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Plastics Recycling Guide

Results and findings from the project „CIRCUMAT“

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Preface

This guide has emerged from the many findings of recent years on the subject of plastics recycling and is intended to show ways of using plastics sensibly and efficiently in accordance with a circular economy. It compactly contains the current state of the art, in particular the results from the „CIRCUMAT" project, which has dealt with various aspects of plastics recycling to close the loop. I have summarized these findings and results here as far as possible and tried to interpret them, draw logical conclusions from them and thus provide you, dear readers, with possible food for thought.

My thanks go to the project partners who have supported this project not only financially but also with their technical input and know-how:

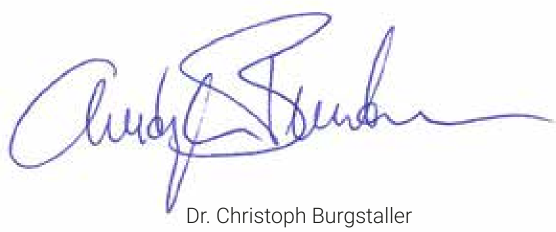
- Borealis AG
- EREMA Engineering Recycling Maschinen und Anlagen GesmbH
- Greiner Packaging International GmbH
- Innplast Kunststoffe GmbH
- Lindner-Recyclingtech GmbH
- MKW Kunststofftechnik GmbH
- O.Ö. Landes-Abfall-Verwertungsunternehmen (LAVU)

Without the involvement and cooperation of these companies, this project could not have been implemented so comprehensively and professionally.

My thanks also go to the Institute for Polymer Extrusion and Compounding at JKU Linz, which supported the project with its expertise as a scientific partner. And, of course, the Plastics Cluster, which played a driving role in disseminating the results and thus helped the project achieve additional reach.

I would like to thank my team at TCKT for their support in carrying out the project. With your dedication, knowledge and commitment, you turn ideas into projects!

Last but not least, I would like to thank the State of Upper Austria, Department of Economics and Research, for the financial support of the project, which made it possible not only to achieve the original objectives, but also to look into the depths of the project in order to learn from it for future projects.



Dr. Christoph Burgstaller

1. Introduction

Polymers - colloquially known as plastics - are constantly under criticism: garbage, microplastics, greenhouse gases - all of this is mixed into a mash in the public discussion, which almost does not allow for a factual discussion of the topic. This guide is intended to help provide a technically sound contribution to such discussions.

It is impossible to imagine modern life without plastic products. Plastics are used in a wide variety of applications. The consumption of plastics has been rising steadily for years; in 2018, 51.2 million tons were consumed in Europe[1].

[1] Platics the facts 2019, www.plasticseurope.org

Do we have a plastics problem?

If we are talking about a problem in this context, then it is more likely to be a packaging or disposal problem. Plastics are used in a wide variety of sectors, packaging being the dominant one (Fig. 1). In packaging and other areas, such as automotive & transportation, construction, or electronics, plastics create sustainability for the various applications because they require fewer resources and less energy than their metal, glass, wood, etc. counterparts. This is not to say that only plastics are useful materials, but:

Plastics are clearly the better choice for many applications in terms of sustainability!

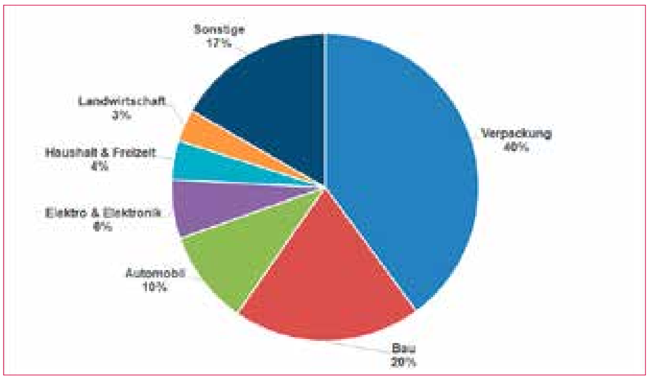


Figure 1: Plastics consumption by sector[1]

Sustainability without plastics - is that possible?

Consumers' demands on packaging are constantly increasing, especially in the food sector. Products should be as practical as possible, as fresh as possible and have the longest possible shelf life. Ideally, they should also be packaged in a sustainable manner. And packaging is sustainable above all when it maintains product quality for as long as possible. In this way, it makes a significant contribution to reducing food waste. Plastic is therefore the preferred material for many applications due to its low energy consumption and weight. Reusable packaging (such as resealable containers) is not always a viable solution either: it often cannot guarantee such a long shelf life for the packaged products, and cleaning it is also comparatively more resource-consuming, which in turn leads to a higher carbon footprint.

Why do plastics have a bad reputation?

