VTT Technical Research Centre of Finland

Recycling food packaging

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DISCUSSION PAPER

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Foreword

Food packaging is essential. By ensuring hygiene and the safety of food, packaging keeps food edible for longer and plays an instrumental role in driving access to affordable food for all, wherever they are in the world. It contributes to the reduction of food loss and waste, and therefore also plays a critical role in limiting the carbon impact of our food system. Huhtamaki is clear that the packaging itself also needs to be low carbon whilst ensuring it remains fit-for-purpose. It is why we take a material-positive approach to food packaging.

Huhtamaki recognises that, while the benefits of food packaging are undeniable, there is more we all need to do to ensure the materials present in post-consumer packaging do not become waste and create negative impacts. Preventing materials becoming waste requires those materials to be prepared for reuse, which calls for more and better recycling. We believe that they should be recognized as valuable secondary materials, which in a resource-strapped world can play an important role in supporting raw material supply.

This comprehensive report from VTT outlines the status of recycling in Europe and the US and the wider societal and technological factors which impact recycling rates. It also provides important insights on the latest technological innovations in food packaging recycling, highlighting those solutions which are expected to become commercially available in the next five years.

Huhtamaki wants to see a real push for systemic change towards low carbon circularity that goes beyond individual companies, bringing value chains together. We see innovation, partnerships and the more effective use of Extended Producer Responsibility as the way forward to building a material-positive system for fit-for-purpose food packaging - where the materials which provide access to safe, affordable foods and help prevent food waste, are then recycled in ways that maximize their value to both the planet and people, delivering a low carbon circular economy.

We trust this report will act as reference point to support that collaboration, which must involve stakeholders from industry, civil society and governments.

Thomasine Kamerling
Executive Vice President, Sustainability and Communications
Huhtamäki Oyj

Executive Summary

Food packaging plays an essential role in our daily lives driving the accessibility and affordability of food. It is key in ensuring the protection, preservation and distribution of food and as a direct result the minimisation of food waste. Historically, in the food sector, plastic has been the material most applied, while paper and metals have also been commonly used. Today, efforts are focused on reducing plastic or substituting it entirely with recycled or biodegradable materials. The emergence of a global middle class and resulting increase in both trade and consumption have led to a significant increase in packaging. Packaging recycling and reuse are thus not only the main focus of Europe's Circular Economy strategy but has also gained significant attention in other regions.

Although considerable development has taken place over the last couple of years, both with regard to package eco-design and recycling technology, recycling rates especially of plastic and polymer-coated packaging remain relatively low. For example, in the United States, recovery rate for packaging and foodservice plastics is at about 14 %. In Europe, the plastic packaging recycling rate reported is somewhat higher at approximately 40 %, compared to approximately 80 % for paperboard on both continents. A well-run recycling system depends not only on the local recycling capacity but also on the collection and sorting infrastructure, which is still less than adequate in many countries across the world.

We anticipate that the coming five years will see the roll out of recycling systems for packaging that today is not being recycled at scale. Substantial amounts of packaging produced today is not easily recycled in existing recycling systems. This is especially true for multi-material packaging, which poses a challenge in mechanical recycling today.

While the recycling of fibre-based material is well established, coated paper packages are not included in many collection schemes and often end up in mixed waste instead of being recycled. Centralised collection schemes offered by, e.g., paper cup and waste management companies to food services and businesses enable their recovery and processing on an improved economy of scale. New solutions have also been rolled out for the separated polymer and or the aluminium coatings.

Major factors affecting recycling rates are linked to the lack of infrastructure for the advanced sorting of recovered used material and the deployment of chemical plastic recycling as a complement to mechanical plastic recycling. Chemical plastic recycling is seen as a solution for multilayer plastic packages, for which there are few mechanical recycling options that have the have the capacity to recycle at commercial scale. As a result, we assume that there will be a significant increase in industrial chemical recycling capacity in the US, Europe and East Asia in the next 3-4 years. An important aspect of chemical recycling is that chemically recycled polymers can be included in food packages when fully depolymerised. Today, recycled polymers which are certified as food contact material (FCM) are, in practice, mainly limited to recycled PET.

Fundamental for the development of recycling solutions are recent alliances between brand owners, recycling and sorting technology developers and waste management companies. Such partnerships are essential for future investment in new recycling technology; on one hand, the partnership provides accessibility to used material and, on the other hand, a potential user for the recyclate.

Abbreviations

EFSA	European Food Safety Administration, evaluates the safety of substances used in food contact materials (FCM). EFSA also evaluates the safety of recycling processes for recycled plastics used in FCM.
EPA	Environmental Protection Agency
FDA	US Food and Drug Administration, evaluates proposed use of recycled plastic on a case-by-case basis and issues informal advice as to whether the recycling process is expected to produce post-consumer recycled material (plastic) of suitable purity for food-contact applications.
FCM	Food Contact Materials (Europe)
FCS	Packaging & Food Contact Substances (US)
ISCC	International Sustainability and Carbon Certification, ISCC, is an independent multistakeholder organisation, providing a globally applicable certification system for the sustainability of raw materials and products. Recycled or bio-attributed products certified by the ISCC Plus standard use a mass balance approach to track the sustainability characteristics of the circular or bio-attributed content. The mass balance approach, which means that a contribution to the use of chemically recycled or renewable materials is made in every material stream.
PE	polyethylene
PP	polypropylene
PS	polystyrene
rPET	recycled PET (polyethylene terephthalate)
rPX	recycled polymer

Contents

Introduction

The packaging industry has undergone significant transformation during the latest decade. Packaging is being engineered towards becoming light-weight with better barrier qualities, designed with an increasing emphasis on end-of-life, which is taken into account already in the design phase. Of the common materials used in food packaging, plastics continue to dominate the market, while paper and metals are still commonly used. Glass is however increasingly more rare as a type of package material. Packaging materials for food often include laminates and coatings, which are developed by systematically integrating materials with different inherent properties to improve the functionality of the final material, enhancing shelf life and lowering the weight of the package, which itself often provides carbon-benefits.

