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WHITE PAPER No. 80

Recycling Strategies for Plastics: On the Road to Circular Economy?

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The goal of a circular economy concept is to hold materials in the loop and to have – in an ideal world – no waste or only biodegradable waste. Especially regarding plastics, this goal is challenging to achieve. We as society are still at the very beginning of a truly circular economy. The production, use, and fate of plastics is a major problem, with plastic waste accumulating in our environment due to improper waste management. Nevertheless, steps have been taken, focusing on better recycling strategies. At the same time, there are a lot of limits regarding the quality of secondary raw material and its use in sensitive areas like food, medicine, or research applications. What are present trends, how is plastic recycled today, and in what ways can recycled plastic also be used in research and laboratory work?
This White Paper overviews the major different recycling strategies and shows how recycled plastic can enter the laboratory.

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Plastics and their Environmental Impact

Plastic is ubiquitous in our daily life – at home and in the laboratory. And we as human beings use a lot of plastic.
In 2019, 460 million tons of plastics were produced globally [1], and this is nearly twice the amount manufactured in 2000 (234 million tons). The manufacturing of plastic released 1.8 gigatons of CO_2 into the atmosphere. Compared to all other emissions, plastic production alone accounts for 3.4 % of the global CO_2 emissions. If you compare these numbers with the CO_2 emissions of countries, global plastic production will rank as 5th place after China, the USA, EU-27, and Japan [2].
90 % of greenhouse gases are released during the conversion of fossil fuels into the building blocks of polymers and the production of individual plastic items [1]. At the end of the life cycle, plastic products end as waste. About 40 % of all plastic waste comes from packaging, 12 % from consumer products, and 11 % from textiles – all products with a lifespan typically below five years, sometimes even months or even days [1]. Alone in Europe (EU plus UK, Switzerland, and Norway), 29.5 million tons of plastic waste were accumulated in 2019 as post-consumer waste. Less than 35 % were used for recycling. Out of these 10.2 million tons, 5.5 million tons ended up as recycled plastic, whereas about 1 million tons were exported, and about 3.6 million tons were lost during the recycling process.
The 65 % "remains" of the post-consumer waste ends in landfill (6.9 million tons) or is burned for energy recovery (incineration) (12.4 million tons) [3], Fig. 1. On a global

basis, the numbers are not better: only 9 % of all plastic is recycled, whereas 19 % is incinerated, 50 % ends in sanitary landfills, and 22 % is leaked into the environment, released into uncontrolled dumpsites, or burned in open pits. The environmental impact can be seen with plastic garbage in rivers and the ocean, accumulating in sea animals or enrichment of microplastics in soils and the most remote areas of the world like Antarctica [1, 4].