This is mainly due to the waste problem: If plastic packaging is carelessly disposed of, one of its most outstanding properties - namely its longevity - becomes its undoing. They „survive" for decades in nature. However, not only plastic packaging is found in the environment, but also metal and glass packaging.

But where does the problem of littering come from? On the one hand, it is the much lower cost of plastic compared to competing products that has given the material a „cheap image". On the other hand, there is often a lack of education. Due to the variety of products and the many different collection options, consumers often do not know what correct disposal looks like. Many plastic products therefore end up in the residual waste.

To clarify - we have a good waste collection and disposal system in Austria, but during our co-operation in various recycling projects we have also seen that some fractions, depending on the regional conditions, cannot be recycled at all as these are not collected separately.

This background laid the foundation for the „CIRCUMAT" project, in which nine project partners along the entire value chain came together to highlight the many relevant aspects of plastics recycling. Together, the existing problems were discussed across industries and sectors, which undoubtedly contributed to the general improvement of the overall understanding.

Figure 2: Project partners in the project CIRCUMAT

Project goals

The objectives of the project - in addition to increasing the appreciation and acceptance of plastics - were:

- to demonstrate the applicability of recyclates by manufacturing at least 3 products from recyclates.
- The percentage of recyclates should be at least 25% for post-consumer recyclates or at least 45% for post-industrial materials, but as many recyclates as technically possible should be used.
- The representation of demanding products, e.g. from technical packaging or in the construction sector.
- The focus was on polyolefins.

The focus was therefore placed on polyolefins, as these account for the largest quantity of plastics used and thus also produced the largest quantity as waste stream. By presenting technically sophisticated products, we want to demonstrate the high-quality results that can be achieved with recyclates. Unfortunately, there have also been products in the past that have been made from recyclate with inferior quality, but such products do not increase the appreciation of plastics and have therefore not been considered. And we have set the percentage of recyclate to be used relatively high for this reason, so as not to run the risk of the „CIRCUMAT" project being dismissed as greenwashing. With a low single-digit percentage of recyclates in the product, it would be difficult to speak of recycling. Selecting only three demonstrators for the project was a compromise in the project planning to make the whole thing „doable". There could have been more, but it was also the case that ideas in the project were discarded because their technical or aesthetic requirements could not (yet) be realized. Food packaging was not considered in this project - due to the high demands on purity.

The project results should show that a sensible application of recyclates is possible. This knowledge will be needed in the future to close cycles and actually keep plastics in an application, as is already being done with PET bottles, for example, or at least to give plastics another useful application after their often very short initial life cycles (as packaging, for example). This is also relevant with regard to the legal framework already in force and also further announced.

Legal framework

In 2015, a circular economy package was published by the EU Commission, which deals in detail with the subject area of plastic waste and the associated problems and opportunities. This package aims to increase and improve plastic recycling, with a focus on economic efficiency and quality. Another focus is to significantly reduce the increasing pollution of waters and oceans with microplastics. The key aspects of this plastics strategy are as follows[2]:

- Plastics recycling is to be significantly strengthened. By 2030, 60% of plastic packaging waste is to be recycled. More waste is to be collected separately and recycling capacities in the EU are to be expanded, and more recycled plastics are to be used.
- Exports outside the EU of plastic waste are to be phased out.
- Single-use plastic products are to be greatly reduced.
- Chemical substances added to plastics that hinder recycling are to be replaced.
- A better understanding of the sources and input pathways of microplastics is to be created. This is to be achieved by involving consumers. With the help of new labels, consumers will be given the opportunity to do without such plastics.
- Intentionally added microplastic particles in cosmetics and other products will be banned under REACH.
- Clear labeling and standards for biodegradable plastics will also help consumers better assess the impact and risks of such products. A clear legal framework, which does not yet exist, should provide an overview and clarity. However, biodegradable plastic is not a solution to the problem of litter, nor should it ever be.

This shows the interest in the topic, but also the understanding that there are no singular solutions here. For example, intentionally added microplastic particles are clearly banned, but the topic of bioplastics - a major issue that cannot be described in detail here - and, in detail, biodegradable plastics are also clearly defined in such a way that they are not the panacea against littering.

This results in essential objectives at EU level[2]:

- by 2030: **„60 % of all plastic packaging is reused or recycled".**
- by 2040: **„100 % reuse, recycling and/or recovery of all plastic packaging in the whole EU of all plastic packaging in the EU is reused, recycled or collected".**

[2] PlasticsEurope AISBL (2018). „Plastics 2030 - PlasticsEurope's Voluntary Commitment to increasing circularity and resource efficiency", Association of Plastic Manufacturers. Belgium

The second stage of the objective in particular shows that new approaches are needed here that take a holistic view of the subject. This must happen both in the collection and application of different recycling processes (material and raw material or mechanical and chemical recycling) as well as already in the product design and manufacture with the consideration of a suitability of the product for recycling.