The main function of packaging is to protect the food. Without packaging, the distribution of food, which is essential for mankind becomes logistically, economically and environmentally challenging, which also creates food waste. At the same time, increasing trade and consumption have led to an increasing use of packaging. Governments are seeking to address the potential negative impacts of post-consumer packaging through the use of policy initiatives such as the EU's Circular Economy strategy.

This discussion paper looks first at the status of recycling in Europe and the US and then societal and technological factors impacting recycling rates. It also provides an insight on the latest technological innovations in food packaging recycling, with an emphasis on the solutions expected to become commercially available in the next five years.

Packaging recycling

The European Commission has set the recycling of packaging as one of its top priorities. Indeed, the latest amendment to the Packaging and Packaging Waste Directive (PPWD) contains updated measures to promote the reuse, recycling and other forms of recovering of packaging waste, instead of its final disposal. It sets targets whereby by 2025, 50 % of all plastic packaging and 75 % of paper and cardboard should be recycled[1]. In addition, the first requirements of the SUP (single-use plastics) directive (2019/904/EC) entered into force in the middle of 2021. The European Commission adopted guidelines on single-use plastics products at the end of May 2021, while a ban on certain single-use plastic products and marking requirements entered into force in July 2021.

Eurostat, the EU's statistical bureau, estimates that 41 % of plastics packaging waste was recycled in the EU in 2019. Each person in the EU generated an average of 35 kg per annum of plastic packaging waste (Eurostat 2021). In the US, the average American tops the global list by generating roughly 130 kilograms of plastic waste per year. The US Environment Protection Agency reports recycling rates of 14 % for plastic containers and packaging and 81 % for paper and cardboard packaging[2]. Corrugated board is by far the largest component of paper packaging recycling, and other uncoated paper-based packaging, such as cartons and sacks,

[1] https://ec.europa.eu/environment/topics/waste-and-recycling/packaging-waste_en
[2] https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/containers-and-packaging-product-specific-data

is mostly recycled as mixed paper. Also, the recycling figures exclude single-service plates and cups, and trash bags, both of which are classified as nondurable goods (Fig 1).

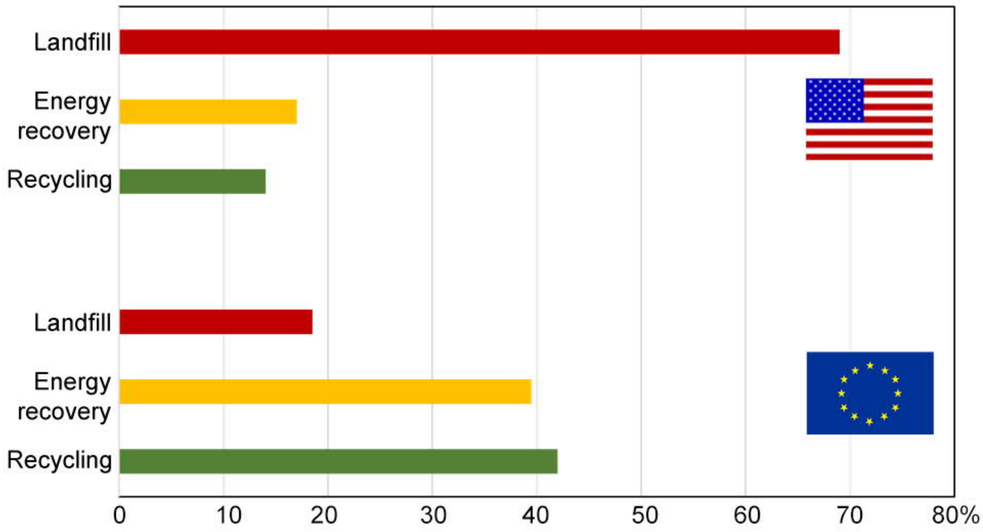

Figure 1. Destination for used packages in the US and EU, 2018.

The recycling rate for carton-based beverage containers is somewhat lower than for cardboard as a whole. According to ACE (Alliance for Beverage Cartons and the Environment), 51 % of all beverage cartons placed on the EU market in 2019 were recycled, i.e., separately collected (Eunomia 2020, ACE 2021). However, when looking at the flow actually entering the technical recycling process, the recovery rate is likely to be lower. This is due to the fact that the separately collected materials also contain wrongly sorted or excessively dirty packages not suitable for the recycling process. In Eunomia's report (2020), the actual recycling rate was estimated to total some 40-60 % of the actual collected flow. Separate collection does not automatically mean that the collected materials are directed to material recycling. In Germany, for instance, only 47 % of plastic packaging goes to material recycling while almost 53 % is incinerated (Conversio 2020).

The following flow diagrams (Figures 2 and 3) picture the end-of -life processes for used paper-based and plastic used packages.

