Microwave-driven Catalysis Beyond Thermal Activation: Spatiotemporal Control for Energy-Efficient and Sustainable Polymer Upcycling

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This talk explores how microwave (MW) irradiation interacts with catalytic materials and molecular systems to unlock energy-efficient chemical processes through MW-initiated or enhanced catalysis. While conventional MW research has largely focused on dielectric heating in insulators or polar molecules, recent experimental evidence suggests that MW-driven reactions can extend beyond traditional thermal activation. Although localised heating has been proposed as an explanation, the inherently non-equilibrium nature of these systems points to the involvement of yet-to-be-explored physicochemical mechanisms.

Our work aims to address fundamental questions about the interdependent dynamics between MW-responsive materials, interfacial architectures, and stable molecules during bond activation. By shedding light on these interactions, we seek to achieve precise spatiotemporal control over the formation of reactive intermediates using MW, guiding reaction pathways towards desired products with greater energy and atom efficiency. As a model system, we investigate polymer depolymerisation using tailored MW-active tandem catalysts, designed to enable spatiotemporal control within a single reactor. This approach facilitates the one-step conversion of diverse polymers into hydrogen, carbon nanomaterials, constituent monomers, or value-added chemicals, depending on catalyst selection and design. By circumventing multi-step processes and minimising energy waste, this method represents a more efficient alternative to conventional recycling strategies.

To probe MW-induced interfacial phenomena—including transient hotspots and non-thermal electronic effects that drive selective bond cleavage—we are developing advanced in-situ and ex-situ characterisation methodologies. Demonstrating the interdependent behaviour between MW and catalyst materials will enhance our ability to control the formation of highly reactive intermediates with precision. Ultimately, this will pave the way for more energy- and atom-efficient chemical transformations, such as establishing a robust framework for circular plastic economies, where waste polymers are systematically regenerated into high-purity feedstocks.