We must also deal with these objectives and their implementation in Austria. According to the Federal Ministry for Sustainability and Tourism, only 20-35% of all packaging waste is currently recycled. By 2025, this recycling rate is to be improved to 50% across all materials. In order to achieve this, a packaging ordinance[3] has been issued that contains various measures: for example, a reduction in plastic carrier bags and an obligation to collect or take back packaging via a nationwide collection and recycling system. The aim is to improve the avoidance and recycling of packaging waste.

[3] VVO, BGBl. II Nr. 184/2014 i.d.g.F

Similarly, there will also be increased regulation of recycling in the construction industry. Here, the circular economy and material efficiency are to be achieved through the separation and recycling of waste generated during construction and demolition activities[4]. The focus here is particularly on preparing components for reuse and ensuring the high quality of recycled building materials.

[4] Recycling-Baustoffverordnung; BGBl II Nr. 181/2015 i.d.g.F.

What are the actual types of recycling?
In general, plastics recycling is understood to mean the separation and recovery of plastic waste after its product use cycle. According to the type of processing, three variants of plastics recycling can be distinguished:

- mechanical recycling
- feedstock recycling
- thermal disposal with energy recovery

Currently, about 30% of plastic waste worldwide is recycled (mechanical recycling), about 40% is used energetically as substitute fuel, and the remaining about 30% is landfilled. Landfilling is unfortunately still far too often the disposal route for waste in general. A landfill ban (for untreated waste), as has been in place for some time in Austria, Germany or Sweden, for example, has a positive effect on recycling, as also shown by the recycling rates[5].

[5] Plastics – the Facts 2018, Plastics Europe AISBL, www.plasticseurope.org.

In **mechanical recycling**, the material as such is not chemically altered, but after cleaning and sorting steps is melted by means of suitable equipment, additionally cleaned (separation of impurities by filtration and degassing), homogenized and then again formed into a processable granulate. Not all steps are always necessary, these are determined depending on the starting material, its degree of contamination and the application. As an example, regrind from PET bottles can be mentioned here, which - depending on various factors - is offered both as cleaned regrind and as regranulate (= granulate from recyclate). Mechanical recycling is also increasingly being referred to as mechanical recycling. This term comes from English and is intended to show that the material is reprocessed only by mechanical processes such as the extrusion process[6].

[6] In plastics processing machines, the main part of the energy input is not provided by the heating system, but by the shear through the screw and thus by mechanical drive power

[7] The recycling of PET is classified as mechanical recycling, although chain building by polycondensation also takes place in these processes, which would fit in with chemical recycling.

Feedstock recycling (alternatively chemical recycling) is that process in which plastics are broken down again into their building blocks through the application of energy or chemical processes so that they can be used again in the manufacturing process (e.g. polymerization). These processes have been around for a while, but they have not yet caught on[7], as both the energy balance and the costs have argued against them. Rising prices and legal requirements to recycle plastics are making the process more interesting again. Raw material recycling is often seen as the “one single solution”, since mixed plastics can also be processed here. However, this should be questioned, because the chemical processes used to break down the polymers, and also those that then lead to polymerization, can also only run efficiently if defined and relatively clean streams can be used.

Thermal recovery is the recycling of the energy used in the material, which has a relatively positive balance for most plastics. This also has a sustainable aspect because, calculated on the calorific value, a life cycle has been run through with a small additional energy input, and then the energy can be used (compared to the direct use of petroleum as an energy supplier without intermediate use). However, a distinction must be made here between waste treatment in pure waste incineration plants, which only ensures a reduction in the volume of the waste and extracts no or hardly any energy from the waste heat. This is still better than the plastic waste ending up untreated in a landfill or, even worse, in the environment. Where possible, plastic waste should be recycled and only if it is no longer recyclable should it be sent for thermal recycling with energy recovery.

What are the different types of recyclates?

Basically, recyclates[8] can be divided into two categories according to their origin: industrial waste (post-industrial recyclates) and consumer waste (post-consumer recyclates). In addition, there is the in-house circulating material for so-called in-plant recycling, i.e. the direct reuse of sprues on the machine, for example. This variant is not explicitly mentioned here, as such materials are only generated by manufacturers of plastic products and are therefore not available on the market[9]. Nevertheless, we want to mention them here because they show that plastics are already very efficient in this area.

Industrial waste is usually sorted, relatively clean and unused, i.e. it has not yet experienced a product life cycle. Recycling such materials is relatively easy because the material is fairly well known and any influences from previous processing steps, such as degradation of material properties, can be compensated for by adding stabilizers, other additives to alter properties, or even virgin material.

Post-consumer recyclates (utility waste) are those material streams that are generated after a completed product life cycle through private or commercial use. After use, the material is variously soiled, damaged and also not sorted by type. For recycling, it must be appropriately prepared (cleaning, separation) in order to be formed into granules or semi-finished products again in a recycling process. Often, additives such as stabilizers, compatibilizers or impact modifiers are also added to raise the properties, which have been reduced by previous use and by non-separable blends with non-species plastics, back to an applicable level.