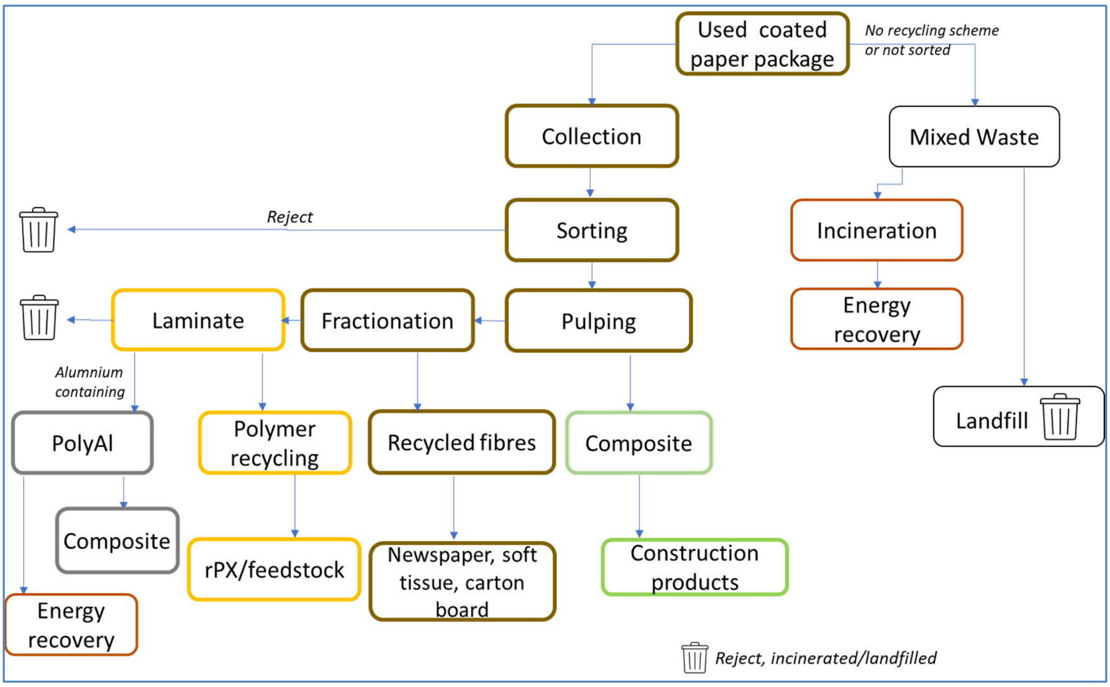

Figure 2. Current processes for used coated paper packages.

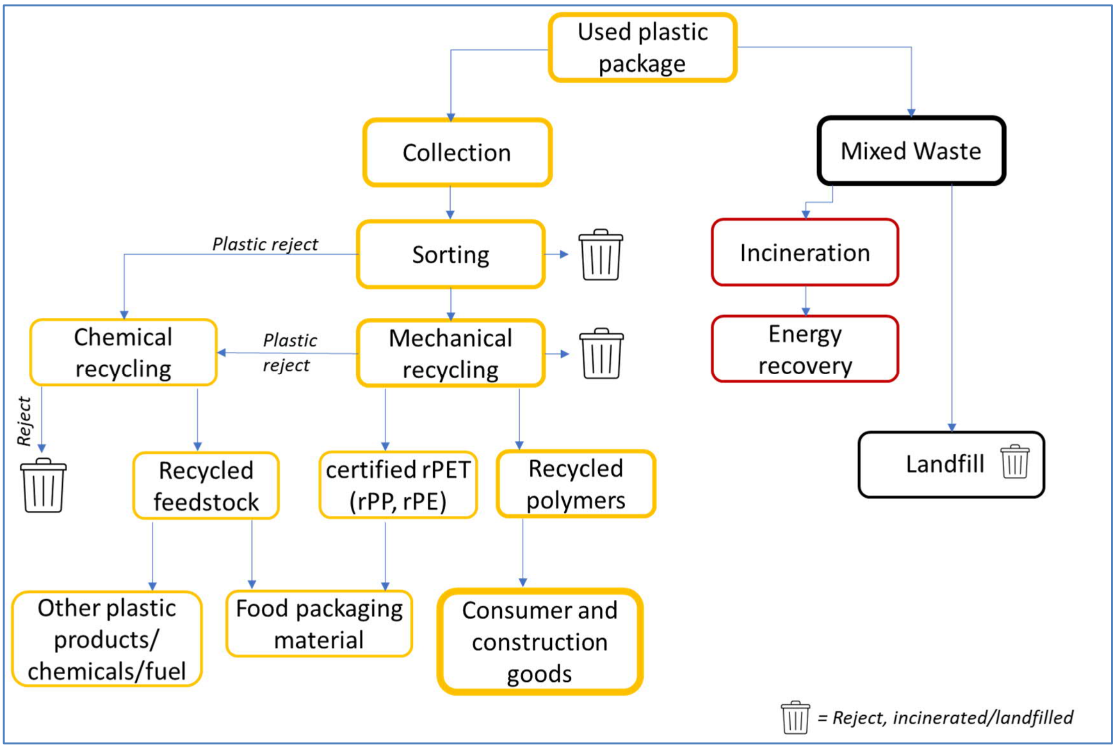

Figure 3. Current main processes for used plastic packages. A thicker line indicates major products/processes.

Factors affecting the recycling value chain of food packaging

Both the regulatory and business side show signs of an increased focus and commitment to overcome the challenges in scaling up the recycling of packaging. The EU has set a target of 65 % target for all packaging waste to be recycled by 31 December 2025 (European Commission 2018). Major multinationals have signed commitments on recyclable packaging and industry collaboration platforms on collection and recycling have been established to assure, on one hand, accessibility to used material and, on the other hand, a potential user for the products or recycled material flows.

One of the major barriers to the expansion of recycling is not only the recycling capacity per se but the collection and sorting infrastructure, which is still less than adequate in many countries. Moreover, even with adequate collection infrastructure, collection covers 80 % of packaging waste, with the rest ending up in mixed waste fractions, where it ends up in landfills or in energy recovery (calculated from (Brouwer et al. 2011, HSY 2019)).

Improving recycling rates therefore requires more than just the technical development of waste management systems. Indeed, a great deal of emphasis has been placed on strategies to promote the role of citizens in driving recycling. Despite the fact that ultimately it municipalities, that are responsible for providing residents with relevant information, to enable residents to separate and sort different waste fractions in their homes, i.e., sorting at the source. Therefore, such a system must avoid confusion and inconvenience for the residents. Research conducted, e.g., in Sweden and France showed that perceived inconvenience by residents hinders proper sorting (CITEO 2021, Rousta and Ekström 2013), and that used paper and plastic packaging has higher rates of mis-sorting, affected by, e.g., a distance between the local collection system and the residential area. A large part of packaging is used for food products, *and food packaging is the most substantial part of mis-sorted fractions in household waste* (Nemat et al. 2020).

In areas with well-organised waste management infrastructure, separate collection and sorting packaging waste has become a routine for most households. Even in these regions, a major part of post-consumer packaging still ends up in mixed waste (HSY 2019). A significant share of collected waste package fractions also get wrongly sorted, illustrated in Figure 4, which depicts the package waste recycling flow in the Netherlands. Of 173 000 tonnes collected, 9 % (15 000 tonnes) was wrongly sorted and 32 % too heavily contaminated for recycling. Altogether 40 % of the collected packaging waste was removed from the recycling stream, disposed of and incinerated (Brouwer et al. 2019).