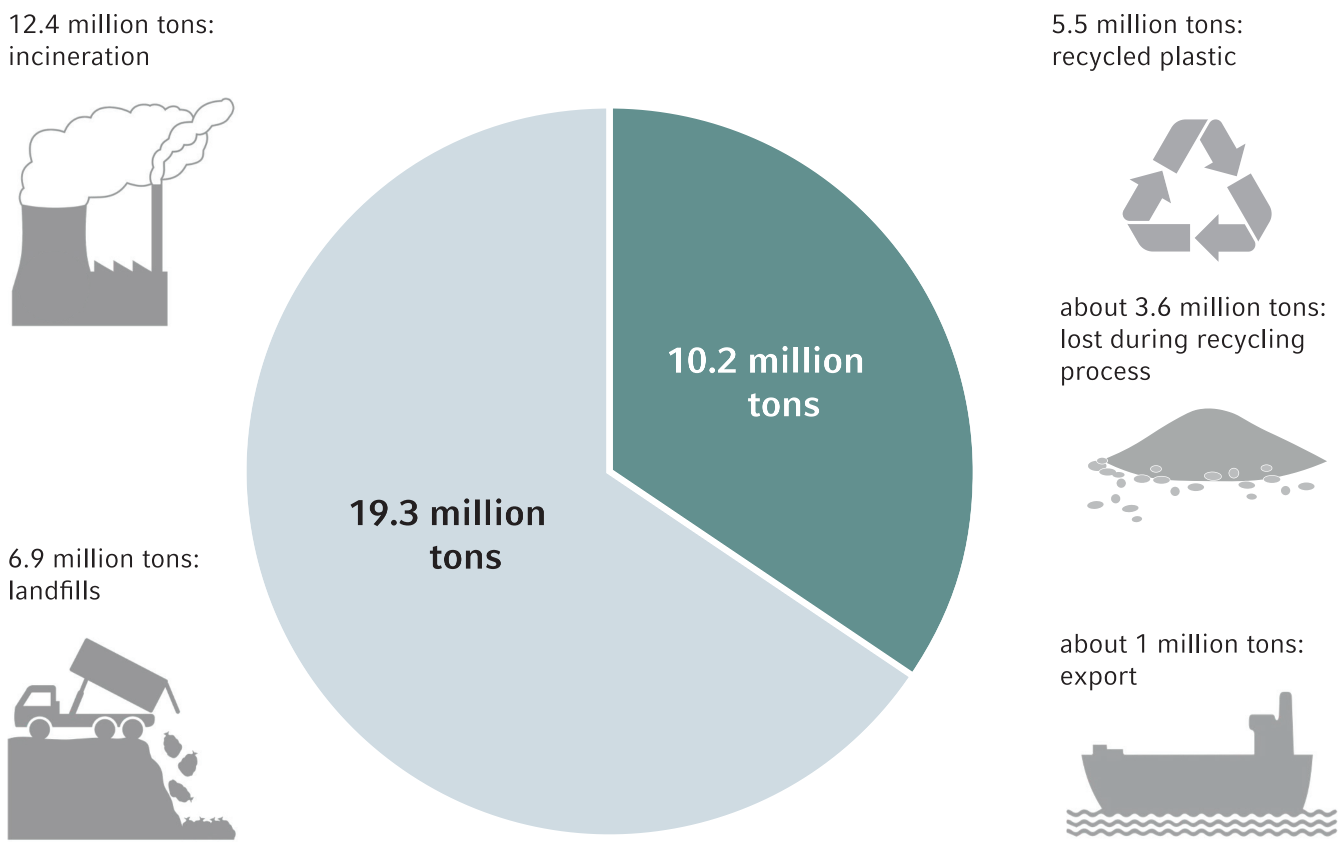

Fig.1: The fate of post-consumer waste in Europe (EU plus UK, Switzerland, Norway) [3]

The Search for Solutions

Given these facts, it is clear that several strategies need to be implemented to reduce the impact of plastic on the environment. Such approaches include using renewable feedstocks instead of fossil-fuel based ones [5] or using recycled material at the beginning of the life cycle. Design strategies must cover the end-of-life of a product combined with proper waste management, making reuse or recycling possible. The goal is to establish a circular economy from a linear “cradle to gate” to a circular “cradle to cradle” approach. Here, plastic waste is not seen as waste but as a source to build new products. This approach starts to be accepted by the industry, and products made of recycled plastics are available in packaging, building and construction products, or gardening items. From 2018 to 2020, the content of post-consumer recycled plastic in new products increased by 15 %, from 4 million tons to 4.6 million tons [3]. In contrast, the quantities sent to landfills decreased by 4.3 % to 6.9 million tons.

During these two years, plastics production has also declined by 10.3 % in the countries of the European Union, the UK, Switzerland, and Norway. This decrease was also due to the COVID-19 pandemic, where global plastic production decreased by 2.2 % [1]. Although these developments look promising at first glance, we have to realize that today most recycled plastic ends in products with minor quality requirements. You will not find recycled content in products of the food industry, medicine, or research products used in life science labs: Recycled material does not always fulfil specified quality requirements. So, is there a way to close the loop in these areas? To answer this question, let's look at the different recycling strategies and then focus on the research and laboratory area.