In order to be able to achieve the strategic goal set by the EU of increasing recycling rates for plastic packaging, the recycling of post-consumer waste in particular must be pursued, as over 80% of all plastic waste in Austria is attributable to this category. Currently, there is little utilization here. Technologies for this recycling exist, but collection and separation must be adapted, and applications must also be found for the resulting recyclates where they can be used sensibly, so that the demand here also improves the supply.

[8] Recyclates are materials that are processed for reuse. Regranulates refers to the fact that these have been formed back into a granulate, while there are also other variants, e.g. regrinds, which are dried and ground after a cleaning step and thus reused

[9] As soon as these become available on the market, they fall into the category of post-industrial recyclate

2. Which recyclate is suitable for which application?

In the course of the project, various applications were realized using recycled materials. The procedure described here can also be applied to other examples of applications or recyclates. There will not always be a recyclate that meets the requirements for every application, or there are areas where the use of recyclates is not (currently) feasible due to technical and legal challenges.

The fundamental question is always: Can I produce my product from recyclate(s)?

- The fundamental question is always: Can I produce my product from recyclate(s)?
- The first step is to clarify the area of application in which the product is to be used and whether there are any specific requirements. In most cases, recyclates can be used, but in the areas of medical technology, healthcare and packaging with food contact, their use is currently not feasible[10]. In areas such as construction, automotive or electrical & electronics, however, the use of recyclates is conceivable. More recent examples can also be found in the packaging of cleaning agents or in household goods.
- The next step is to determine the properties that a recyclate must have in order to meet the requirements. Some properties are strictly defined by the application, while others are difficult to quantify. The better a definition of requirements is, the easier it is to search for a suitable material - finding it is another matter. The data sheets of the material used can often be used as a basis for defining the requirements. However, this information must be questioned. There is only a limited selection of virgin products and often individual properties are difficult to achieve with a recyclate, but are also not always necessary for the application. Transparent, uncolored recyclates are an example of this, especially if the product is darkly colored. Such knock-out criteria should be questioned and, if possible, rejected.
- If recyclates are found that meet the above requirements, then testing in the application is required. This requires sampling - on the one hand to obtain the parts for subsequent tests, and on the other hand also to determine processability. Questions arise here about process stability, effects such as odors or outgassing, or even deposits on mold surfaces, which can be clarified by trial processing.
- The manufactured parts must be tested for their properties. For this purpose, tests close to the application are required. Examples of such application-related tests are, for example, the stacking compression test for containers that are placed on top of each other in use, or a component tensile test for a spacer loaded in tension. Depending on the application, in some cases not only short-term tests have to be carried out, but also long-term tests, for example to determine the creep behavior or the resistance to environmental influences if an application has to withstand a longer period under load.
- If a material does not meet the requirements, it can often be remedied by modification - more on this in a subsequent chapter.

[10] this is a snapshot - if we succeed in making the cycles truly circular and thus closing them, then in the future there may be recyclates that meet these requirements.

If it is technically possible to use a recyclate, there are a few other questions to be answered:

- Is the availability of the material given? This question in itself must be clarified before the tests, but any modifications must still be taken into account in this step.
- What quality consistency can be expected? It is advisable to check the quality of the material, especially at the beginning, so that any problems can be identified as early as possible.
- Is there the necessary customer acceptance for this product? Surveys could clarify whether the end consumers are actually aware that the purchased product is made of recyclate(s). The recycled content can also be highlighted[11,12], which is an advantage in advertising.

[11] www.blauer-engel.de
[12] www.eucertplast.eu

If all these points are clarified and can be implemented, then nothing stands in the way of an application using recycled material. If material problems should occur, then there are solutions described in the next chapter.

3. Problems and possible solutions

It often turns out that a component sampled from a recyclate does not meet the expectations or does not fulfill the requirements[13]. Does this automatically mean that the recyclate is not suitable? Not necessarily - in such cases it is advisable to involve the expertise of recognized researchers. In Upper Austria, we have an excellent structure, for example with non-university institutes such as the TCKT or with experts from the JKU Linz or the FH Oberösterreich. By way of example, I would like to mention some frequently occurring problems here - also to show that a failed initial test does not have to mean the end of a recyclate application.

[13] By the way, this is not specific to recyclates; it also happens with material developments using virgin materials. The advantage of virgin materials, however, is that they have usually been known for a long time and are better known, and there is a certain degree of standardization, which is not (yet) the case with recycled materials.

