Integration of anaerobic digestion with hydrothermal carbonization and gasification for the valorization of organic waste

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Abstract
The amount of organic waste produced has been dramatically increased due to the adoption of a linear economy approach, growing population, and increasing resource consumption (Atabani et al., 2021). More specifically, huge amounts of organic wastes (2 billion tones/year) are produced in cities from food and fibrous lignocellulose (Thygesen et al., 2021). Therefore, cutting-edge and effective ways to valorize waste should be investigated. In particular, this work focuses on an innovative strategy to valorize organic waste from an energy perspective.

Organic wastes are traditionally treated by landfilling, composting and incineration that need land/energy/cost requirements, and emit greenhouse gases and pollutants (Legge, 2021). However, several processes have been used for the production of sustainable energy from organic waste, such as anaerobic digestion (AD), hydrothermal carbonization (HTC) and gasification. AD is a technology for converting biomass into renewable gas (Daglioglu et al., 2024). HTC is an efficient method for the management of organic wastes with high moisture content that decreases the volume of wastes, increases chemical and biological stability and energy content (Ebrahimi et al., 2023). Gasification generates synthesis gas used in some industries such as chemical industries, fuel industries and power plants to produce thermal and electrical energy while releasing lower emissions than other thermochemical technologies (Chanthakett et al., 2021).

In general, the integration of biochemical and thermochemical processes has been recently known as a promising strategy for the valorization of biomasses under an energy perspective (Daglioglu et al., 2024). Transforming residues of AD into carbonaceous solid and liquid materials with the help of technologies such as pyrolysis and HTC has been received much attention (Parmar and Ross, 2019). HTC is a pretreatment method which utilizes water for breaking down the structure of the biomass under appropriate pressure and temperature for producing a coal-like material (i.e., hydrochar) via increasing the fixed carbon content and heating value of the feedstock. For instance, HTC can be used to decrease the problems related to the current digestate land spreading, while producing a fuel in the form of hydrochar (Pecchi and Baratieri, 2019). Subsequently, hydrochar can be combusted or gasify into gaseous products (H_2, CO_2, CO, and CH_4).

The integration of AD, HTC and gasification was evaluated by Attasophonwattana et al. for valorization of empty fruit bunch and their conversion into green electricity (syngas and biogas), fuel alternatives (char and tar) and carbon precursors (char) (Attasophonwattana et al., 2022). Another study reviewed the integration of AD with HTC and steam gasification and reported that hydrochars produced the highest H_2 yield when pre-treatment with AD compared to non-pretreatment (Daglioglu et al., 2024). Seemingly, the integration of AD, HTC and gasification increases process efficiencies and product quality.

Although there are studies reviewing the integration of these processes, the details have not been elucidated yet. Therefore, further research is needed to fill this gap.

In this study, each process unit (AD, HTC and gasification) has been analyzed in detail in terms of energy and mass balance and different scenarios were investigated to demonstrate the advantages that this solution could offer.

The integrated process under investigation is described below.
Firstly, an AD step is foreseen during which biogas and digestate are produced. Biogas is mainly composed of CH_4 and CO_2 in different percentages (dos Santos et al., 2020), (Scano et al., 2014), while digestate is essentially composed of water. This is because biogas originates from the total solids fraction (and in particular from volatile solids) of the substrate. After AD, digestate enters the HTC unit, where hydrochar is produced. Subsequently, part of hydrochar can be transferred into the gasification section and the rest to AD. Indeed, hydrochar is used as a source of total solid for AD and produces methane. Gasification produces char, tar and gas mainly composed of CO_2, H_2, CH_4 and CO. A standard gas is composed from 25% CO_2, 20% CO, 45% H_2 and 10% N_2 (Postacchini et al., 2023). A schematic view of integration is depicted (see Figure 1).

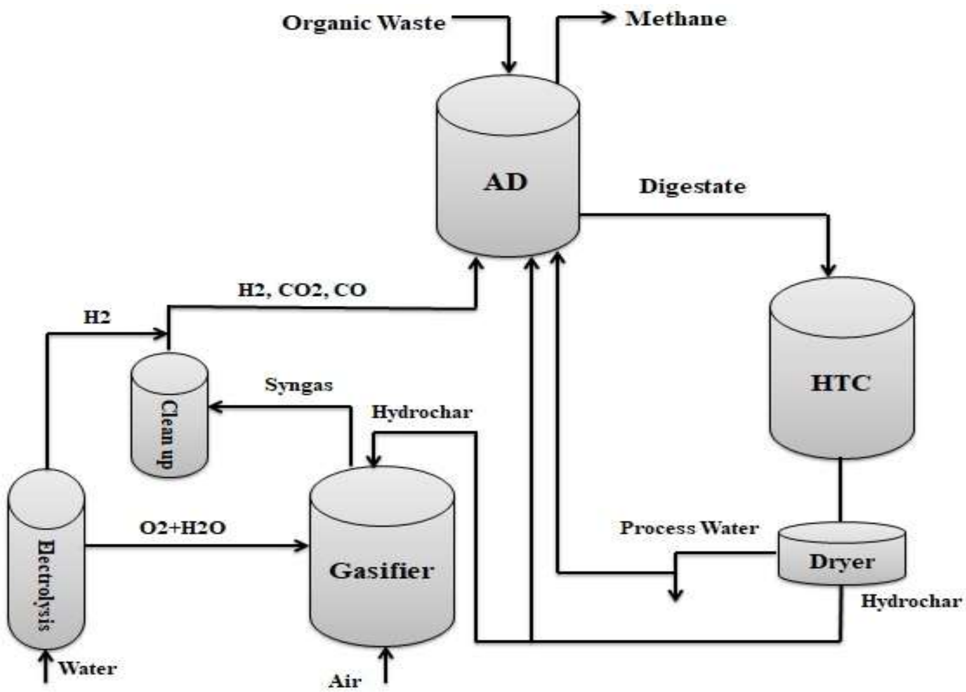

Figure 1: Schematic view of the integration of AD, HTC and gasification

Gas could also enter the AD process to foster methane production. Thus, produced gas not only needs to pass through a cleaning step, but also needs to be enriched with H2 to meet the composition requirements for further methanation. Therefore, gas could be mixed with H2 from an alkaline electrolyzer, condense and finally pass through a pressure swing adsorption unit for the removal of residual CO2, CO, and other impurities (Menin et al., 2021).

The ultimate goal of this integration is to valorize organic waste, minimizing losses and by-products, while increasing methane production through the application of a circular approach. . Products in each phase can be used in next phase and thus, decrease the requirement for external materials. Moreover, combining biochemical (with lower energy requirements) and thermochemical (with higher energy requirements) processes decreases energy consumption and could allow for a positive energy balance.

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