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POLYOLEFINS FOR A SUSTAINABLE FUTURE

Despite the still large gap to be closed in order to have a proper waste management and efficient recycling process, the fact that polyolefins have a relatively low CO_2 footprint and can be designed to help reducing food and water waste, as well as energy consumption for transportation, makes them a material of selection to enhance sustainability in these and many other applications.

Fig. 1 - United Nations Sustainable Development Goals for 2030[a]

What is "sustainability"?

In the Cambridge dictionary, the term "sustainability" is defined for environmental and economical issues as "the quality of causing little or no damage to the environment and therefore able to continue for a long time". Natural, stable ecosystems are role models for sustainable industrial and generally economical activities. In these systems, nutrients are circulating between the different media - air, water and soil - and organisms - primary producers (mostly green plants), herbivores, carnivores and decomposers (like fungi and bacteria). The formation of short- and long-term deposits of nutrients within the cycles is normal and necessary for balancing periods of over- or undersupply, but the rapid exploitation of solid, liquid and gaseous carbon deposits (i.e. coal, oil and gas) resulting from geological periods of very high productivity is presently disturbing the global carbon cycle **[1]**. Despite being known in principle since the days of Arrhenius, the actual dimension and danger of global warming as result of increased concentrations of carbon dioxide and other greenhouse gases has only entered common awareness in recent years **[2]**.

How much human activities contribute to this change is commonly expressed as the "carbon footprint", considered as the key measure of sustainability by many authors. However, a look at the Sustainability Development Goals (SDGs) for 2030 defined by the United Nations in 2015 at an historic UN Summit and shown in Fig. 1, shows that there are multiple aspects to consider. Even when taking the limited perspective of a polymer scientist, numerous SDGs relating to development, production and application of polymers can be identified. While "responsible consumption" is relevant from a production perspective and directly relates to CO_2 emissions, just like "climate action", polymers are also capable of contributing to other goals such as "zero hunger" (both in agriculture and packaging) and "clean water and sanitation".

Carbon footprint analysis

The global average annual per capita CO_2 emission (fossil-based) was 4.98 tons in 2014[b], the relative spread ranging 0.045 t/a for countries like Burundi or Somalia to 43.85 t/a for Qatar. The European level is on average 6.38 t/a with a slightly negative trend in recent years, but also here the spread is significant **[3]**. In Fig. 2 we present the relation be-

[a]Details available online at **https://www.un.org/sustainabledevelopment/sustainable-development-goals/**
[b]Data from World Bank statistics, see **https://data.worldbank.org/indicator/en.atm.co2e.pc**

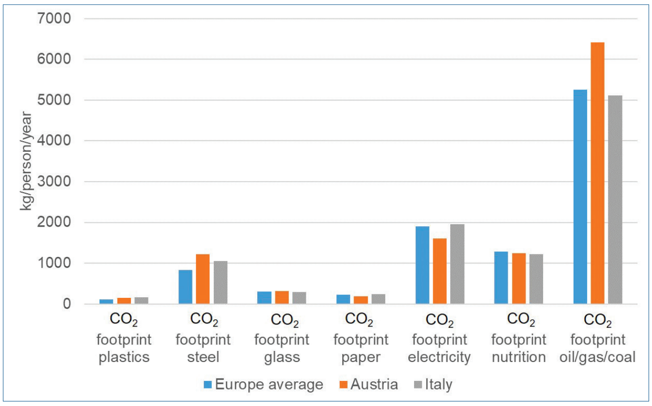

Fig. 2 - Overall fossil-based carbon footprint of Europeans, Italians and Austrians including various contributions to the same

tween the total fossil-based carbon footprint and various contributions to the same, mostly based on Eurostat figures[c], for the European average as well as for Italy and Austria. While the total value and the electricity fraction are accessible directly, material contributions resulting from the usage of plastics, steel, glass and paper as well as the nutrition fraction are based on per capita consumption and conversion factors. As an example, the annual per capita consumption of plastics is 69 kg/a in Europe, which can be converted into 117 kg CO_2 per year. This diagram not only shows the actually higher contributions of 'traditional' materials to the carbon footprint (even paper, consumption 150 kg/a), but also the fact that nutrition causes 8-10 times more emissions than all packaging together. Coincidentally, this relation goes very well together with the results of a UK study on energy demand in the food supply chain from 2009 **[4]**. The sum of primary and transport packaging was found to have a share of about 10% in the total energy consumption, with primary production amounting for 51%. The fact that even purely plant-based food like bread has on average a significant fossil-based energy content is in turn demonstrated in another UK study **[5]**, giving the fertilizer-related carbon footprint of bread production at 41%.

