

Engineering circularity for absolute sustainability: from laboratory innovation to industrial scale

Abstract

The transition towards a circular industry requires more than innovative reactions or promising laboratory results. A technology becomes industrially relevant only when it can operate reliably at a larger scale, accommodate variable feedstocks, meet product specifications and integrate with existing plants and value chains. Chemical and process engineering therefore play a central role in transforming scientific advances into technically feasible, environmentally sound and economically viable solutions.

This contribution presents a methodological approach to the scale-up of circular technologies, moving from laboratory evidence to process understanding, pilot validation, plant design and industrial integration. Particular attention is given to the factors that often determine the success or failure of scale-up, including mass and heat transfer, continuous operation, feedstock variability, impurity management, product recovery, energy demand, process control and safety. Within this perspective, the main reactor represents only one component of a broader system that must also manage utilities, recirculation streams, residues and by-products.

The approach is illustrated through research activities focused on the valorisation of agro-industrial residues, food-processing side streams, organic waste, textile waste and composite materials. The investigated pathways combine chemical extraction, fermentation, anaerobic digestion, pyrolysis and integrated thermochemical and biochemical processes. Examples include the recovery of polyphenol-rich extracts from food by-products, the use of plant-derived side streams as potential components of culture media for cultivated meat, and the conversion of mixed textile waste into sugars, terephthalic acid and precursors for bioplastics. Further applications concern biochar production from biomass and industrial residues, carbon-fibre recovery from composite waste, two-stage anaerobic digestion for energy and fertiliser production, and the conversion of olive-mill wastewater into hydrogen and volatile fatty acids for subsequent biopolymer production.

These case studies show that waste valorisation cannot rely on isolated technologies. Effective circular processes require an integrated biorefinery approach in which each material and energy stream has a defined function or destination. Process simulation, life-cycle assessment and techno-economic evaluation support the comparison of alternative pathways and guide the transition from experimental performance to plant-level feasibility.

The resulting framework connects reaction engineering with industrial ecology and territorial resource management. It also highlights the importance of collaboration among universities, companies and local stakeholders. By designing complete, scalable and controllable processes, chemical and process engineering can turn heterogeneous residues into products, energy carriers and secondary raw materials, creating robust industrial routes that reduce waste generation and dependence on virgin resources.