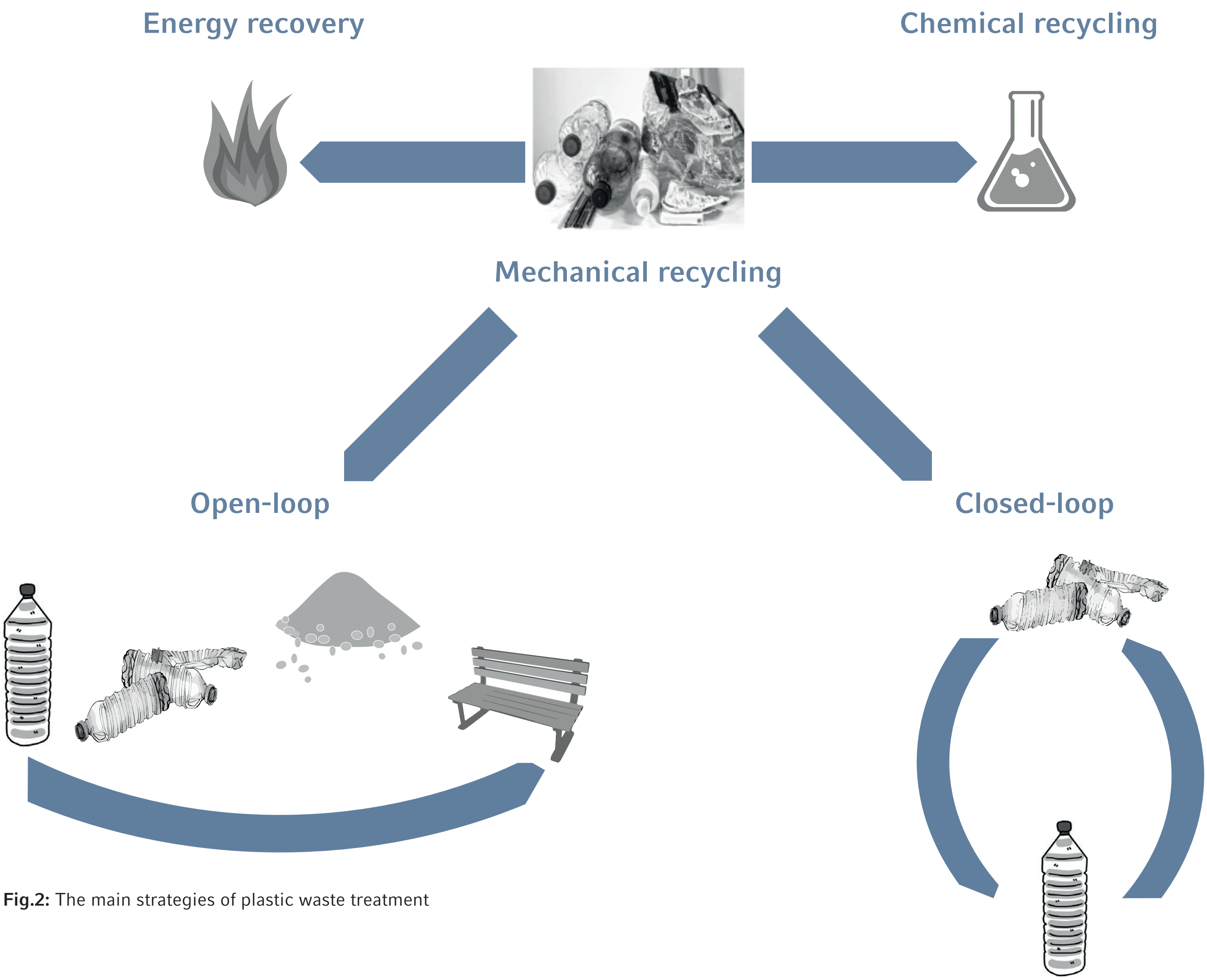

Fig.2: The main strategies of plastic waste treatment

The Fate of Plastic Waste – three Main Routes at the End of Life

There are different ways to recycle plastics: depending on their properties, the source, and the quality. Some of them, like mechanical recycling, are well-established, whereas others, like chemical recycling, are still part of pilot projects [6,7].

