

Rethinking chemistry for a circular economy

Chemical complexity complicates product recycling and manufacturing sustainability

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Earth is running out of resources needed for manufacturing materials such as chemicals, minerals, and petroleum. Thus, these components are available only at increasing economic and environmental costs. As an important contribution to a sustainable future, chemistry and its products must be adapted to a circular economy (CE)—a system aimed at eliminating waste, circulating and recycling products, and saving resources and the environment (1).

Nearly 140,000 industrial chemicals are marketed worldwide, and new chemicals are becoming more complex (e.g., stereochemistry, functional groups) (2). Products of the chemical and allied industries contain mixtures of elements and molecules, and these products and their constituents are found everywhere, including in waste products, soils, water, air, plants, food, animals, and the human body.

SHAPING A CIRCULAR ECONOMY

In a CE, products should be used as long as possible until the end of their lives. Modern circularity thinking includes the design of products with adapted lifetime, reusability, ease of repair, and recycling ability—all made with renewable resources (3). The development and implementation of CE approaches in China (4), the United States (5), the European Union (1), and other countries (6) are supported by international organizations such as the World Health Organization (WHO) and the United Nations (UN) (2). These efforts will help address Earth's resource and waste challenges and contribute to sustainable development. However, greater success will have to come from changes at the product-design level, led by scientists who strive to decipher, at the atomic and molecular levels, how chemical products and their underpinning synthetic chemistry fit into a CE. This includes identifying suitable starting materials and modifying them to the

desired grade, structure, and function for an application. With today's diverse and interconnected chemical, material, and product flows, manufacturers must learn what can and should be circulated and recycled and what can and should not.

LIMITS OF CIRCULATION AND RECYCLING

Scientists expect metal demands to increase substantially for use in industrial chemistry and for products and processes that reduce CO₂ emissions or increase digitalization and (electro)mobility or enhanced communication. A sustainable future depends on the availability of high-grade metals—both common (e.g., aluminum and copper) and specialty (noble, rare earth) ones—sourced from virgin ores or from recycling.

Copper, for example, is indispensable for many products, such as wiring, wind turbines, electric motors, information technology, generators, sensors, and electronic devices. Since the beginning of the 20th century, copper production has grown more than 3000%, with a predicted market deficit of 600,000 metric tons by 2021 (7). New copper ores frequently fall short of the desired quality; thus, upgrading requires more energy and resources. Extraction of ores from deep mines creates a large environmental footprint, as this process generates more waste, mobilizes more toxic elements (e.g., arsenic), and is more likely to require access to protected lands of indigenous peoples, risking social disturbance.

Metal recycling can be advantageous given the energy-intensive processes of mining, grinding, and extraction of ores. However, many materials need specific grades and mixtures of metals and other elements, and each of these demands separation and purification at the atomic and molecular levels in the recycling process. Some ingredients cannot be separated and are lost from further use by dissipation.

By 2012, humankind had mined ~560 million metric tons of copper (19 million in 2010 alone) (7, 8), and about half of this is still in use. But where is the other half, and what can researchers learn about the CE from this loss? Some irrevocable losses result from low recollection rates. Other losses occur when recycled materials can only be reused by mixing with virgin metals so as to meet the desired quality (i.e., high grades of steel or aluminum). Some

products have a long lifetime, such as those used in the human-made environment (the “built world”), e.g., metals and polymers. As societal demand for products increases, manufacturers will need more virgin resources, because, for the foreseeable future, demand cannot be met entirely by a CE. Scientists have begun to exploit the vast quantities of accumulated wastes, including those that are metal-rich (e.g., from electronics and steel). But along with these wastes come other unwanted wastes and added energy demands.

Unlike metals, organic compounds can be synthesized. However, their recycling can require added chemicals and be energy-intensive and expensive. Plastics, for example, often consist of one or more (co) polymers along with several additives, such as plasticizers, flame retardants, coloring agents, ultraviolet-light stabilizers, and antioxidants, which are often hazardous and difficult to separate in recycling. Even when recycling pure materials, such as polyethylene terephthalate from plastic water bottles, more than 5% is lost in the process. Often recycling is only possible at the atomic or molecular level (e.g., depolymerization of plastics or extraction of metals and other elements from electronic materials), which results in the loss of macroscopic form, molecular structure, and desirable properties of the products. In some cases, recycling is impossible. Such materials and products must be avoided in a CE.

The use of renewable bioresources for organic molecules has a long history and is increasingly practiced in industrial chemistry. Agro-industrial or forestry waste products, for example, are complex and difficult to separate. Thus, the challenge lies in transforming waste into specific products with defined properties and degrees of complexity. Additional complications arise from the buildup of unwanted chemicals in products during use, natural aging, and the recycling process itself, as well as the connected flows of materials and products. For example, mechanical recycling (remolding) results in polluted and lower-quality recyclates, thus preventing reuse in the same application.

In fact, recycling unavoidably leads to the downgrading of materials and dissipative losses of utilizable elements and energy. The complexity and diversity of today's products and their components (on atomic, molecular,

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material, and building-block levels) enlarge this dissipation of metals and other elements, pollutants, and energy.