- **The mechanical properties of the component/product do not fit!** This is one of the most common problems. Often, a recyclate is too brittle or not impact resistant enough. This can be remedied with impact modifiers. The recyclate used can also be too soft, in which case either the addition of small amounts of inorganic fillers or the addition of virgin material can help. There are a myriad of ways to modify a material.
- **The appearance of the component does not correspond!** Here, a distinction must be made as to how badly the optics are affected. Streaks can be caused by poorly mixed components, for example when virgin material and recycled material are used as a granulate mixture in injection molding (especially if the viscosities differ greatly). Streaks can also be caused by moisture. Other visual defects must be evaluated in detail: Dark spots can come from degraded material, gels from cross-linked parts, foreign substances can be present in small amounts in the material despite melt filtration.
- **The odor does not fit!** There are residual materials in recyclates that - although only present in small quantities - cause unpleasant odors. This can be a processing problem: too high temperatures or incorrect preparation. Adding odor traps or reprocessing with odor removal can help here. Our tip: Do not „perfume" the materials. This usually has the opposite effect.
- **The material cannot be processed!** Here, too, in order to find and eliminate the cause, an analysis of the defects that occur is necessary. Is it the filling of the mold or a thread pull on the hot runner? Or is the material getting stuck at the die wall/nozzle exit in the extrusion? There are many causes - it is best to ask the experts.

As you can see, there are many possible problems, but also many ways to solve them. Don't let small setbacks at the beginning of your project discourage you from using recyclates!

4. What you always wanted to know about recyclates

A recyclate is probably cheaper than virgin material, right?
The quality determines the price. This is also true for virgin material. Good quality costs money. On the one hand, the starting materials are already of very high quality, but on the other hand, the effort required for production is also greater - for example, through better preparation of the recyclate or better melt filtration.

But the recyclate can't be more expensive than virgin material, can it?
Yes, it can - especially in times of strongly fluctuating crude oil prices and high demand, a drop in the price of virgin material can result in similar or even higher prices for recycled material.

Does it still pay off to use recyclates then?
In the short term, this is certainly difficult to argue. In the long term, however, this should not prevent the use of recyclate, because with better products suitable for recycling and better recycling cycles and processes, the supply of high-quality recyclates will increase. In addition, financial incentives, such as the Single Use Plastic Tax, will also be created, making virgin material more expensive and encouraging recyclate use or recyclability per se. Likewise, legal requirements for recycled content and recyclability of products are increasing, making recycling more and more profitable.

Where do I get my recyclate?
There are different suppliers, such as recyclers themselves, who offer defined qualities. Examples are the project members mtm/Borealis (mtm-plastics.eu) or Innplast (innplast.com). The Plastics Cluster has an up-to-date and neutral overview. The best thing to do is to contact the experts there: www.kunststoff-cluster.at.

Why does the recyclate not look like new?
Despite all efforts, a recyclate already has a certain life cycle behind it. This does not leave no trace on the material, and not every material is the same. There are enough recycled materials that it is not obvious that they have already gone through a life cycle, because the cycle has been well closed. However, minor impurities may still occur. It is important to clarify whether the quality of the recyclate meets all the necessary requirements or whether the quality is just not sufficient. In that case, another material must be found as an alternative.

Where can I get transparent/colorless recyclate quality?
Depending on the material - very difficult to impossible. Again, this is something that will improve over time as more packaging is designed to be improved for recycling, so that packaging is no longer heavily printed or fully glued, but with sleeves that can be easily separated in the recycling process. With the shift to such solutions (and also others that ensure that better quality recyclates are created), the available quantity of these „like-new" recyclates will also increase. However, these should then only be used again for applications that are transparent. This is because subsequently dyeing them dark again interrupts the cycle and the material then has to be replaced by virgin material all the more.

Where can I use it?
As described in the previous chapter, it depends on the requirements of the application. However, these must also be checked with regard to their necessity, so that unnecessarily high requirements do not prevent the use of recyclates here. Some examples of such applications are shown in the following chapter.

Who can test the product?

It is best to contact the material developers you trust - they usually have many years of experience in the application, processing and testing of materials or components. You can find experts at the non-university institute TCKT (www.tckt.at), at the Johannes Kepler University (www.jku.at) or at the Upper Austria University of Applied Sciences (www.fh-ooe.at).

5. Case studies

Various case studies are given below, all of which show what is possible with recyclates. Often it is a material development with recyclates - which also shows how the topic of recycling has developed over the last years. In addition, these examples are intended to show the above-mentioned system for evaluating the use of recyclates in application and thus make it easier to understand.

5.1 Used cooking oil collection bucket

The first example is a packaging application: the Öli made of recycled material - an idea of the project partner LAVU (Fig. 3). This container collects cooking oil residues from households so that they do not end up in wastewater. The Öli must meet the following requirements:

It is relatively thin-walled, i.e., the flowability of the material must be sufficiently high so that filling can take place quickly and sufficiently uniformly. In addition, good dimensional stability must be achieved so that the lid also sits firmly and tightly - this property must also be given if the bucket falls to the floor from a low height, otherwise the old cooking oil will leak out. Mechanically, the bucket must be stackable - without buckling, but also without deformation, which would again create a leak. Thermally, the material must be able to withstand filling with oil that is still hot (80°C is defined here), but also emptying and subsequent washing at higher temperatures, and this several times.