Today, we distinguish three recycling strategies: mechanical recycling, chemical recycling, and energy recovery [Fig.2].

Energy Recovery

Energy recovery is a way to dispose of plastic waste but benefit from the high calorific value [7]. Incineration recycles the energy from the plastic but it's not a real recycling as the material is lost. The burning releases CO_2 emissions into the atmosphere contributing to climate change and the ash of the combustion process can contain heavy metals like cadmium or lead and microplastic particles. So, energy recovery is not recycling in the sense of a circular economy approach but is today one of the main methods to get rid of plastic waste.

Chemical Recycling

Chemical recycling is a promising method that could complement mechanical recycling in the future. It cuts down polymers in feedstock material for new plastics, either monomers or oligomers from a specific plastic type like PVC (polyvinyl chloride) or PS (polystyrene), or the plastic is broken down via thermolysis into basic chemicals like ethene and propene. These can serve as starting points for new plastic with the same properties as virgin plastic. Significant disadvantages of chemical recycling are high temperatures in the thermolysis process with related high energetic input, no mature technology at the moment (but some pilot plants), and high costs [7,8].

Mechanical Recycling Part 1

Finally, mechanical recycling refers to reprocessing plastic waste to a product with comparable properties or processing it into secondary raw material, respectively recyclate [9]. The first alternative is also known as primary recycling or closed-loop recycling [10]. Bottle-to-bottle recycling of PET (polyethylene terephthalate) is an excellent example of closed-loop recycling. The processing of plastic waste into recyclate is also referred to as secondary or open-loop recycling. Mechanical recycling does not significantly alter the chemical structure of the polymers. It is the most established procedure, and the single steps are described below in more detail [Fig. 3].