These losses are apparent in an observed increase of thermal and material entropy. Whereas Earth can export thermal entropy to a certain degree by emission into space, it cannot get rid of the material entropy that comes from the mixing and diluting of materials, including lowering the concentrations of the elements therein. These insurmountable limitations (according to the laws of thermodynamics) must be taken into account and considered for chemistry, including metallurgy and materials science and its products necessary for a CE.

Products with open-environmental applications, such as pesticides, cosmetics, biocides, and pharmaceuticals, can be neither circulated nor recycled, because low concentrations and high dispersion on application make recollection impossible. For liquid waste and waste water, even advanced treatment removes product components poorly (9). In addition, nearly 80% of the world's effluent is not treated at all (9). Furthermore, environmental wastes and pollutants often are the sources of new, sometimes even more toxic, molecules. Therefore, scientists must design new molecules and materials for such applications, to permit fast and complete environmental mineralization while retaining their desired functions (10).

SIMPLIFYING COMPLEXITY

A series of chemistry keystones lie at the center of a CE and must be introduced into education, legislation, and industry (see the box). Most of today's chemical products are synthetic, based on nonrenewable resources, and formed into complex articles such as plastics. Recovering molecular value from these will require a considerable investment in funding and energy. Future products must constrain the levels of complexity of their constituent resources and not change them in recycling.

Keeping the chemical structure of the final product and its building blocks (form, composition, stereochemistry, and functional groups) as similar as possible to the starting material is desirable for both virgin and recycled materials. This will aid subsequent recycling and reduce the number of downstream chemical processes and unit operations, as these cause waste production, entropy increase, and resource consumption, including energy (11). If materials and molecules must be changed in form and composition, manufacturers should aim to further reduce complexity. Final products should be as simple in composition as possible, minimizing additives and avoiding toxic components and elements not easily separated for recovery.

Integrating chemistry into a circular economy

- **Keep molecular complexity to the minimum** required for the desired performance, including end of life (complex molecules require more synthesis steps, may have additional undesirable properties, and can be more difficult to recycle).
- **Design products for recycling**, including all additives and other components of the product.
- **Reduce and simplify diversity and dynamics** of substance, material, and product flows; e.g., use fewer chemicals overall (both number and quantity), design for less resource intensity, and adapt innovation speed of products to adaptation speed of recycling.
- **Avoid complex products** (e.g., multiple components, materials).
- **Minimize use of product components** that cannot easily be separated and recycled (e.g., solvents, metals).
- **Design products** not suitable for capture and recycling for complete fast mineralization at the end of their lives (e.g., pharmaceuticals, pesticides, personal care and cleaning products).
- **Prevent raw materials** from becoming critical through reduced use and efficient recovery and recycling (e.g., many metals).
- **Avoid entropic losses and transfers** (e.g., dissipation of metals, energy).
- **Avoid rebound effects** (e.g., using less carbon often means higher demand for metals).
- **Be responsible for/develop ownership of your product** throughout its complete life cycle, including recycling.
- **Ensure traceability** and consider use of product digital passports (e.g., composition of products, components, and processes).
- **Develop and apply circular metrics** (e.g., giving credit to the use of by-products).
- **Change traditional chemical practices** based on "bigger-faster" into "optimal adapted-better-safer" and change ownership to rent, lease, and share business models.
- **Keep processes as simple as possible** with a minimum number of steps, auxiliaries, energy, and unit operations (e.g., separations, purification).
- **Design processes for optimal material recovery** of auxiliaries, unused substrates, and unintended by-products (based on quality and quantity).

To avoid mixing varying constituents and increasing unnecessary complexity, flows of products and their constituents must be kept as separate as possible at all stages of their life cycle, from resource extraction and synthesis to use and recycling. If the flows are highly variable, recycling will be hindered. Similarly, local flows are preferable to global ones, and more complete knowledge of the composition of materials and products will help with speedy recycling. Of course, it is necessary to locate waste streams and decipher how to collect them, or they might be lost forever.

If speed of innovation on the product side is higher than on the recycling side, then the problem will outpace the solution. Society needs a greater investment in cutting-edge recycling technologies. Industry and academia must give these advances the same recognition as that received by new molecules, materials, and product designs. Making companies as responsible for recycling of their products as they are for product performance should drive industry participation in research and development (R&D) of recycling technologies and in product design for a CE. The high value attracted by some recycled products and the increasing costs of virgin resources should transform recycling and product-design research from a burden to a business opportunity.

Integration of the waste and chemical sectors, including industries that produce large volumes of chemical or metal-rich wastes (such as agri-food, textiles, electronics, plastics, metals, and alloys), allows for a better understanding of chemistry and its products and links sources with sinks. Demanding only a "green" CE without reflecting on the systemic role of chemistry will not contribute much to sustainability. The chemistry necessary for a CE will come to fruition only through a new attitude toward chemistry education, chemical research and engineering, and product design (12, 13). ■

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