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HOW CAN SUSTAINABLE CHEMISTRY CONTRIBUTE TO A CIRCULAR ECONOMY?

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ABSTRACT

The transformation from a linear to a circular economy and from a fossil oil-based to a biobased economy creates challenges that need to be solved. Challenges are associated with the introduction of biobased compounds, such as bioplastics, as new compounds, in existing material cycles and the difficulties to separate such compounds in a circular economy from conventionally used materials. The transformation, however, is necessary due to the expected limitation in fossil resources and associated climate and environmental issues. Sustainable chemistry aims on a simultaneous consideration of resource, production, product and recycling. The focus is not only on sustainable transformation of matter, but also on its origin and fate. Whenever biobased products are to be introduced in existing material cycles, following question might be considered beforehand: 1. Are renewable resources available to carry out production processes in order to meet the demand of certain products?, 2. Is the technology available to carry out recycling and production processes efficiently?, 3. How likely is the separate collection of products after use?, 4. Does the product eco-design allow a recycling of resources?, 5. Are additives as unwanted compounds circulated as well?, 6. Are recycled resources useable in repeatedly carried out production processes? and 7. Does society accept products based on recycled resources? Those questions can be addressed when totally new material cycles are generated. The challenge, however, is finding the beginning of an already existing cycle in a circular economy which allows an introduction of new materials and/or production as well as recycling processes.

1. INTRODUCTION

1.1 Sustainable chemistry and circular economy

Chemistry is generally defined as discipline dealing with the transformation of matter. Over time, several subdisciplines, such as inorganic chemistry, organic chemistry, physical chemistry and biochemistry, have been developed. Those disciplines deal with a narrowed but still complex aspect of chemistry. In order to address the challenges of sustainable development, a new approach – sustainable chemistry – has been emerged (Kümmerer 2017). Sustainable chemistry might be defined as discipline dealing with the sustainable transformation of matter, but this definition is incomplete. Sustainable chemistry does not only address the sustainable transformation of matter, but also its origin and fate. It further addresses social aspects, such as the demand and acceptance of products by society. Particularly the consideration of societal acceptance and demand for products goes beyond the 12 principles of green chemistry formulated by Anastas and Warner in 1998 (Anastas and Warner 1998).

In a circular economy, sustainable chemistry considers following four key elements: resource, production, product and recycling (Figure 1). The key elements are strongly influenced by resource availability, demand, eco-design and recyclability of products. The availability of resources influences the efficiency of production processes. The efficiency usually decreases when sufficient resources are available. The demand decides which product is formed. Product eco-design influences recycling and consequently recyclability is central to resource availability (Figure 1). The improvement of products and processes in order to sustainably address the four key elements is challenging. It is common to adjust production processes regarding the demand for products and to ignore the availability of resources, or to eco-design products regarding functionality and to ignore the need for recycling.

Even in a circular economy an increase in entropy and dissipative loss of materials cannot be avoided (Kümmerer 2017). Every approach to avoid a loss of materials would consume a disproportional amount of energy. Thus, a more realistic approach considering resource, production, prod-

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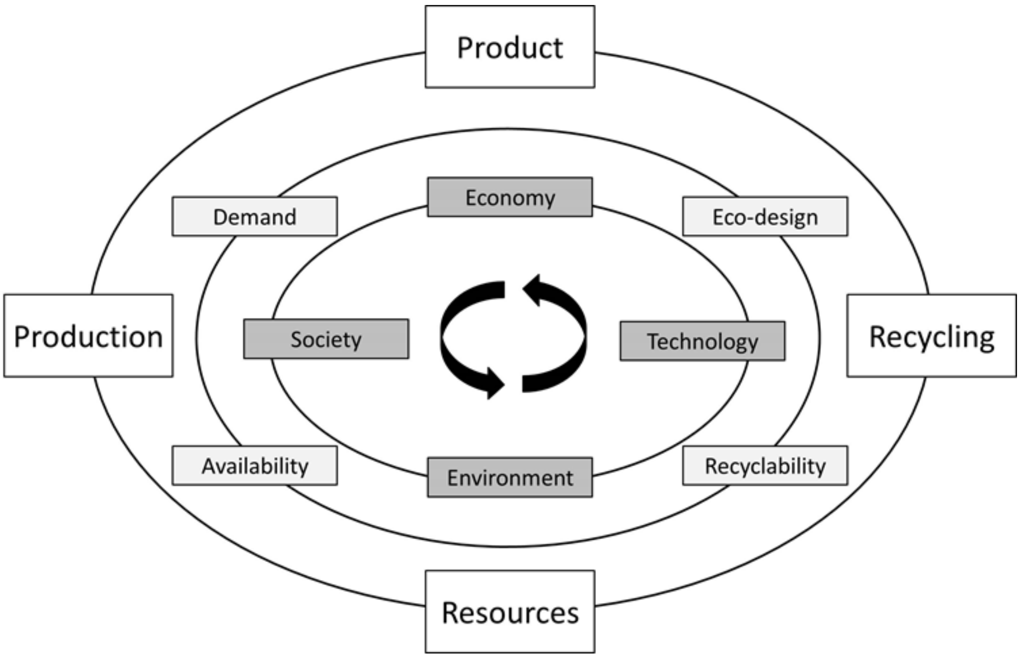

FIGURE 1: Sustainable chemistry and the circular economy. The key elements: Resources, production, product and recycling are dependent on availability of resources as well as demand, eco-design and recyclability of products. The two inner circles represent those aspects which are essential for a circular economy. The most inner circle is considered moving and it should be admitted that new approaches addressing the key elements may not be successful when societal acceptance, economic feasibility, technological possibilities and environmental impacts are considered inappropriately.

uct and recycling is needed which minimizes the loss of material. Recycling and production technologies are essential elements of a circular economy as resources provided by recycling are to be processed into new products. Failing to provide a sufficient amount of resources with a certain quality cannot result in new high quality products. Sustainable chemistry aims on considering the aforementioned elements simultaneously. The challenge, however, is finding the beginning of an existing cycle allowing an introduction of new materials and/ or processes which address resource availability as well as existing technologies with lowest environmental impact and highest social acceptance (Figure 1).

