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The plastic age – where and what is the future?

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We are currently living in the "Plastic age" as rightfully predicted in the classic movie "The graduate" in the 60's where main character young Benjamin, just graduated and asking himself what to do next gets the famous advice: "I just say one word – Plastics. There is a great future in Plastics!" This was certainly correct; our daily life relies on synthetic polymers for all aspects of modern life. Going back in history, one of the first synthetic resins, a thermoset produced by a catalyzed reaction of phenol and formaldehyde, was introduced already 1909 under the name Bakelite. The creation of a synthetic plastic was revolutionary for its electrical non conductivity and chemical, solvent and heat-resistant properties in electrical insulators, radio and telephone casings and such diverse products as kitchenware, jewelry, pipe stems, children's toys, and firearms. Bakelite was particularly suitable as a molding compound, an adhesive or binding agent, a varnish, and a protective coating and as such extremely useful for the emerging electrical and automobile industries. In the following years a number of new polymeric materials, thermoplastics and thermosets were developed, mainly formed by linking small molecules – monomers - together in a repetitive formation. Plastics are today available with extremely versatile properties ranging from, resistance to corrosion, low density, high strength, transparency, low toxicity, durability and a remarkable affordability and therefore used by almost every industry in the world, from food packaging to space exploration. Plastic is the ultimate commodity of convenience.

Especially hydrocarbon polymers like polyethylene and polypropylene, which account for more than half of the world plastics production and more than 90% of packaging materials are ubiquitous in single-use and short-term applications because their starting materials are abundant and inexpensive. In addition, we have learned to vary the chemical structure of the polymer chains (such as branching, molecular weight, and dispersity) through catalysis, and in such to alter their physical properties. The single-use nature of plastics is essential in sterile packaging for foods, strong-but in expensive materials for transportation and storage, and safe and disposable components in medical devices, leading to their manufacture in tremendous quantities. Three hundred and eighty million tons (380 Mt) of plastics are created worldwide each year, which corresponds to roughly 7% of crude oil and natural gas produced. Moreover, the plastic market is currently increasing, and some analysts predict quadrupled production by 2050 (~1100 to 1500 Mt per year).

However, the good properties of plastics, namely the mechanical performance connected with low density, are intrinsically connected with the existence of large molecules in the material. This long chain molecular nature turned out to be a major draw-back in the circularity and recycling. Mixtures of polymers are thermodynamically not stable; in fact only a few polymers are miscible at all and thus small impurities (not speaking of non-polymeric ones) deteriorate the functional properties significantly! Processing of plastic waste is limited by technical challenges, which include contamination from mixtures of polymers and additives as well as oxidative degradation during melt re-processing. Current recycling processes rely mainly on primary recycling (termed closed-loop recycling, reprocessing an uncontaminated, single plastic to give a product used for the same purpose as the original plastic) and secondary (mechanical) recycling –down cycling- results in lower-in-value materials with different uses compared to the original material. Both primary and secondary recycling involve sorting, grounding, washing, and extruding, which cause varying degrees of polymer degradation, resulting in a limited number of reprocessing cycles of polymers. This accounts even more for cross-linked polymers, often referred to as thermosets and another class of plastics comprising ca. 15–20% of polymers produced. The outstanding performance of conventional thermosets like the first material Bakelite originates from their covalently cross-linked networks but results directly in a limited recyclability. The available recycling techniques include mechanical, thermal, and chemical processing. These methods typically require a high energy input and do not take the recycling of the thermoset matrix itself into account but focus on retrieving the more valuable fibers, fillers, or substrates. Thermoset materials are in particular amongst the most difficult materials to recycle, and in most cases even considered impossible to recycle. Most attention is given to the recycling of fiber-reinforced composites, since the fibers are generally more valuable than the matrix material, especially when carbon fibers are used. The most favorable method of recycling, the direct re-use of components in similar or lower performance applications without any form of reprocessing is virtually impossible for the existing thermoset materials.

The downside of the plastic age is the massive quantity of waste, pollution and lost value associated with single-use plastics. Over 75% of materials produced each year, 300 Mt, are discarded after a single use. Currently, most of this waste is either lost to landfills and the environment, or inefficiently incinerated in power plants to produce electricity, generating greenhouse gases (e.g., CO_2) and toxic by-products in the process. Inefficient recycling and extremely slow environmental degradation of plastics are causing increasing concern about their widespread use. After a single use, 90 % of these materials are currently treated as waste creating a global environmental crisis,

despite of their inherent chemical and energy value. Plastics have got themselves a bad name, mainly for two reasons: most are made from petroleum and they persist in the environment for decades or centuries beyond their functional lifetimes and end up as litter in the environment. Durability, one of plastic's greatest assets is now its curse. Its robustness means that plastics stay in our environment for hundreds of years turning them into a persistent part of the landscape, and more importantly of the seascape. Once discarded, bulk plastics are polluting the oceans. Converging sea currents are accumulating plastic waste in a floating island known as the Great Pacific Garbage Patch, which now covers an area larger than Greenland. The bigger bits of plastic are life-threatening to marine life and sea birds, they can strangle marine animals and birds or build up in their stomachs. More recently, the awareness of the presence and danger of micro plastics has raised concern about their presence in the food chain. If nothing changes, by 2050 there will be as much plastic in the sea as there is fish. Who wants to eat plastic then?

