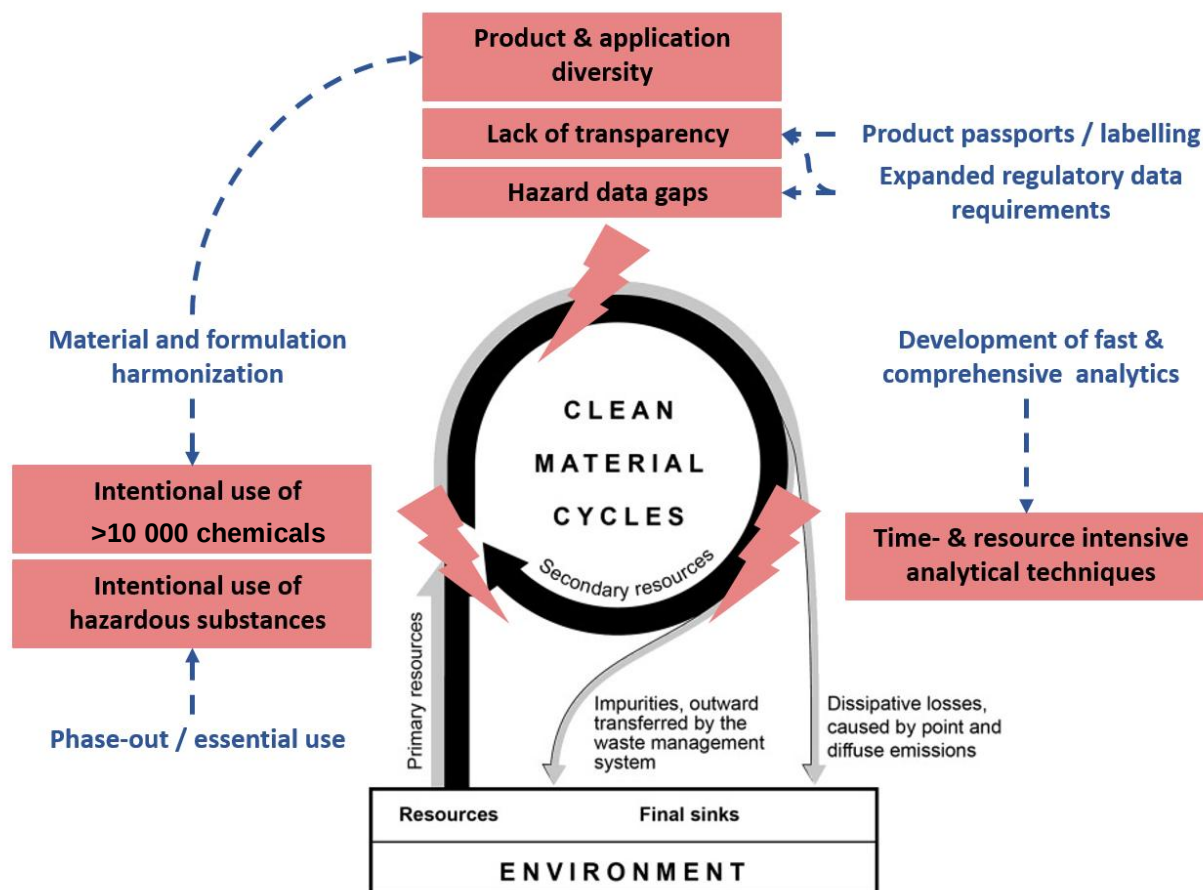


Figure 14: Ensuring the chemical safety of recycled plastics comes with many challenges (red), such as the diversity of materials and chemicals used and the challenges in identifying them at the recycling stage. Solutions (blue) may include the harmonization of materials and formulations, the phase-out of hazardous chemicals, and improved transparency measures. Adapted and expanded from Kral et al. (2013) in Wiesinger 2024.

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4.2 Moving toward a safe circular economy

For achieving a safe circular economy, **better monitoring and regulation** of chemicals in plastics is needed. This can ensure that recycling processes do not perpetuate or even increase the risks associated with hazardous substances. A combination of several measures will be needed to enable increased circularity while controlling health and environmental hazards.

1. Improved transparency

Challenge: More than 10'000 different chemicals may be used in plastics, many of them known to be hazardous, a large share of them lacking hazard data. The chemical composition of plastic products is commonly not known beyond material or product manufacturers. However, transparency regarding substance use is required for avoiding hazardous substance recycling to exposure-relevant products. Knowledge about the exact composition of products is also required for a data-based assessment of risks versus benefits of the use of a substance.