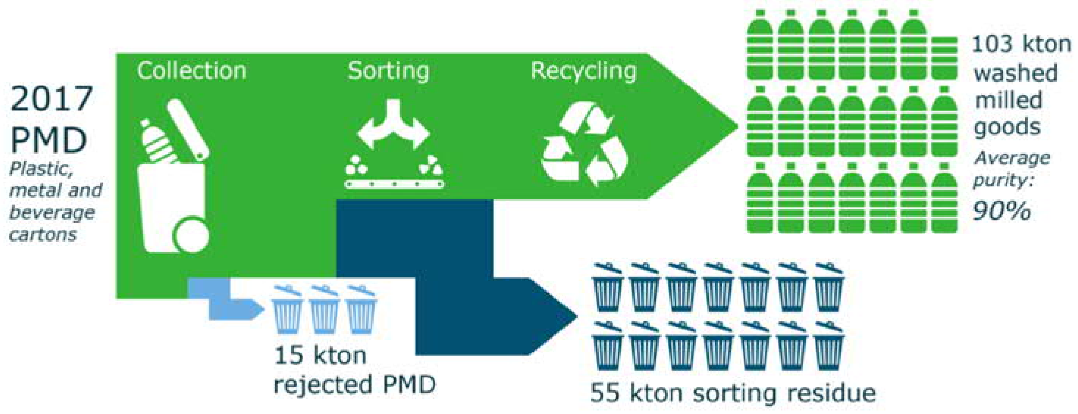

Figure 4. Collection and recycling of post-consumer plastic waste. PMD = plastic, metal and beverage cartons. Adapted from Brouwer et al. (2019*).*

Several packaging companies have announced new and novel approaches to sustainable packaging. These include designing for optimised resource use, such as 1) decreasing the proportion of fossil polymers in the package and 2) designing lighter packages, increasing recyclability and/or reusability. For recyclability, a special challenge is created by multi-layer and multi-material packaging that, on one hand – protects and extends the shelf life of food products (which is the main function of the package in the first place) - but on the other hand, does not readily fit into current recycling systems.

Box 1. Design for circularity
An example of optimised resource use, which also includes higher recyclability, is substitution of the aluminium layer in beverage cartons with renewable material, such as MFC (microfibrillated cellulose) or nanocellulose. MFC is used as bio-barrier layers for grease and oxygen, as well as biodegradable films that can replace aluminium and plastics in paperboard packaging (Stora Enso 2019). By substituting these materials, the package's carbon footprint is significantly reduced.
Aluminium reduction is also addressed by, e.g., Huhtamaki lidding laminates (www.worldstaraward.com) and Aronax Technologies, who is replacing aluminium with a thin layer of magnetic particles for easier separation (EMF 2018).

Market uptake of recycled food packaging material

According to CEFIC, the European Chemical Industry Council, today, only 15 % of the collected plastic waste in the EU currently finds its way back into the EU market.

Most plastic food packaging that is not made of PET cannot be recycled into new food packaging due to missing processes and safety concerns. Therefore, it is typically used in other applications than food packaging, for example, in construction and agriculture.

Currently, only 10 % of recycled polymers are food-grade, with the majority being polyethylene terephthalate (PET) (Leardini et al 2021). Plastic recycling is mainly done by means of mechanical recycling, where washed and sorted plastic waste is re-melted and processed into new food packaging. However, the recycling process may involve risk factors regarding the safe use of the recycled plastics as food packaging due to an increase in possible contamination sources which might migrate into the food. To prevent placing such materials on the market, both the EU and US have several pieces of legislation in place on the use of Food Contact Materials (FCMs), including plastics and recycled plastics (De Tandt et al. 2021). Materials and articles made either entirely or partially from recycled plastics and used in contact with food should only be obtained from processes which have been assessed for safety by EFSA and authorised by the European Commission. rPET resin has also been approved for food contact by the FDA in the US. China does not allow recycled plastic to be used in food packaging at all.

In addition to rPET, which is currently the major recycled polymer on the market, certified for food contact use, smaller volumes of chemically recycled rPP (Packaging Europe 2021, SABIC 2020) are also entering the European market (see Box 2). In the US, the FDA has also sanctioned recycled HDPE for food contact on a case-by-case basis for over 20 years (Custom-Pack 2018). Likewise, in Britain, recycled HDPE from milk bottles can be used in the production of new milk bottles (Ellis 2019).

Box 2. Recycled polypropylene for food packaging

The Swiss dairy company *Emmi* is partnering with *Borealis* and *Greiner* Packaging to produce Emmi CAFFÈ LATTE drinking cups made from chemically recycled polypropylene. The technology that recovers the polypropylene is currently still in its infancy. Thus, only limited quantities of chemically recycled polypropylene are currently available. Emmi has secured a share of the plastic through early commitment with the development companies. In the future, *depending on the availability of suitable material,* the amount of recycled plastic in Emmi's caffe latte packaging is set to be further increased.

The chemically recycled material used for the Emmi caffe latte cup consists entirely of ISCC (International Sustainability & Carbon Certification) material, on a mass balance basis. As the recycled PP is produced by chemically recycled polymers, it can be used as food contact material.

A similarly structured partnership was established between *SABIC*, providing chemically recycled polypropylene for *MARS* pet food packaging. The PP film structures are manufactured by *Huhtamaki.*

Until now, multilayer food packaging consisting of different plastic polymers or combinations of different materials has almost not been recycled, because the layers are difficult to separate. As for beverage cartons, mainly the paperboard fraction is separated in established recycling processes, but the recovered material is, due to regulations, not used in contact with food again (Geuke 2021). However, recycled paperboard can be used in food packages when coated with a proven barrier material (Virtanen 2022).

However, new processes for the plastic and possibly aluminium laminate in cardboard and paper food packages are developing, as well as chemical recycling processes for mixed plastic fractions. Chemically recycled polymers can be allowed as food contact material when fully depolymerised (European Commission 2021).