Now all these properties are not easy to achieve. For the tests, a post-consumer PP was selected that was colored (in the typical recycled gray) but had a high purity and that was also improved in its flowability. PP was used to achieve good heat deflection temperature (and the original material is also a PP) and so that the stiffness would also provide sufficient stacking pressure resistance.

Figure 3: Used cooking oil collection bucket Öli, made from post-consumer recyclate.

The first sampling was performed with the selected recyclate at 100% and in a 50:50 mix with the virgin material used. A remarkable effect was seen here: Those buckets sampled with the mixture showed streaks and slight beginnings of surface deformation, due to the non-optimal mixing of the two materials. The bucket made of 100% recycled material, on the other hand, showed a good result - both in appearance and in filling (the fine structures for stiffening the edge of the bucket were all filled just as well as the edge itself, which provides the seal).

Various comparative tests were then made with these buckets - stacked compressive strength, drop and fill tests, all comparing with the buckets made from virgin material (Fig. 4). The buckets - although the recycled material had slightly lower properties on the data sheet (Young's modulus and impact strength) - all performed equally well.

Figure 4: Examples of component tests on the bucket made of recyclate (top left: Compression test, top right: stacking compression test, bottom: Drop test on filled bucket).

Even a repeated washing test in the plant did not change the dimensions, tightness and properties of the bucket. So it is possible to produce this bucket from 100% recyclate! Since this recyclate comes directly from the rigid plastic collection of LAVU, this is a „double" cycle - the discarded hard plastics get a new life as an oil, which can then be recycled again after its service life.

5.2 Protective clip

The next application is a protective clip for openings in profiles of lightweight walls, the ÖkoEff (Fig. 5). It is used to cover the sharp edges caused by punching the breakthrough in the sheet metal profiles. This prevents pipes or cables passing through these openings from being damaged by the sharp sheet edges, which can lead to water leaks in pipes or short circuits in cables. This, together with significant improvements in the insertion of the apertures and the defined statics in the profile, is the idea behind this application.

This protective clip must now be easy and inexpensive to manufacture (since many of these clamps are needed in a construction project) and it must have a defined dimensional accuracy, because this clip is clipped into the aperture and must then also hold under load during installation and in the application.

This requires a material with good processability so that the mold can be filled and is also reproducibly dimensionally accurate. In addition, a certain flexibility or resilience to the applied deformation during clipping into the wall profile must be given so that the clip also holds.

For this application, a polyolefin recyclate (PP with a low PE content and good flowability) was selected on the basis of the required properties (especially toughness) and the clip was sampled with this material. In comparative component tests (Fig. 6) with virgin material, the suitability of the material for this application was demonstrated. This shows that the recyclate meets the requirements without any problems, and careful selection also made processing unproblematic.

Figure 5: Examples of the ÖkoEff clamp made from virgin material (left) and recycled material.

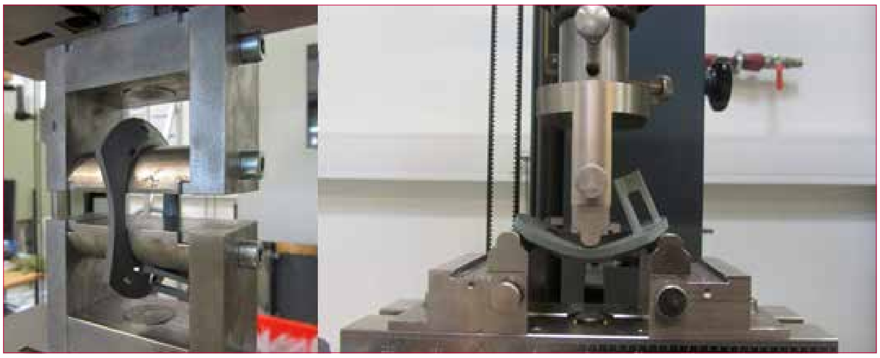


Figure 6: Component testing on the ÖkoEff clamp made of recyclate (left: ring tensile test, right: component bending test).

5.3. Nail cone

The next application also comes from the construction sector. Here, a nail cone (Fig. 7) was selected, which is installed on formwork to fix sleeves so that they remain in the right place during concreting. This part, which at first glance appears to be quite simple, is only designed for a short application, which is why no long-term tests are necessary here. In the application, the approx. 5 cm cone is nailed to the formwork, which means that it must be insensitive to impact. This property must also be given at lower temperatures, since in the construction sector work is also carried out at temperatures below zero degrees.