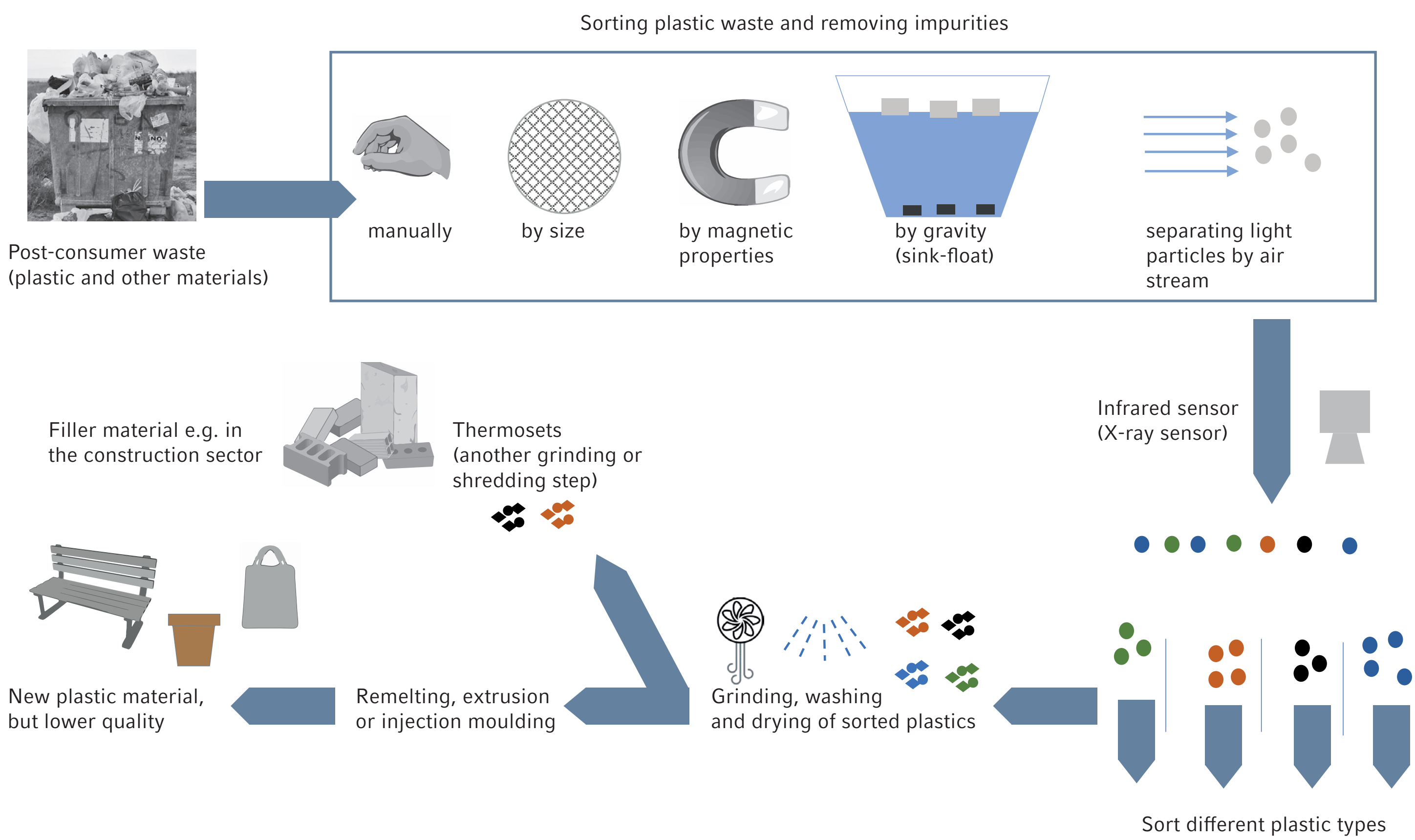

Fig.3: The recycling process of post consumer waste

Preparation Steps for Post-Consumer Waste are Key for Mechanical Recycling.

The most common source of secondary raw material (recyclate) is post-consumer plastic waste which refers to plastic products that have been discarded and can no longer be used [3]. Post-consumer waste consists mainly of packaging material (61 %), minor parts from electrical devices and electronics (6 %), building and construction (6 %), automotive (5 %), agriculture (5 %), and other sources (17 %) [3]. If you want a high quality of recyclate, it is mandatory to get pure waste streams and sort them accordingly to their chemical nature. If plastic waste is already collected separately (pre-sorted), the recycling rate is 13 times higher [3]. But in general, post-consumer waste is a mixture of various plastic types like PE (polyethylene), PP (polypropylene), PET (polyethylene terephtalate), or PS (polystyrene).
Different types of plastic are quite often mingled in one product in blends or layers of diverse polymers [6] which further increases the complexity.
The first step in processing the plastic waste consists of sorting the material according to its size with the help of sieves and is sometimes even done manually. It also includes elimination of foreign materials like glass, paper, or metal. These impurities can disturb all further processing steps. Metal can be picked out due to its magnetic properties. Other impurities are separated by gravity in airflow or by a water stream, where items with a lower density than water will float and objects with a higher density will deposit to the bottom [11].