Sorting and recovery of used packages

Post-consumer packaging is usually an inhomogeneous and contaminated waste fraction. It comprises a huge range of material types (e.g., multilayer packages, blends and composites) with shape, colour and size varying widely. To achieve a consistent quality output, recycling facilities set quality criteria for its feedstock and the facilities are normally equipped with a sorting line that sorts out contaminating materials from the waste flow. With the push towards digitalisation and the automation of processes, these sorting technologies have advanced significantly in the last decade. Both identification capabilities and the speed of the sorting line have improved. The progress is supported both by packaging design (e.g., optical tracers, avoidance of multi-material sleeves and dark colours) and new sensor systems which, through the combination of technologies, are better at distinguishing different polymers. Sorting is currently often done by applying near infrared (NIR) technologies, while new development involves, e.g., the deployment of hyperspectral cameras, which are suitable to sort plastics, regardless of their colouration. Depending on the application requirements, different cameras can be used. On the package design, side digital watermarks are evolving. A well-quoted development is the HolyGrail 2.0 project, which is now rolled out into the demonstration phase in a material recycling facility in Copenhagen, Denmark. The watermark covers the surface of a consumer goods packaging carrying a wide range of attributes, such as packaging type, material and usage (Figure 5). Used packaging is collected and scanned on the sorting line with a high-resolution camera, which detects and decodes the digital watermark (Staub 2021).

Figure 5. Digital Watermark by Digimarc (www.digimarc.com)

Recycling of paper and cardboard packages, trends and outlook

Paper- or cardboard-based food packaging is normally a composite material consisting of 1-2 fibre layers (ca 80-95 %), a polyethene layer and for so-called aseptic beverage container, aluminium (5-15 %). The recycling of paper- or cardboard-based food packaging (liquid board packaging) is an established process, traditionally focussing on recovering the fibre fraction. In the recycling process, plastic is separated from fibre by washing, and the fibre is used to make new products such as cardboard boxes, core stock, napkins or notepads. Paper wastes are typically recycled multiple times, but through the recycling process, the fibres are shortened by mechanical erosion. Each time cardboard is recycled, its fibres become shorter, making it thinner and less durable. Paper products, including cardboard, are in practice recycled up to 5 to 7 times. At the end of its lifecycle, it can be made into a paper paste and used for, e.g. egg cartons or disposed of in different ways.

Various other valorisation options have also been suggested for the recycled paper sludge consisting of short fibres. These are for instance its use as building material supplemental or feedstock for nanocellulose, as substrate for biotechnology production (lactic acid, lipids, cellulase), or biogas production (Peretz et al. 2020). These solutions have not scaled up to the market though.

Collected used carton board and paper packages are processed in established recycling systems. The process most often involves mixing the used paper with water and chemicals to break it down. It is then chopped up and heated, strained through screens, which remove plastic (originating from plastic-coated paper) that may still be in the mixture, de-inked, possibly bleached, and mixed with water. This pulp is then used in the manufacturing of new recycled paper. More advanced processing includes automatic sorting with optical sensors and screens separating brown fractions from other papers and plastics contamination (https://fibrepure.bulkhandlingsystems.com/).

However, food packaging is more often coated with one or several layers of plastic and/or aluminium (aseptic beverage packages), which make recycling more challenging compared to pure carton or paper packages. Recycling of these structures is done in dedicated recycling facilities, specialised in coated materials.

Paper and cardboard recycling processes focus on improved energy and material efficiency, smart sorting and developing industrial utilisation of the polymer- aluminium laminate in the recycling of aseptic beverage packages.

Towards closing the water loops

As such, the production of recycled fibre-based paper consumes significantly less water than paper from virgin raw materials (Jung and Kappen 2014). Several paper mills producing packaging grades from paper for recycling run their processes in a water reuse circuit. However, a further reduction in effluent volume is often prevented by enrichment of detrimental substances and its consequences. In recycled paper mills, common detrimental substances found in the water circuits are starch, volatile fatty acids (VFA) from bacteria on recovered paper contaminated during its usage, storage and recovery, salts, etc. These cause problems throughout the papermaking process, such as strength properties and foul odour (Stetter, 2012). Membrane treatment is evolving into a key technology for closing water loops (Jung and Kappen 2014).

Most mills are unable to produce in a fully closed water circuit. Normally, the arising wastewater is treated fully biologically in on-site or municipal wastewater treatment plants. Further reduction of the water footprint can take place, e.g., in collaboration with a municipal wastewater treatment plant, as in Madrid, where the freshwater intake is produced from municipal wastewater (see Box 3).

Box 3. Urban-industrial symbiosis

International Paper's Madrid mill producing recycled carton board uses 100 % recycled water in its papermaking process, which is recovered using a closed-loop system in cooperation with the municipality. This makes us the first mill in Europe to produce 100 % recycled paper with 100 % recycled water. This translates to a very low level of water consumption per tonne of paper produced, and the water is reused internally up to 13 times.

The joint effluent treatment plant also generates 7 Mm^3/a biogas covering 25 % of the electricity needs in the steam boiler.

Although research in the laboratory indicates the feasibility of biogas production from recycled paper wastewater and (e.g., Bakraoui et al. 2020, Bonilla et al. 2018) the use of anaerobic digestion for P&P mill biosludge only has not been industrially established. The reasons are low methane yields, reportedly due to the complexity and recalcitrance of pulp and paper mill biosludge and the potential presence of toxic chemicals (Bonilla et al. 2018, Gonzalez-Estrella et al. 2017).

Recycling of aseptic beverage containers

According to Eunomia's study (2020), there were just over 20 specialised recycling mills in Europe that can process beverage cartons. Most plants use a single separation method, with the remaining polymer/aluminium fractions being incinerated for energy or co-incinerated by the cement industry.

In this process, the used cartons are washed intensively with water at an ambient temperature, so that the paperboard fibres separate from the aluminium and polyethylene layers and dissolve into the water. The aluminium and polymer fraction are then separated for possible further recycling, and the pulp continues to the production of recycled paper/carton board.

While hydrapulping to recover the paper fibres that constitute > 75 % of the carton is the most widespread process, processes also exist aiming at manufacturing construction materials, such as boards and tiles, utilising the complete carton. Lately, process development has been concentrating on processes separating the PolyAl (polyethylene and aluminium) residual that remains after the paper fibres have been recovered. The simplest process involves agglutination followed by extrusion to obtain pellets that can then be used in industrial and consumer products or combined with other materials, such as lignocellulosic wastes. Chemical approaches involve the solubilisation of polyethylene and the removal of aluminium.

Although it can be considered as a direction generating products with reduced functional value, Robertson (2021) suggests that the focus in future years is likely to be on recycling cartons into construction materials, where there is a theoretical yield of 100 %, compared with 75% for hydrapulping.