Figure 7: Nail cone made of original material (HDPE, left) and PE recyclate (right).

A PE-based recyclate was selected for the cone to ensure low-temperature resistance. This was checked by means of an impact test, prior to which the samples were stored in a freezer at -20°C. This temperature is certainly an extreme value, but the tests confirm the suitability of the PE material: it does not splinter in contrast to a mixed PE-PP recyclate (Fig. 8).

Figure 8: Nail cone after impact test at -20°C (left: PE recyclate, right: PE recyclate with higher PP content).

5.4 Thermoformed cups

However, there are not only post-consumer recyclates, but also post-industrial materials that have few applications. In the project, we had a material from film extrusion consisting of LDPE (approx. 70%) and PA6 (approx. 30%), which is produced as edge trim, for example. This material cannot be directly reprocessed - a film can be made from it, but the properties are end-produced because the LDPE and PA6 do not mix and thus no homogeneous film is produced.

To solve this problem, 3% of compatibilizer were added to the recycled material to make the two components compatible. The films, which are about 1 mm thick, were produced at JKU and thermoformed on a cup mold (35 mm deep, 50 mm diameter) at TCKT using vacuum. It was found that although a cup can be produced without compatibilizer[14], the molding is not satisfactory and the wall thickness distribution is also inhomogeneous. In the case of the recycled film with the compatibilizer, the wall thickness distribution is much more uniform and the forming is good (Fig. 9). In our opinion, these results are also transferable to larger thermoformed parts and automatic equipment, and with this small modification, a material can be used which otherwise can only be used for low-value applications.

[14] Ein Test auf einer industriellen Anlage hat gezeigt, dass die Folie aus dem Rezyklat ohne Haftvermittler dort nicht verarbeitbar ist.

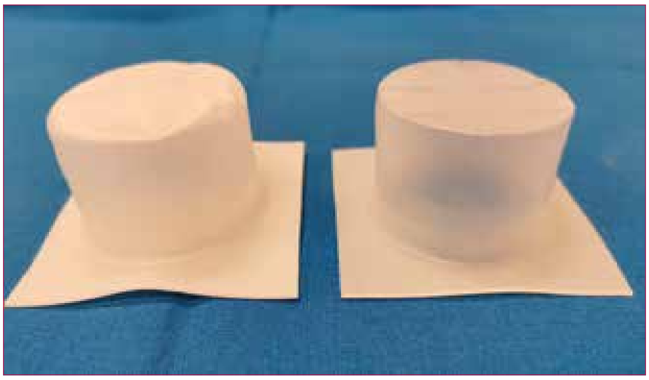


Figure 9: Thermoforming cup (test form, left without and right with adhesion promoter in the formulation)

6. Additional (technical) challenges in plastics recycling.

One reason why recycling solutions for post-consumer waste are often not yet available is that these material streams are very complex, which makes reprocessing into reusable material sometimes impossible - both technically and economically. We believe that many of these problems can be solved by thinking about end-of-life recycling when designing the plastic application. In addition, collection must also capture these streams, and separation and processing technologies must be suitable for converting these materials back to a high quality material.

The most common challenges are listed here to show the issues that need to be addressed in the coming years to further improve plastics recycling.

- **Complex, non-separable material mixtures** – Applications made of plastics often fulfill a combination of properties that are incompatible at first glance. An example of this is film packaging, which in itself is very efficient because very little material is used to protect the packaged goods. However, in order to meet all these requirements, different materials have to be combined in a composite. In reprocessing, however, this causes problems because the materials used to combine these different properties are not compatible. Composite materials are also worth mentioning here, e.g. fiber-reinforced materials, which are also not easy to reprocess. Efforts are already being made to reduce the complexity of materials without negatively affecting the quality of the products[15,16,17]. This „design for recyclability" will certainly become even more important in the future.

- **High moisture content in washed materials** – To separate adhering contaminants from the life cycle of the material, such as residual food or cleaning agent residues, even single-grade plastics must be washed. The residual moisture remaining after this process causes problems here during reprocessing in the extrusion process. Separation of the moisture, for example by centrifugation or drying, is not easy, especially in the case of packaging, due to the thin wall thicknesses and the resulting large surface area (e.g. in the case of films). Here, the preparation and extrusion process must be able to cope with the amounts of moisture. Also, further improvements in the technology used in preparation of the materials will help greatly.

- **Different plastic fractions are difficult to separate** – A wide variety of materials can be found in the collection, in terms of both form (such as films vs. rigid packaging) and materials. These are not or only very difficult to separate with typical processes such as floating-sink separation or even (near-)infrared sorting. In addition, it must also be taken into account that such a separation can never be done one hundred percent due to the technical possibilities (detection speed, particle size) and the economic framework conditions. At the very least, impurities in the lower single-digit percentage range must be expected. Here, the design must already ensure that, for example, colors that make detection more difficult are not used. But sorting systems will also continue to develop, and as a result improvements can be expected in the future.