From carbon footprint to circular thinking

For most examples of food packaging, the energy input is more than compensated by the resulting lifetime extension and protection. A combination of reduced water loss, less oxidation, lower exposure to germs and fungi as well as other factors on average allows saving 350 g of CO_2 emissions per kilogram of food while investing 70 g of CO_2 emissions for packaging **[6]**. Detail studies are available for numerous examples, but at least one of them explains why even shrink-wrapping of cucumbers, often quoted as example of 'over-packaging' in social media, makes sense **[7]**. Both in terms of weight loss and of firmness, a simple polyethylene shrink-wrap film can extend the storage time without quality loss by a factor of 2-5, depending on storage temperature.

At the same time, polyolefin (PO) based film constructions also save energy both in production and - because of their reduced weight and volume in comparison to steel, glass and even aluminum - in transportation. Stand-up pouches (SUPs), in use for a wide range of food products from olives to soups, consume up to 90% less energy than tinplate and up to 80% less than glass for the same packaged volume.

The superior packaging efficiency of PO films is partly overshadowed by the complexity of modern multilayer packaging systems with their plurality of materials. Combinations of a 'carrier' film from polypropylene (PP) or polyethylene (PE) with special barrier polymers, aluminum and poly(ethylene terephthalate) (PET) are common and cause problems in mechanical recycling **[8]**. The PO industry is therefore, together with customers and food producers, working on alternative mono-material solutions for packaging films (see Fig. 3), for example combining biaxially oriented (BOPP) films for gloss and barrier performance with special impact copolymers for the mechanically most relevant main layer. PP terpolymers with ethylene and butene are used in the sealing layer in order to ensure high

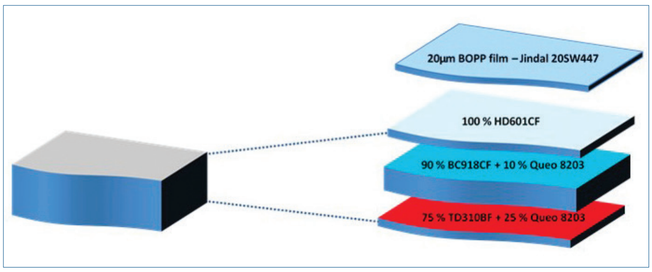

Fig. 3 - Layer structure of a flexible film for stand-up pouches of PP-based materials

[c]See **https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics_-_carbon_footprints**

efficiency and leak-tightness of the packaging, and PE plastomers can be added in fractions of up to 10% referred to the total structure, without impairing the recycling, for enhancing the toughness and extending the sealing window. Similar constructions are also possible based on different PE types.
Reducing weight to save energy is a general principle of PO applications in many different fields, as PP and PE have among the lowest densities of all commercial polymers. The area of individual mobility, which is also contributing significantly to greenhouse gas emissions, is a good example because PP is one of the most widely used polymers in the automotive segment. Vehicle mass can be reduced significantly by substituting metals or other polymers of higher density, reducing fuel consumption while at the same time improving design freedom and comfort. This is of special interest for the rapidly growing segment of e-mobility, where reduced energy consumption is a precondition for extending the range at given battery capacity.
Long glass fiber reinforcement has been for many years the upper limit of stiffness, but Borealis is now exceeding the earlier possibilities. One of the most recent additions to the PP-based material portfolio are carbon-fiber reinforced materials, allowing elastic moduli up to 17 GPa in combination with a density of only 1140 kg/m^3 **[9]**, bringing the specific bending stiffness to a higher level than even magnesium. Innovative constructions for both interior and exterior elements allow weight savings of up to 50% over standard steel-based constructions, examples including tailgates and front modules. Further density reductions are possible by foaming, again in combination with specific polymer design.