Recovery of PolyAl

The polymer-aluminium (PolyAl) composite layer recycling has been mainly focused on energy recovery, taking into account the relatively high heating value of the aluminium–polyethylene composite (ca. 40 MJ/kg) (Platnieks et al. 2020). With the ambition to move up in the waste hierarchy, processes for material recycling are developing. The first designs involved rigid board manufacturing using a hot press. Another promising application for the used aseptic beverage containers is the production of thermoplastic composites (Martínez-Barrera et al. 2017).

EXTR:ACT, the alliance of Europe's main liquid packaging board producers and beverage carton converters, is targeting the improved recycling of the PolyAl rejects from recycling of aseptic beverage packages. They estimate that as of today, these European projects allow roughly 30 % (ca 50,000 tonnes) of non-fibre components of beverage cartons to be recycled annually (https://www.extr-act.eu/).

*Ecoplasteam'*s recycling plant in Italy (capacity 7 000 tonnes PolyAl per year) produces product aluminium/polymer product (trade name EcoAllene®) that can be injected, extruded, blended and compounded like a normal polymer, and further recycled into products. The process involves a pulping process followed by settling and centrifuging to obtain a solid PolyAl fraction, which is extruded and subdivided into granules. The final material is a mix of 85 % LDPE and ca 15 % aluminium. The material can be used for household and garden tools, non-food packaging, etc.

ReconPolymers in the Netherlands also manufactures a blend of LDPE and AL. Still at the pilot site stage, the company has developed various applications based on PolyAl, such as bird feeders made from PolyAl, marketed by a Dutch producer. Recon Polymers now operates a production plant since September 2020. Its annual capacity is approximately 6 000 tonnes of PolyAl, which is expected to be reached in 2021.

Plastigram's patented process relies on separating the aluminium fraction from the polymer by washing with formic acid and water in certain concentrations and temperatures (Pelikan 2020). Plastigram started the construction of its PolyAl recycling line in the Czech Republic in 2019. They are also scaling up in partnership with Tetra Pak and Stora Enso in Poland, which will triple the annual recycling capacity of used beverage cartons in Poland from 25 000 to 75 000 tonnes. This will allow for the recycling of the entire volume of beverage cartons sold in Poland and its neighbouring countries, including Hungary, Slovakia and the Czech Republic. Recycled fibres will be integrated into Stora Enso's recycled board. The separated polymers and aluminium will return to the market as plastic pellets and aluminium foil. Both lines will be operational at the beginning of 2023 (Stora Enso 2021).

Palurec in Germany, which is operated by the beverage carton manufacturers, separates polyethylene and aluminium in a water-based washing process, and polypropylene and HDPE are separated from soft LDPE by air fractionation. The plant produces HDPE, LDPE and aluminium fractions for the industry. Plant operations started in early 2021 (EXTR:ACT 2021).

Paper cups recycling

A paper cup is typically made from 90 % paper with a 10 % polyethylene plastic coating. The fibres used in paper cups are generally quite long and the good quality fibre in paper cups can be recycled up to 7 times. While the cup is technically fully recyclable, a large share still ends up in the mixed waste in Europe. In the US again, because of the plastic coating, many waste collectors and local authorities do not accept paper cups in mixed recycling streams. However, the number of cities now including the recovery of paper cups in their residential recycling programmes is constantly increasing, while several mill companies in the US have made a commitment to increasing the recycling of paper cups (FPI 2021).

At the same time, a growing number of coffee outlets, cafés or retailers, as well as other businesses, have contracts directly with recyclers. The cups are collected and baled close to the source, so they can be delivered directly to recycling and waste management partners efficiently on a large scale. Such collaborations are likely to become more common with the increasing use of disposable cups. The global paper cups market reached a volume of 244.7 billion units in 2020 (IMARC Group 2021). The demand for paper cups has been influenced by the rising trend of takeaway services and ready-to-eat food across the globe and a growing number of time-scarce consumers.

Specialised recycling plants can handle the coated paper by recovering the plastic film after pulping by flotation. The recycling step is similar to that of aseptic beverage packages. The PE coating is recovered from the pulp, granulated and put back on the market as recycled PE. Yield from the cup is in the 70 to 90 % range, depending on whether the cup has a single or double-sided coating and the pulping system in use.

At the same time, packaging innovations, e.g., water-based polymer solutions, for coating are entering the market, and a number of food package manufacturers are putting on the market biodegradable paper cups, which can be handled in standard paper board recycling facilities or composted. Both trends, advanced recovery of paper cups for recycling and market uptake of biodegradable cups, are likely to strengthen in the near future.

Plastic packaging recycling

Europe produces nearly 30 million tonnes of plastic waste annually, and the amount is increasing. Food packaging accounts for almost 60 % of the plastic waste produced (Åkerman & Sundqvist-Andberg 2021). When separately collected, the post-consumer packaging is recycled by physical thermal treatment to produce plastic granules (mechanical recycling) or by breaking the polymer structure down into chemicals or mono/oligomers (chemical recycling), while mechanical recycling processes are globally well established, and chemical recycling is only now rolling out into full commercial scale.

Mechanical Recycling

Mechanical recycling of plastics refers to the processing of used plastic products into secondary raw material without significantly changing the chemical structure of the material (grinding, washing, separating, melting, compounding and re-granulating). It is currently the dominating method of recycling post-consumer plastic waste in Europe. It is a well-established technology for the material recovery of plastic materials, such as polypropylene (PP), polyethylene (PE) or polyethylene terephthalate (PET).

To avoid significant loss of quality of the output, mechanical recycling requires careful sorting into single polymer fractions. Multilayer and composite packaging are, in this respect, complicated fractions and normally discharged from the recycling process.

