From Waste Biomass to Hydrochar: A Circular Economy Strategy through Hydrothermal Carbonization

Federica Barontini [a], Marco Landi [b], Nicola Silvestri [b], Eleonora Stefanelli [a], Sandra Vitolo [a] & Monica Puccini [a]

[a] Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy
[b] Dip. di Scienze Agrarie, Alimentari e Agro-ambientali, Università di Pisa, via del Borghetto 80, 56124 Pisa, Italy

E-mail: federica.barontini@unipi.it

The transition to a circular economy and the reduction of waste are central goals of European environmental policy, as reinforced by the European Green Deal. In this context, hydrothermal carbonization (HTC) has emerged as a versatile thermochemical process well suited for the valorisation of wet waste streams without energy-intensive pretreatment. Operated under aqueous conditions at moderate temperatures (180–270 °C) and autogenous pressure, HTC converts biomass residues into a carbonaceous solid—hydrochar—whose potential applications range from solid biofuel and soil amendment to adsorbent media and electrode materials.

Our research was focused on a systematic investigation of HTC applied to different unconventional substrates: fractions from mixed municipal solid waste treatment, invasive alien species such as the aquatic plant *Myriophyllum aquaticum* for which reclamation authorities are obliged to carry out mandatory eradication, and agro-industrial by-products as brewer's spent grains, the main byproduct of beer production. Our objectives were to (i) demonstrate HTC feasibility on these substrates, (ii) elucidate the combined influence of process operating parameters (temperature, residence time, and solid load) on process yields and hydrochar characteristics, and (iii) assess hydrochar suitability for different applications. Laboratory-scale HTC experiments were performed using a Design of Experiment (DoE) – Response Surface Methodology (RSM) approach, enabling both individual and interaction effects of process variables to be modeled through non-linear parametric equations and optimal operating conditions identified. Results confirmed that HTC effectively processes all the feedstocks investigated, suggesting HTC as a promising treatment path for the production of hydrochar with multiple applications. Beyond the use as a biofuel, bioassay tests indicated negligible phytotoxicity for hydrochars derived from the different waste feedstocks, confirming the hydrochar potential for agronomic applications as organic growth medium or soil amendment.

By applying HTC across a variety of waste streams and employing DoE-RSM for process optimisation, we deepened insight into HTC process and highlighted hydrochar potential. The results demonstrate that HTC can be a win-win strategy for valorising diverse biomass residues—simultaneously reducing waste and generating valuable hydrochar for agricultural, energy, and environmental applications—thereby supporting scalable circular-economy frameworks across multiple sectors.

Keywords: *Hydrothermal Carbonization, DoE–RSM, Circular Economy, Sustainable waste management, Biofuel, Soil amendment*