- **Filtration of contaminants** – During the use phase, plastics also become contaminated, for example with solid (e.g. sand, aluminum) or soft contaminants (e.g. wood, paper). The separation of these materials is sometimes very demanding for the machines because, for example, the screen inserts of the melt filtration wear out very quickly due to the abrasion, or because the contaminants decompose due to the temperatures in the treatment pro-

[15] https://www.fh-campuswien.ac.at/forschung/kompetenzzentren-fuer-forschung-und-entwicklung/kompetenzzentrum-fuer-sustainable-and-future-oriented-packaging-solutions/circular-packaging-design-guideline.html

[16] https://www.youtube.com/watch?v=LKOyujFiXeI

[17] https://ecodesign-packaging.org/downloads/

cess, for example in the case of wood or paper. Some of this can certainly be separated by an upstream washing process, but paper labels that stick too tightly to the plastic are very problematic. Therefore, this must be considered upfront in the design process of a packaging product.

- **Intense odors contained in the material** – Removing odors from recyclates is still an unsolved problem. They usually originate from residues from the use phase: food residues that decompose or fillers such as detergents or soaps that then have an unpleasantly strong odor when the plastic is processed are just as problematic here as paper labels and heavily printed packaging. This is where the first approaches come in after the washing process: On the one hand, through degassing in the extrusion to the recyclate, and on the other hand, through downstream treatment to remove such odors from the material. However, these technologies also need to be further developed, or new approaches for the separation of persistent odors will also be required.

- **Degradation of plastics during and after the recycling process** – Plastics are damaged by thermal stresses during processing and application. Stabilizers are used to counteract this, but they are also consumed, making degradation of the polymer chains unavoidable. While a condensation step can be used with polyesters to increase the chain length, this is not possible with polyolefins, where the chain structure is achieved by polymerizing double bonds. Here, it is necessary to find new ways for polymer buildup.

- **Undesirable additives in plastics** – Additives are used in plastics in many applications, for example to improve resistance to degradation by environmental influences or to achieve flame retardancy. If a material is later recycled, there is often a lack of the necessary information about exactly what and how much additives are contained. Here, additional stabilization is almost always needed. Another problem with recycling is that additives were also used in the past that are now banned because harmful effects have been found. In the case of older materials from applications with a longer service life, it is now also always necessary to check whether such additives are not contained. This can be simple, for example in the case of heavy metals, but also more complex when it comes to other compounds. Here, methods are still lacking that allow rapid detection in the process, so that only those materials are discharged that contain harmful additives, but the other material flows can be kept in the cycle.

7. Conclusion

As shown by the realized application examples, polyolefin recyclates can be used again in high-quality applications. The same basic principles have to be taken into account as otherwise in material development - in addition, there are peculiarities of recyclates such as not exactly defined accompanying substances and additives, which also have to be dealt with.

Nevertheless - it works. Even if it is arguable that the examples presented correspond more to a cascading use and not a true cycle where the material ends up back in the same application, it is still an important step. On the one hand, the aim is to keep the material in the use phase for longer and thus have to use less virgin material. On the other hand, the positive properties of plastics, which include recycling, should be better highlighted.

The goal of true circularity can only be achieved if all partners along the value chain participate. Collection, sorting and processing are just as important as the technological solutions used and the design of the products to ensure that recycling works well. Recycling does not follow an end in itself. On the contrary, the manufactured products must fully serve their original purpose, otherwise the most important criterion in the cycle is missing - the consumer, who uses the product and thus closes the loop.

The path to true circularity with plastics is certainly still a long one, which must be solved at various levels - legal, organizational and technical. In Upper Austria, we have excellent conditions with all the necessary partners on site to realize this goal. Not least through cooperation between companies and organizations, supported by research, we will certainly succeed.

The author

Photo: DP Photography_TCKT

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Since 2006, he has led more than 25 different research projects at TCKT with industry participation, dealing with various topics such as property modification and recycling. His work deals with structure-processing-property relationships of thermoplastic materials in general, with a clear focus on recycling in recent years. He is a lecturer at the University of Applied Sciences Upper Austria as well as author of more than 45 peer-reviewed journal articles and more than 70 conference papers and a member of the „Society of Plastics Engineers".

About TCKT

The Transfercenter für Kunststofftechnik (TCKT) is the point of contact for application-oriented research and development in all areas of plastics technology. A team of experts along the entire technology chain and offers a broad portfolio of expertise for commercial and industrial companies.

offers a broad portfolio of expertise for commercial and industrial companies. This includes material testing in the accredited testing laboratory, trials on equipment, series tests and the preparation of studies. The focus of research projects is on recycling, materials development, bioplastics, lightweight construction and composites.

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