Possible solutions: To avoid hazardous exposure and allow for conscious substance utilization, manufacturers should be required to disclose the chemicals used in their products. They should also be required to provide more comprehensive hazard and physico-chemical data for their products. This would allow for better tracking and management of hazardous substances. Current requirements, e.g., under EU REACH (The European Regulation on the registration, evaluation, authorization and restriction of chemicals), are not yet sufficient for assessing all hazards and potential risks. When implementing such a disclosure requirement, an issue that has to be dealt with is intellectual property related to competitive advantage, which is partly the reason for the current non-transparency.

2. Better data collection

Challenge: Hazard data is lacking for many substances that are employed in plastics. In addition, besides intentionally added substances, many more chemical compounds may be present in plastics, for instance due to degradation or external contamination. These substances can only be identified with chemical analysis.

Possible solutions: More research is needed on the chemicals present in plastics and their hazards, particularly in product categories like consumer packaging and construction materials. To assess recyclates, rapid and cheap analytical methods need to be developed, to be implementable in a recycling context. For this, screening is often not enough. Screening methods may, for instance, only be able to detect the presence of certain metals, but not their chemical form, which, however, determines their hazard properties. The large diversity of both polymer matrix material as well as contaminations make the chemical analysis complex. At the same time, most analytical methods target specific groups of chemicals. Therefore, to obtain a holistic picture of substance presence, a multitude of analytical methods need to be employed. One way to address the issue of the presence of numerous unknown substances, are effect-based methods, determining the effect, rather than the chemical identity of the substances present.

3. Aligned substance use

Challenge: The multitude of chemical substances used in plastics is a main hurdle for recycling. On the one hand, this multitude makes it very difficult to obtain a holistic picture about the presence of substances in recyclates (see point 2.). This prevents a targeted utilization of resulting secondary materials, and, especially, can lead to the utilization of secondary materials containing hazardous substances in exposure-relevant products. On the other hand, the presence of numerous substances in plastic wastes usually leads to a blending of different substances during recycling, meaning that the resulting secondary materials often do not have the specific properties required for use in any of the

original applications from which the wastes originated. For avoiding blending when the waste diversity is huge, high sorting efforts are required.

Possible solutions: The number of substances present in plastic waste can be reduced, if the product design is aligned among manufacturers. For instance, manufacturer organizations could establish an agreement on the use of only certain stabilizers in PVC flooring. Such an alignment may face similar hurdles as a transparency requirement, related to competitive advantage issues (see point 1.). However, if an aligned substance use were achieved, it would greatly help (e.g. marker-based) sorting of waste, reducing the number of different fractions, as well as testing of waste for chemicals contained, reducing the testing need for different substances.

4. Enhanced recycling practices

Challenge: Problematic chemicals present in plastic waste are often not identified nor removed.

Possible solutions: New technologies are needed to ensure that hazardous chemicals are removed during the recycling process. For this, as a first step, knowledge needs to be gained about the waste composition. This could be achieved by developing better screening methods to identify contaminated materials before they are recycled into new products (see point 2). Another way could be product labelling connected with information on their chemical composition. Moreover, it needs to be safeguarded that hazardous constituents detected are removed. This goal can be accomplished by either completely removing hazardous substance-containing waste from recycling, or by selectively removing contaminants by separating them from the polymer matrix.

5. Stricter regulation

Challenge: Many substances are in use that are either known to be hazardous or lack hazard data.

Possible solutions: Stricter regulations around the use of hazardous substances in plastics would help to maintain clean cycles. This includes updating regulations to cover not only new products, but also those entering the market through recycling. The essentiality of a given hazardous chemical in specific products could be used as a criterion (e.g., when they are critical for health, safety or the functioning of society and there are no viable alternatives, the use of this chemical would be regarded as essential). For example, brominated flame retardants in electronics can reduce the risk of fire, but some are hazardous to human health. In such cases, the essentiality of brominated flame retardants in specific products should be carefully evaluated. Especially in long-lived products, the use of hazardous or concerning substances should be avoided. The requirement for a safe stock of materials could, for example, be introduced in alignment with policies aimed at increasing material circularity such as the European Circular Economy Action Plan under the Green Deal. However, industries such as PVC flooring manufacturers can also show self-responsibility by seeking to ensure a safer material stock by agreeing on a positive list of non-hazardous additives to be used. This has been done for PET bottle recycling, for example. Due to the cross-border nature of recycling, cooperation and harmonization of products must take place at least at the European market level (Wiesinger 2024).

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4.3 Outlook

Managing chemicals in plastics recycling is a complex challenge. Nonetheless, by improving transparency, research, testing and screening strategies systems may be created within which plastics can be safely recycled without continuing to expose humans and the environment to harmful substances. Based on improved transparency, more targeted specifications and regulations can be implemented. The insights gained in the context of the Clean Cycle Project on the identity and properties of substances used in plastics and the obtained understanding of the plastic recycling streams are a step toward addressing the plastic recycling challenge. However, continued efforts will be required for ensuring that benefits of plastic recycling do not come with environmental or health impairments.

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