Automated sorting process for used plastic material

The second step focuses on the separation of the various plastic types. Polyolefins like PP or PE can be separated from polycarbonates, PVC, or PET due to differences in density. Another more sensitive technology identifies the single polymer types via an infrared detector and sorts them with the help of an air jet or mechanical selection. X-ray detectors are one of the latest developments which improve the sorting results as they can separate challenging fractions like HDPE (High-Density PE) and LDPE (Low-Density PE) or identify black plastic particles.
These constitute a significant source of impurities in recyclate and finally downgrade its quality. Infrared detectors cannot identify them. Further improvements focus on integrating fluorescent pigments in plastic products to place them under UV light or digital watermarks containing information about the products. Cameras can read out this information on sorting lines. But these technologies are still in development [11].
The sorted plastics are then ground into smaller particles before they are washed to remove dirt, remains of food, and other contaminants. Hot or cold water, mixed with detergents, cleans the plastic particles. Organic solvents remove odorous components and other non-water-soluble contaminants. The particles are then air dried and pass through a second sorting and control process before entering the real recycling step [11].

Mechanical Recycling Part 2

The further fate of the sorted plastic depends on its chemical composition. Reprocessing into new products is limited to so-called thermoplastics like PE, PP, or PET as they remelt without their chemical structure being destroyed. On the contrary, thermosetting plastics like PU (polyurethane) or PVC cannot melt as they already decompose below their melting temperatures. They can only be shredded or ground and be picked out after the grinding step. These polymers end up as filler material, e.g., in the construction sector. When added to concrete, they change its properties and make it lighter than the concrete commonly used, which is appreciated in the building sector [6].
Thermoplastics are more versatile, and after the washing and second sorting step, they are remelted and changed into new products by extrusion or injection moulding. But the quality of the recycled material differs from the virgin quality for several reasons:

First of all, compared to non-recycled material the chain length of recycled polymers is lower. Polymer chains can already degrade during the use phase by UV-radiation or oxidation processes. During the extrusion process, which takes place at high temperatures and strong shear forces, impurities like catalyst residues or hydroperoxide lead to further scission of polymer chains. Properties like the hardness of the material, its impact strength, or break resistance can significantly deteriorate. Polypropylene which has undergone several recycling cycles, becomes more fragile, shows a loss in viscosity and even becomes more yellowish. Such quality losses make this material unusable for high-end applications. Better purification of the recyclate can achieve improvements by reducing impurities, as well as through the addition of virgin material or copolymers that lengthen the polymer chains.

Mechanically ground plastic

Maleic anhydride is successfully used as a copolymer to alter recycled polypropylene properties. But all these improvements mean further steps, more resources, more energy and – in the end – a higher price for the recycled material [11,6].
Also, traces of other polymers can be present through imperfect sorting. For example, PET or PP are possible contaminants in recycled polyethene. Different polymers usually do not mix homogenously but segregate in the polymer structure. As a result, the recycled material contains so-called weak spots built up by the foreign, unrequested polymers, worsening the quality of the recycled material [11].
Secondly, the preparation process cannot remove additives like fillers, antioxidants, pigments, or flame retardants. These impurities are still in the recycled material and make them unusable for high-end requirements in the food industry, research, and medicine, where traces of possible toxic contaminations are not allowed.

Finally, odour and colour can pose a problem.
Intensive washing steps and chemical treatments are necessary to remove odours, increasing both effort and cost. The pigments in coloured plastic products cannot be extracted. Therefore, excessive coloring is necessary, resulting in a darker recyclate. Alternatively, a perfect colour sorting in the preparation steps allows obtaining fractions of the same colouring. Again, this increases effort and is costly [11,12].

In summary, converting post-consumer waste into recycled plastics is possible but needs a lot of sorting and processing steps. The recyclate can be used mainly for products with low-quality demands like packaging material, building, agriculture, or gardening articles. Recycled HDPE or PET are used for bags or other packaging materials, whereas recycled PP is for compost bins.
The bottle-to-bottle recycling of PET is undoubtedly the most sophisticated and advanced example of closed-loop recycling. But products in research labs have far higher quality requirements that second raw material made from post-consumer-waste cannot fulfil today.
But there's another option.