Box 3. Mechanical recycling of multilayer materials
One of the few mechanical processes for multilayer plastics that developed into commercial scale is *APK's Newcycling*®, a solvent-based recycling process. It allows for selective dissolution of desired polymers in laminated waste material, and thus extracts the targeted polymer from a mix of multilayers or other mixed plastics, obtaining LDPE that can be returned into packaging. At the same time, deodorisation and removal of impurities takes place.
With one commercial facility operating in Germany, APK specialises in the production of plastic granulates. The plant in Germany, features an annual capacity of 8 000 tonnes/a. APK also plans to expand in 2022-2023 with a facility having a capacity of around 20,000 tonnes/a.
Another newcomer is the Spanish *Repetco,* who has developed a process for PE-PET laminates, separating the layers with pressurised vapor. The company is constructing a plant in Albacete, Spain, which will start operating by the end of 2022, aiming at a 45 000 tonnes/yearly production of rPET.

Chemical (advanced) recycling

Chemical recycling (also referred to as advanced recycling in the US) aims to convert plastic waste into chemicals. It is a chemical or thermochemical process (e.g., pyrolysis), where the chemical structure of the polymer is changed and converted into chemical building blocks, including monomers, oligomers and higher hydrocarbons that are then used as raw materials for the manufacturing of new products, which excludes production of fuels or means of energy generation. Chemical processes are less mature than mechanical but starting now to enter the market with announcements on industrial partnerships and investments. According to a report from 2019, more than 40 advanced plastics recycling technology providers were operating on a commercial scale (Closed Loop 2019).

The term "chemical recycling" includes various technologies that break down used plastic with some combination of heat, pressure, depleted oxygen, catalysts and/or solvents into either fuel or building blocks for new plastic. For instance, pyrolysis and gasification use heat to break down plastic, with limited oxygen to prevent combustion. Other techniques are solvent-based, like solvolysis.

In Europe, some chemical recycling plants are already up and running as either pilot or small commercial plants, producing some REACH-registered material entering the market. The development around chemical recycling for plastic mixed waste is intensive, and significant progress will be achieved over the next 5 years. The major part is based on pyrolysis technology. Pyrolysis is the degradation of material under thermal conditions in the absence of oxygen into vapours. This technology allows both biogenic and plastic waste to be decomposed into valuable chemicals that can be used to make new products.

Chemical Recycling plants

One of the primary chemical plastic recycling technology providers is *Plastic Energy,* which operates two demonstration plants in Spain à 5000 tn/a each. Their pyrolysis produces yields 80-85 % TACoil, 15 % syngas and minor shares of char, which all have industrial users. Plastic Energy has partnered with several (petro) chemical companies, either building joint ventures or as contracted users, such as

SABIC, Exxon and Total. At least six plants are under construction or in the planning phase with the capacities of 15 000-33 000 tonnes plastic waste/a in France, Spain, the Netherlands and the US (TX). Foreseen implementation is 2022-2024. TACOil is REACH certified and it also complies with the EU food contact material legislation. It is used e.g., for Unilever's brands Magnum and Knorr (Figure 6).

Figure 6. Food-grade material using recycled TACoil (Monreal 2020).

Brightmark is finalising a 100 000 tn/a pyrolysis plant in Indiana and developing another in South Korea. Recyclate procurers are BP and SK Global Chemical respectively. Shell again is the user of BlueAlp's and Pryme's recyclates from their plants in the Netherlands, with the capacity 30 000 and 60 000 tonnes/a by 2023 and 2022 (Mapleston 2021a).

Water-based technologies

In addition to pyrolysis, water-based technologies are evolving. The motivation is to achieve a lower footprint of the recycling process by avoiding the input of solvents and possibly applying a lower temperature. The UK-based company *Mura,* together with Dow Chemicals, will finalise its first of four HydroPRS Cat-HTR™ technology lines in Germany à 20 000 tonnes/a in 2022. Together with *Mitsubishi*, a similar-sized plant is foreseen in 2023. The technology, which employs supercritical water, heat and pressure to convert waste plastics into valuable chemicals and oils, by breaking down the long-chain hydrocarbons and donating hydrogen to produce shorter-chain, stable hydrocarbon products, can be used in the chemical industry.

Aduro Clean Technologies is a Canadian developer of patented water-based technologies to chemically recycle plastics and transform heavy crude and renewable oils into higher-value fuels and other recyclate chemicals. In partnership with *Brightlands, Aduro* will complete a demonstration plant in Limburg, NL that applies Aduro Hydrochemolytic™ technology (HTC) to demonstrate, on a tonne-per-day scale, the conversion of polyethylene (PE) waste to feedstock for chemical processes. Some benefits of the HCT compared to more traditional refining technologies, such as pyrolysis and gasification, is said to be higher selectivity due to operation at lower temperatures (240-390 °C) and no reliance on hydrogen production (Canadian Plastics 2021).

Catalytic pyrolysis

Anellotech's (US) Plas-TCat technology uses a one-step thermal-catalytic process to convert single-use plastics directly into basic chemicals, such as benzene, toluene, xylenes (BTX), ethylene and propylene for consequent use in plastic production. Together with R Plus Japan Ltd., and a group of plastic waste organizations in Japan, commercialisation of this plastic recycling technology is foreseen by 2027. Owing to the use of a catalyst, upgrading the pyrolysis products in a steam cracker to yield the desired components is unnecessary, as is the case with non-catalytic pyrolysis of (mixed) plastic waste. The latter often yields a significant proportion of waxes over oil, which restricts its direct use in the subsequent (petro)chemical industry and contributes to the overall process' environmental footprint.

PET recycling

Today, the majority of current recycled food grade polymers are polyethylene terephthalate (PET).

PET can be commercially recycled by thorough washing and re-melting, or by chemically breaking it down to its component materials to make new PET resin.

After the sorting process, the PET material is ground into flakes. Flake purity is central to preserving the value of the reclaimed plastic. Further separation techniques involve washing and air classification, as well as density-based separation in water, where material either sinks or floats, which helps separate residual foreign materials.

After the completion of grinding, washing and separation, the material is rinsed to eliminate any remaining contaminants or cleaning agents. The recycled PET (rPET) is then dried before reintroduction as a manufacturing material or before further processing, usually melting and extrusion.

Melt filtering can further purify material through the removal of any non-melting contaminants that may have survived earlier steps. Extruded material passes through a series of screens to form pellets, while non-melted particulate is blocked. Pelletised plastic provides a uniform-sized material that can be reintroduced into the manufacturing process (LeBlanc 2020).

