# Integrated pyrolysis–steam reforming of biomass and plastic waste for renewable methanol production: experimental validation and process simulation

Mariangela Guastaferro, Federico Baglioni, Leonardo Tognotti & Cristiano Nicolella

University of Pisa, Department of Civil and Industrial Engineering, Largo Lucio Lazzarino 2, 56126 Pisa (Italy)

E-mail: mariangela.guastaferro@unipi.it

The transition to sustainable chemical processes is accelerating the development of technologies capable of converting heterogeneous waste into valuable fuels and chemicals. This research contributes to this effort by investigating an integrated thermochemical route for the conversion of non-recyclable biomass and plastic waste into renewable synthesis gas (syngas) suitable for methanol production. The work addresses two key challenges in chemical engineering: the valorization of mixed waste streams and the generation of low-carbon alternative fuels.

The proposed process is based on a two-stage configuration combining pyrolysis and catalytic steam reforming. In the first stage, biomass and plastic mixtures undergo thermal pyrolysis to produce volatile compounds. These are then processed in a second stage via catalytic steam reforming to generate hydrogen-rich syngas. Laboratory-scale experiments were conducted to evaluate feedstock conversion behavior and catalyst performance, using Ni-based catalysts supported on alumina and ZSM-5. The ZSM-5-supported catalyst demonstrated higher hydrogen yields and better resistance to deactivation.

To assess industrial viability, experimental results were used to develop a process simulation in UniSim® Design. The simulated plant, operating with a feed rate of 1000 kg/h, produces 706 kg/h of methanol with a purity of 99.8 mol% and an overall energy efficiency of 48.9%. The syngas generated meets the stoichiometric requirements for methanol synthesis and shows strong adaptability to variable waste compositions.

A lifecycle carbon analysis, performed in accordance with the European Renewable Energy Directive (RED III – Directive 2023/2413), indicated up to 81% reduction in $CO_2$ emissions compared to fossil-based methanol pathways. These results support the classification of the process as a renewable fuel technology and reinforce its relevance in the broader context of energy transition and climate policy.

Compared to conventional waste treatment or syngas production methods, the combined pyrolysis–steam reforming approach enables enhanced process control, reduced catalyst fouling, and efficient hydrogen production. The integration of experimental validation with process modeling underscores the potential of this route for scale-up and industrial implementation.

**Keywords**: *Waste-to-Fuel, catalytic steam reforming, renewable methanol*