Post-Industrial Waste – a pure Material ready for Recycling

As described, plastic waste occurs at the end of a product's life cycle but also at the beginning. Faulty-produced items, edge sections of plastic sheets, or production leftovers end up as so-called post-industrial waste even before they enter a product life cycle [3]. This material is a valuable source for all processes requiring high-quality polymers. Already 3.6 million tons of pre-consumer recycled plastic were produced in 2019 in the European Union, UK, Norway, and Switzerland [3].
One of the most significant advantages of using post-industrial waste is knowledge about the material. Whereas the composition of recycled material from post-consumer waste is not specified, recycled material from post-industrial waste is very well-known. Hence, the content of the material, possible contaminations, and the homogeneity of the material are well controlled and documented. The material is pure and its properties are close to virgin material. This offers the possibility of direct reuse or reuse with only some minor processing steps like classification, sorting, or sizing. It may be necessary to slightly customize the production process when using this material [13,14]. Studies showed that the inner structure of post-industrial PP can be different from virgin PP because the material has been exposed to high

shear forces during the extrusion process. This alters the mechanical properties, mainly the tensile strength.
By changing the re-moulding conditions in a specific way, the mechanical properties nearly reach the values of virgin PP [15]. Lastly, recycling plastic scrap lowers the environmental impact shown by life cycle analysis, which considers a recirculation of polypropylene scrap into production [16].

Laboratory Plastic: a Sophisticated and Challenging material

Disposable plasticware is used routinely in most life science laboratories. To achieve highest reliability and consistency for your experiments, this plasticware needs to be optimized in respect to materials and processes for the production to minimize the risk of interference.

Laboratory tubes (5 mL) made of Polypropylene

Chemical substances such as slip agents, plasticizers or biocides leaching out of plastic consumables are still frequently underestimated in the majority of life science applications. However, increasing scientific evidence shows that this heterogeneous group of chemicals may significantly affect experiments and pose a likely source of error in various as say systems. They slow down evaporation, skew absorbance readings and lead to erroneous DNA quantification.
Some of these slip agents have also been shown to negatively affect the outcome of biological tests like enzyme activity or receptor-binding assays.
When combining these high-quality requirements with recycling material, a few challenges are obvious:

> Clear materials for tubes and plates are required. Therefore, recycling material is limited to clear original material.
> No leachables are allowed. As a consequence, recycling material must be free of other components.
> Extreme stability for high speed centrifugation is needed. Recycling material must not contain traces of other plastics in recyclate as these can lead to weak-spots and –as a consequence – to material break-down.
> Sudden temperature changes of 100 °C must be withstood. Recycled material has to contain long polymer chains as one prerequisite for material stability and material resistance in a broad temperature range.
> Handling of chemicals has to be safe. Only defined and homogenous recycled material can guarantee chemical resistance.

Seeing these high demands on laboratory plastic ware and the current quality of recycling material, it is obvious that post-consumer waste based recyclate is currently not usable for high-tech consumables in the laboratory.

Promising Starting Points on the Way to a Circular Economy

The goal of the circular economy is to hold materials in the loop and to avoid waste. While the technologies to recycle post-consumer waste are getting more sophisticated, the high requirements on the quality of single use plastic used in research can currently not be fulfilled by these recyclates due to contamination, unknown composition and mechanical properties. Hopefully, there will be better sorting technologies in the near future which will provide recyclate of highest polymer quality for laboratory tubes, plates, and tips at reasonable efforts and costs. Until then, post-industrial waste recyclates provide a far better starting point.
Its quality is high and its properties are close to virgin material: A good starting point for laboratory products in the near future, even if the usage of these recyclates is challenging. In a first step, the usage of recyclate from post-industrial waste in packaging material like foils or bags can be an option. Based on current knowledge, the usage should still be limited to plastic products which are not in direct contact with critical and high-value samples. But this alternative recycling approach already helps to reduce plastic waste; it reduces the amount of virgin material and is another building block in creating a circular economy.

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