The switch from a linear economy with its throwaway culture to a circular economy with efficient reuse of waste plastics is therefore mandatory. An increased focus on bio-derived and degradable composites as well as recycling could lower the degree of pollution. Reduce, reuse and recycle have been embraced as the common approach to tackle the escalating plastic waste problem. The goal is to create a circular plastic economy where products are 100%recyclable, used for as long as possible, and their waste is minimized. Compared to plastics, massive recycling of much older man-made materials like iron and steel (> 70 %!), copper, glass, aluminum and paper is the current technology and already since a long time developed and optimized. For a circular economy, the vast majority of plastic materials should be recyclable and the materials entering the chain should be bio-based. Although biodegradable polymers and in particular PLA have been the focus of much research over the last decades, only ~1% of plastics are currently produced from renewable resources. Besides, polymers derived from bio-renewable resources, commonly referred to as renewable polymers, bio-based polymers, or even sustainable polymers in the literature, are not necessarily sustainable or degradable, where as degradable polymers are not necessarily recyclable. For example, 100% bio-based polythene (bio-PE) and bio-based polyethylene terephthalate (bio-PET) are not biodegradable. Dreams and reality of green polymer chemistry have no match, conflicts and competition with food production and unrealistic high CO_2 production are consequences. Biopolymers are also not a realistic alternative to synthetic polymers (properties and processing). Recycling is costly, reliant on changes in human behavior and produces partially lower quality materials, in terms of both thermal and mechanical properties. Additionally, recycling does not change our plastic addiction; if we want to maintain our current lifestyles, modification to plastic manufacture needs to go hand in hand with effective recycling. So a change in mind-setting is mandatory!

A already developed way to reduce the demand for finite raw materials and to minimize the negative impact on the environment involves chemically recyclable polymers which are capable of being returned to the corresponding monomers in a depolymerization process ready for repolymerization to virgin-quality polymers. This seemingly ideal strategy has motivated the research on the exploration of chemically recyclable polymers and also the mild processes for the catalytic conversion of the recyclable polymers to monomers or new polymers, namely chemolysis (by depolymerizing or decomposing the polymer in the presence of a chemical catalyst, typically needing relatively low temperature or even ambient temperature). Consequently, to advance plastic recycling practices, improving chemical recycling selectivity and efficiency through monomer and polymer design and catalyst development is mandatory, minimizing the need for sorting and expanding recycling beyond polyesters, polyamide and polyurethanes [1]. Recent advances report on the catalytic selective hydrogenolysis of PE at moderate conditions (300 °C, 9 bar H_2) on nanoparticles in a solvent free process offering an option to obtain high value re-usable materials out of waste-PE[2] showing as such an opportunity to deal with the already existing large quantities of plastic waste in an economic and ecological way. Key feature of circular economy is preventing waste by making products and materials more efficient and reusing them. The challenge in a circular economy is the development of environmentally friendly polymers with better properties and at the same time facilitating reuse of plastics. This can be e.g. realized by polymers custom designed for recycling such as e.g. all-polymer (one component) composites, self-reinforcing polymers (molecular composites) [3] or the use of reversible chemistry [4]. Starting with the already about 15 year development of instruction of self-repair functionalities [5] in plastics and as such enabling these materials to react early on a developing damage or defect and reducing over-design of systems and realizing weight and cost reduction in a new way the future for plastics and other materials is not only a design or use (self-repair) but a design for recycling. This starts with a design of products to encourage a re-use as well as in a material choice for less impacting and recyclable materials, for reduction of quantities and variations in one product and an optimalisation of process technology. In the design phase, material sorting processes, separation and dismantling considerations are as important as the introduction of extension of lifetime and preservation of functional property technologies like self-repair. Consequently, there is a need for a new generation of materials that can be reprocessed like thermoplastics that still retain the beneficial properties of high performance thermoplastic or thermoset materials[4]. Such a material can be realized by the incorporation of dynamic interactions and dynamic covalent bonds into linear polymers and networks. In such plastics, thermal depolymerization and solvent assisted depolymerization and especially dissociative depolymerization and adaptable cross-links can transfer the non-recyclable plastics to small thermoplastic piece and thus enabling complete recycling and re-use. Alternatively (and parallel)it is the intrinsic production of cost-, resource-, eco- and energy efficient high performance polyolefin's using modern multisite polymerization catalysts as reported recently by Mühlhaupt et al. resulting in all polyolefin injection moldable composites with a unique combination of high toughness, stiffness and strength which show virtually no change in properties during 7 cycles of remolding one of the most promising trends[3]. While following these ideas, the future of Plastics and ourselves will be still great. The need is to shift

now from the Design-for-Use –self repair – strategies to the Design for recycling–multiple use- strategies to guarantee a bright Future for Plastics.

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