An example where key elements have not been addressed adequately is the introduction of bioplastic in the material cycle of conventional fossil oil-based plastics. Bioplastic, such as poly(lactic acid) (PLA), is often characterized as biodegradable. This stands as synonym for environmental benignity and sustainability. Biodegradability is an important aspect when plastic is released in the environment by accident or design. The eco-design of products, however, should not only focus on biodegradability, but also on recyclability. In Germany, the recycling of bioplastic is basically non-existent. PLA is not compostable fast enough to be mineralized in composting plants. Consequently, PLA is banned from being disposed with the organic waste. Due to difficulties to separate PLA from conventional plastic material it is also banned from being disposed with the so called recyclable material, a category where it actually should belong to. At the end, PLA is disposed with the residual waste and either incinerated or stored in landfills. This means not only a loss of functionalized material, but also a loss of all resources initially applied in biomass production (PLA is formed from lactic acid obtained after biotechnological conversion of sugars from biomass) and PLA formation.

The introduction of bioplastic was a reaction to the societal concern regarding the environmental impact of conventional fossil oil-based materials. The last couple of years industry has been using the commonly positive attitude of society regarding biomaterials. This created a pseudo-sustainability on the consumer's and producer's side, but the missing recyclability and material utilization at the end contributed to unsustainability on the side of waste management.

In a bioeconomy biobased products substitute fossil oil-based ones (Fitzgerald, 2017). This makes sense due to the concerns associated with the limitation in fossil resources and environmental impact of fossil-oil based products. Biobased products can be food and feed, chemicals and materials as well as fuels. At local scale, biobased products can be produced where needed. At global scale this involves a transport of biomass. The energy density of biomass, for instance, is low compared with fossil oil and more biomass is needed to be transported to reach the same amount of energy. Consumed food, feed and biofuels cannot be collected after use, but chemicals and materials basically can and should be considered for recycling. However in bioeconomy concepts the recycling of biobased products is usually not properly addressed and degradation is favored. Recycling, however, contributes to the preservation of resources applied in production.

Even though processes are available to convert biogenic resources into wanted products (Koutinas et al., 2014) it remains a challenge to meet resource availability and demand. Biogenic resources, such as biomass and organic residues, are literally available everywhere, and thus bioeconomy concepts can theoretically be applied everywhere. Quality and quantity, however, are not equally distributed due to differences in water, fertilizers and arable land availability around the globe. The different availability of resources makes bioeconomy concepts case specific for certain areas. Establishing a recycling of biobased products can contribute to resource efficiency. This is particularly of interest in areas which are limited in water and/ or land. Furthermore, it is contradicting when a bioeconomy starts with an extensive use of fossil resources, such as fertilizers.

The progressing interest in developing bioeconomy concepts worldwide makes it necessary to elaborate on following questions: How many material cycles (biobased and fossil oil-based) can be maintained in parallel? How can all the different streams be collected separately and recycled or can we even combine the cycles of biobased and fossil oil-based materials?

A couple of biobased materials, such as polyethylene and polyethylene terephthalate, are chemically identical to their fossil oil-based equivalents, and thus a mixing of materials is uncomplicated. However, as elaborated above, a mixing of PLA with fossil oil-based materials causes serious difficulties when it comes to separation.

The term recycling is well defined and describes the reuse of materials after disposal. For polymers, recycling can either occur by degradation to monomers and reuse of monomers as secondary raw materials or by maintaining the initiate structure and functionalization. Degradation thereby contributes to an increase in entropy. The higher the entropy the more energy is necessary to structure and reform new materials. Therefore, if possible, the target should be on maintaining the original structure and functionalization. The closure of the cycle of matter by recycling depends on the separate collection of materials in order to maintain the purity of material streams. In existing circular economy concepts this has already been shown to be challenging. Materials are either too distributed and/ or materials are mixed with other materials. A concentrated and pure material stream cannot be achieved without applying a disproportionally high amount of energy.

Whenever it comes to the introduction of new materials in an existing cycle, it seems appropriate in terms of circularity and resource efficiency when following questions are considered beforehand:

- Are renewable resources available to carry out production processes in order to meet the demand of certain products?
- Is the technology available to carry out recycling and production processes efficiently?
- How likely is the separate collection of products after use?
- Does the product eco-design allow a recycling of resources?
- Are additives as unwanted compounds circulated as well?
- Are recycled resources useable in repeatedly carried out production processes?
- Does society accept products based on recycled resources?

The answers to those questions are relevant for every circular approach. Resources and production processes are usually properly addressed due to economic planning. However, eco-design and recycling of products are not, but necessary to achieve a sustainable development.

2. CONCLUSIONS

Challenges associated to the transformation to a circular and biobased economy need to be overcome. It is rather unsustainable to introduce new products in form of biobased materials in existing cycles without aiming on a recovery and recycling after use. The aim of sustainable chemistry to address resources, production, product and recycling simultaneously is ambitious, challenging and difficult to achieve. Sustainable chemistry creates the disciplinary basis to discuss the sustainable transformation of matter, its origin and fate in a bioeconomy and is necessary to critically reflect and evaluate all the solutions and technical improvements that come along with a sustainable development.

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