Circular economy: closing the loop

Whether the application area is packaging, automotive, household goods or infrastructure, eventually the end of the useful lifetime will be reached, and then the material should return to the circle. Fig. 4 presents an overview of the necessary elements in such a material circle, for which traditional materials like glass or paper are offering valuable role models. On a global scale, about 50% of all paper and cardboard and about 32% of all container glass is based on recycled material, the result of more than 100 years of effort of the respective industries. The polymer industry still has a long way to go in this respect. Even in Europe, where organized collection of packaging waste has already some history, the most recent figures are not satisfying **[10]**. In 2016, the mechanical recycling rate was 40.2% and still 20.4% of all plastic waste was

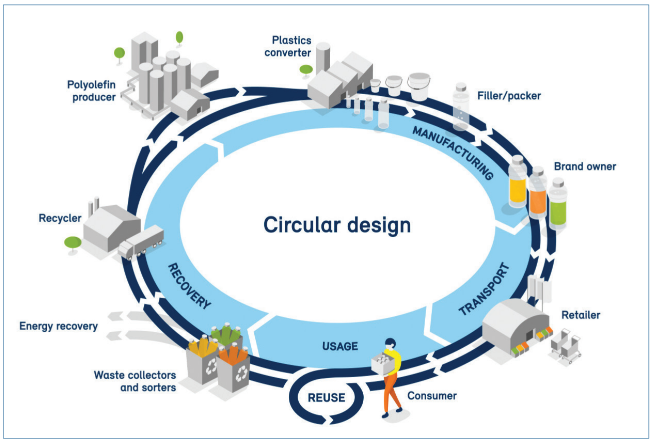

Fig. 4 - Material circle for the packaging segment of polymer applications (©Borealis AG)

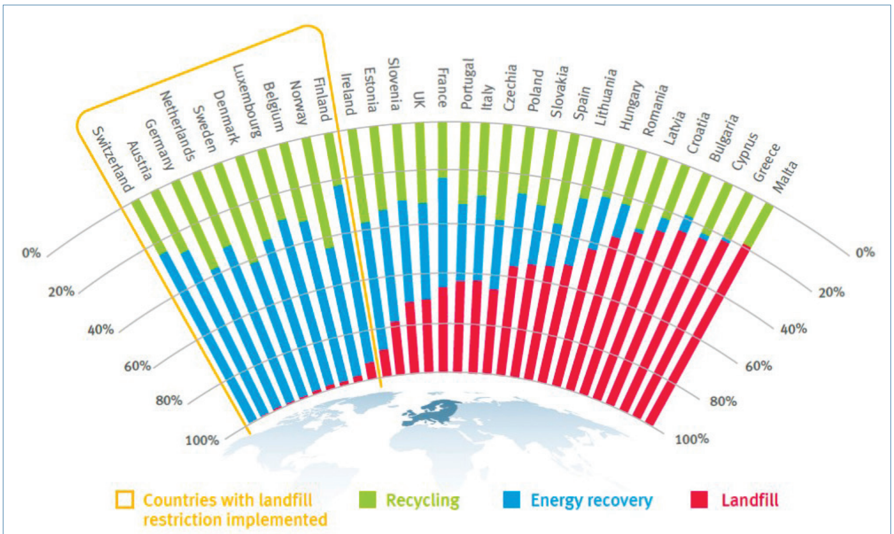

Fig. 5 - Plastic post-consumer waste rates of recycling, energy recovery and landfill per country in 2016 (from **[10]**)

