Modular, Intensified Options for Conversion of Wastes to Products

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Global challenges such as climate change, unsustainable development, and ocean plastic pollution highlight the need to rethink the linear lifecycle of most products. Raw materials are typically taken from the ground and processed into products that are distributed, used, and landfilled or incinerated at the end of their useful life. Alternative approaches to manufacturing focus on transitioning from a linear lifecycle to a closed loop in which waste, rather than primary raw materials, is used as feedstock to create new products.

Recycling efforts are a step toward a more-circular approach to manufacturing. Common recycling approaches, however, typically use mechanical methods to process paper, metal, and plastics, which usually downgrades the material properties. For example, plastic soda bottles are washed, melted, and reformed for less-demanding applications, such as carpet fibers and detergent bottles. Alternative chemical recycling approaches are being developed that break plastics into their monomers, expanding the potential uses for the recycled material.

These chemical recycling approaches are central to a new circular economy initiative called waste-to-products (WTP or WTX). WTX initiatives can create a broader range of products than mechanical recycling. Many types of waste can be used as WTX feedstocks, including:

- municipal solid wastes (*e.g.,* common household trash, food waste, and yard trimmings)
- construction and demolition debris (*e.g.,* lumber, drywall, and insulation)
- municipal wastewater treatment plant (WWTP) byproducts (*e.g.,* sludge, biosolids)
- industrial and electronic waste
- agricultural residues (*e.g.,* corn stover, rice straw)
- pollutants (*e.g.,* CO_2 and fly ash).

While it is easy to find colloquial definitions of waste (*i.e.,* undesirable or discarded materials), more precise, regulatory definitions are complex and often lack the detail needed for process development. It is important to define characteristics of the waste to understand the processing options. Critical characteristics include concentration of valuable materials or impurities, toxicity, heterogeneity, energetics, and collection and transportation logistics. The energy content and transportation logistics of the waste are especially important and present opportunities for process intensification (PI) and distributed manufacturing.

A barrier to developing circular economies is the lower chemical potential energy of most waste feedstocks compared to conventional raw materials (*e.g.,* oil and gas). When comparing the environmental footprints of processing virgin vs. waste feedstocks, the entire lifecycle of the product must be considered from resource extraction to use and disposal. This includes mass and energy inputs to the cycle and the yield and efficiency at each stage. Some PI approaches, such as selective microwave heating, can be used to electrify processes with low-cost renewable power, and may play a role in the development of more energy efficient WTX processes that can utilize nontraditional, low-carbon sources of energy.

Another challenge is the distribution of wastes over large geographical areas and the expense of transporting often low-density waste feedstocks to the plant. For example, a typical municipal WWTP produces the equivalent of 100 dry tons per day of sludge that could be converted into fuels, whereas biorefineries are typically expected to be 20 times this size to achieve economies of scale. The distributed nature of the waste feeds provides opportunities for smaller, modular systems that are built in a factory and deployed to the source of the feedstock. These modular processes could be sited at or near a WWTP, landfill, or farm to simplify feedstock transportation logistics, thus producing a smaller quantity of refined product that is more easily transported to the downstream consumer.

The modular chemical process intensification (MCPI) strategies championed by the RAPID Manufacturing Institute are well-suited to address the challenges of turning distributed low-value wastes into viable and sustainable products. RAPID is involved in innovation research to advance WTX process technologies, including:

- using adsorbents to purify and valorize low-quality natural gas
- using microwave catalysis to upgrade stranded carbon in shale gas to aromatics
- using graphene-oxide membranes to efficiently recover pulping chemicals from black liquor at paper mills
- developing low-carbon routes to produce renewable natural gas from dairy and food waste
- recovering purified water from industrial wastewater or the concentrated byproduct from reverse-osmosis plants.

Additional research, development, and demonstration work is needed for this vision of a more-circular chemical process industry to become a reality. As a first step, RAPID is planning a WTX conference — part of a new DEPLOY series on distributed, numbered-up processes — to convene stakeholders in early 2021. CEP