While food-grade processing has been established, efforts are being made to improve the efficiency of processing technologies, and depolymerisation technologies are being developed as an alternative to mechanical recycling.

The Swiss company *Gr3n* is deploying microwave technology to depolymerise PET. The target is a demonstration plant with the capacity of 30 000 tonnes/a before the end of 2024 (Mapleston 2021b).

Ioniqa has a 10 000t tonnes/a plant producing monomer from PET bottles in the Netherlands. In the process, PET is a depolymerised process using a solvent (Glycolysis) and a reusable ionic ferromagnetic catalyst (Vilaplana et al. 2014).

Also, the Canadian *Loop Industries* bases its process on the use of a solvent and a catalyst for depolymerisation (Essaddam 2017). The company is scaling up in partnership with SK Global Chemicals, building a plant in Ulsan to be operational by 2022; 70 000 tonnes/a. Loop is also partnering with Suez, with the objective to build a manufacturing facility in Europe, projected to be commissioned in 2023 (Mapleston 2021b).

Carbios in France is scaling up a unique enzymatic process for depolymerisation PET. Currently, it is at the demonstration stage (2 tonnes per cycle) aiming at a 40 000 tonnes/a reference plant in 2025.

Industrial applications of PET are numerous, and many packaging and textile brands have made a commitment to increase the proportion of recycled material in their products. Among others, Coca-Cola intends to use 50 % recycled PET in its containers by 2030. Companies are increasingly recognising the urgency of recycling PET into food-grade products. The availability of post-consumer PET material is becoming a challenge, and the low-quality feed stock for the recycling plants is becoming more common. At the same time, recovery rates in the United States, for instance, have remained flat or declining in recent years.

Discussion

Signs can be seen of an increased focus and commitment to overcome challenges to scaling-up the recycling of packaging on several fronts. New directives and regulations and commitments on recyclable packaging from multinationals on the increased use of recyclates and sustainable design are supporting this trend. Industry collaboration platforms on collection and recycling on one hand, and potential users of the recyclate on the other hand, have been established.

However, one major barrier to the expansion of packaging recycling is not only the recycling capacity but the collection and sorting infrastructure, which is still not adequate in many countries.

Also, when the infrastructure for collecting post-consumer waste is in place, the system is efficient only when consumers are actively involved in it, and if there is a basic understanding of environmental awareness and information.

A prerequisite for recycling is separate collection of the generated waste fractions; here, the system relies to a great extent on consumers' and businesses' interest in sorting their waste. While the willingness is there, the proportion of consumers actually sorting recyclable fraction is less and recycled fractions commonly contain a significant amount of contaminating material (CITEO 2021, HSY 2019).

With regards to the actual recycling process, pre-sorting is essential. Most recycling processes will generate a certain proportion of rejects, that is collected fractions which are not suitable for very contaminated or, e.g., halogen containing fractions which carry over to the recyclate and lower its value for further use. In the mechanical recycling processing of post-consumer waste, this proportion can be as much as 30 % of the overall feedstock. The reject can be further processed with chemical recycling, which is designed for more heterogenous feedstocks. However, chemical recycling is not a silver bullet, but pre-screening of the input is still needed in order to be able to produce an output that meets the quality criteria for industrial (re)use. The process itself, and required downstream processes (distillation, halogen removal, etc.) generate a certain level of rejects. Thus, today with the existing technology, packaging recycling cannot even theoretically meet a full recycling rate. When looking at the balance between packaging volumes put on the market and uptake into recycled products, it become evident that the average recycling rate is considerably lower than what is officially reported today. In the EU, current national-level reporting, which looks at packaging volumes generated vs. waste collected, will move to neglect the collected proportion that is not eligible for processing. Increasing the actual recycling rate is a challenge for the whole EU.

At the same time, the design for recycling has moved high up on the agenda of packaging manufacturers and industry players have fast-tracked the development of high potential circular technologies. At the packaging level, the aim is to design the packaging so that it is (IK 2021):

- **Collectable by consumers** – meaning it is clearly identifiable as plastic packaging by the consumer
- **Detectable by sorting plants** – meaning it ends up in the sorting fraction designated for recycling
- **Recyclable by state-of-the-art recycling technologies** – so that secondary materials can be produced according to market requirements.

A key to improve the recycling processes (especially relating to mixed plastics waste) is future sorting technologies, such as digital watermarking, visual recognition or optical tracers. All recycling technologies require a certain input quality in order to, in their turn, be able to produce a material meeting their customers quality criteria. This leads to the generation of residuals, which cannot be further processed by the technology in question. In the future, with increasing collected volumes, an efficient cascading approach of technology deployment is foreseen to be economically and technologically feasible.

A small share of current recyclates is approved for food contact, the major part being recycled PET. Paper and carton board packages are not viable and are not recycled back to the primary food package manufacturer, but the recovered fibres are used to manufacture other packages, soft tissues, etc.

The current fast development of chemical recycling and construction of new facilities with +200 000 tonnes/a combined capacity projected in Europe in the next 2-3 years, and over double of that in the US will give the recycled food-grade plastic market a good upswing. Chemical recycling plants will also be able to process multilayer materials, for which commercial mechanical solutions are rare today. Globally, chemical recycling is new, so the infrastructure to provide feedstocks is still catching up with the technology. Current technology providers and investors are indeed usually partnering up with feedstock providers (waste management organisations) to secure raw material for their facilities.

Chemical recycling is a more complicated processes, which is often associated with larger investment needs and energy requirements compared to mechanical processes. Chemical recycling will probably not be the main route in future plastics recycling, but it can make a significant contribution to the recycling of waste plastics, especially for the fraction not meeting the criteria for mechanical recycling processes.

In order to guarantee the sustainability of the recyclate, the ISCC plus certification is commonly used in the packaging industry. It certifies the exact and complete traceability of the materials used in the package with a mass balance approach and confirms that the materials processed actually originate from sustainable (recycled or renewable) sources.

As a whole, the recycling industry is today very dynamic. With the shift towards sustainable practices, and the adoption of automation, waste industry participants and industry players have fast-tracked the development of high potential recycling technologies. These developments will improve the technical, economic, and sustainable viability of circular technologies and will, in turn, aid more wide-scale adoption of sustainable practices in the business models of players in the whole value chain.

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