landfilled (values for EU + CH + NO) - the respective EU targets for 2030 are 65% and 10%. Moreover, only a limited number of countries, as shown in Fig. 5, achieves high recycling rates.
The same figure already indicates that this relates to national legislation, as nearly all countries with a landfilling rate below 20% have a restriction forbidding the deposition of waste with significant calorific value. As even the best recycling scheme will then generate a certain fraction of material, which is impossible to recycle mechanically without excessive energy input, incineration for energy recovery is used as second option. These considerations are not limited to plastic waste, and a similar picture results from a view at the overall handling of municipal solid waste (MSW) **[11]**. While the overall development in the EU has been a very positive one, with MSW recycling increasing from 12% in 1990 to 48% in 2015 and landfilling decreasing from 75% to 28% in the same period, the spread among different countries is significant here as well. Croatia, for example, is approximately at the EU 1990 level, Italy close to the present European average and Austria (like Germany) is landfilling less than 5% and mechanically recycling more than 55%.
Several facts are very important in this discussion about optimizing the handling of MSW in general and post-consumer plastic waste in detail. First, an effective shift in the right direction requires a combination of legislative measures and infrastructure investment, each of these two being insufficient alone. Second, modern MSW incinerators are not only capable of delivering valuable electricity and heat (with an efficiency of 66% in case of combination), they also reduce greenhouse gas emission in comparison to landfills **[12]**. Third, 'energy recovery' does not need to be simple incineration; it can also be the use as alternative (and normally cleaner) fuels for the cement industry or as substitute reduction agent in iron production. The Austrian steel company Voestalpine is presently using about 220 kt/a of plastic waste as coke substitute, with a significantly positive effect on the CO_2 emissions per ton of product. And fourth and last, companies can only recycle what is collected first, meaning that an efficient collection system must be part of the overall construction. In that respect, nationwide actors like ARA in Austria, DSD in Germany or Corepla in Italy play a decisive role in the coordination of individual companies. From 1995 to 2015, ARA has for example managed to increase the annual collection volume of 'lightweight packaging material', i.e. plastics and aluminum, from 10 to 17.2 kg per capita[d], and even glass and paper collection volumes are still increasing.
There are, however, also numerous challenges for polymer researchers in the field of circular economy. Different collection and sorting schemes only rarely give access to high quality feedstock for post-consumer recycling (PCR), making both precise selection procedures and compatibilization of minority fractions valid targets for research. In relation to its relevance for circularity, mechanical recycling has only received rather limited attention by the scientific community, with few notable exceptions **[13]**. In line with market figures, polyolefins make up more than 50% of PCR materials, making them, next to PET, ideal candidates for pure fractions. Still, also these materials require purification, emission reduction and long-term stability, with research necessary on each of these aspects.

Practical approaches to circularity

For Borealis, circular economy solutions symbolized by the EverMinds™ trademark, does not start at the end of a product's usage life, but rather at its beginning. Optimizing material selection starts at polymer design and stabilization, and necessarily involves 'Design for Recycling' **[14]**. Minimizing material diversity and pigmentation as well

Fig. 6 - Re-usable and recyclable 'Corretto' coffee cup produced using the Bockatech EcoCore process (©Bockatech)

[d]Original data can be found at **https://www.ara.at/en/presse/sammlung-verwertung-in-zahlen**

as combining circularity on two different levels are exemplified in the 'Corretto' coffee cup developed in cooperation with Bockatech Ltd., Huntingdon/ Great Britain (see Fig. 6). The EcoCore foam injection molding process used here allows particularly light and thermally stable products to be manufactured. The new cup, based on 100% PP as material, is an inexpensive, break-proof alternative to the currently widely criticized disposable cups made from coated cardboard. Due to their high strength, packagings produced in this way are suitable for e.g. deposit and return systems that have proved to be successful with their recovery rates of up to 94%.
The next level are PO recycling operations delivering high-quality products for numerous applications. Two daughter companies of Borealis, mtm plastics in Germany and ecoplast in Austria, deliver an output of 70 kt per year and are capable of handling both PCR and industrial recycling material. The high material performance which can be achieved in engineering compounds with up to 25 wt% PCR content, for example producing materials for exterior and under-the-bonnet uses in the automotive industry, has already been demonstrated in several pilot projects with different OEMs. An example is the Volvo XC60 T8, a hybrid plug-in SUV of the Swedish company leading in innovation: for a demonstrator series, 60 kg of PCR-material were used, and over 170 components usually made of conventional plastics could be replaced with lightweight, recycled material equivalents.
Overall, the cycle shown in Fig. 4 cannot be closed without also employing chemical recycling to turn more contaminated or highly mixed polymer waste fractions into valuable primary materials again **[13]**. Here, Borealis is cooperating with the Austrian petrochemical company OMV, which is already producing raw material for the cracker on an expanded pilot plant for its ReOil process with a capacity of 100 kg per hour.

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Poliolefine per un futuro sostenibile

Nonostante l'ampio divario ancora da colmare al fine di avere una corretta gestione dei rifiuti e un efficiente processo di riciclaggio, il fatto che le poliolefine abbiano un'impronta di CO_2 relativamente bassa e possano essere progettate per aiutare a ridurre gli sprechi di cibo e acqua, nonché il consumo di energia per i trasporti, le rende un materiale di selezione per migliorare la sostenibilità in queste e molte altre applicazioni.