Maximising bio-oil yield from industrial dairy sludge: a paradigm on pyrolysis temperature and heating rate in the context of the EU FLEXBY project

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Introduction

The dairy industry produces significant quantities of sludge, which is characterised by its high organic content. If these by-products are not recovered, they are classified as wastes and therefore have to be managed as such, which entails a number of environmental and economic disadvantages. The physical and chemical characteristics of biological sludge generated in wastewater treatment processes depend on the type of wastewater treated and the treatment processes employed.

As the world increasingly transitions away from fossil fuels, recycling different industrial residues into biofuels is emerging as an environmentally and economically sustainable strategy. Pyrolysis, defined as the process of thermal decomposition of a substance in the absence of oxygen, has been extensively studied for the purpose of converting residue into biofuels, with conventional pyrolysis being the most widely used method. Several experimental variables, such as pyrolysis temperature or heating rate, play a crucial role in determining the yield and quality of the final biofuel products (Kaur et al. 2015). Lower temperatures tend to favor the production of biochar, while higher temperatures enhance the yield of liquid bio-oil and gas (Vilas-Boas et al. 2021). Slow pyrolysis is the most effective technology for high-yield biochar production, while fast pyrolysis provides higher bio-oil yields, and intermediate pyrolysis produces a balanced distribution of biochar, bio-oil and gas (S. Safarian, 2023). The conversion of dairy sludge into biofuels through pyrolysis processes offers a comprehensive value proposition for the management of such waste, while reducing dependence on fossil fuels and promoting sustainable energy practices.

The aim of this study is to assess the feasibility of using sludge from the dairy industry to produce biofuels or biomaterials through conventional pyrolysis processes, where temperature and heating rate will be the main parameters of study.

Methodology

The residue is a biological sludge of a dairy industry located in the north of Spain. The company, with a 175-year history, specialises in the production and marketing of dairy products. Given the industrial nature of the waste, the sludge sample was meticulously collected, dried and prepared to a particle size that was suitable for characterisation and pyrolysis (≤1 mm).

The dairy sludge sample was characterised to determine its physico-chemical properties and suitability for use in pyrolysis processes. This was done by studying its proximate and ultimate analyses, as well as other relevant analyses. Thermogravimetric analysis showed the evolution of the sludge residue with temperature.

The conventional pyrolysis was carried out using a cylindrical, electric, horizontal oven of original design. The sample (7-8g) was put into the oven at room temperature. Nitrogen gas was flowed at 100 ml/min to create an inert atmosphere inside the reactor. The furnace was heated at different speeds (25°C/min or 5°C/min), reaching different pyrolysis temperatures between 450 and 750°C and the sample was held at the final temperature for one hour. After pyrolysis, bio-char, bio-oil and gas fractions were studied.

Results

The sludge waste has a high carbon content of 44.2%. Proximate analysis showed a moderate ash content (22.6%) in the residue, which will favour the production of biochar in the pyrolysis process with a composition suitable for alternative applications (fertilizers, activated carbon precursors). Proximate analysis also indicated a remarkably high volatile matter content (79.8%), which will favor a considerable yield of the liquid and gaseous fractions. The chlorine content is significantly low (0.052%), indicating that the biomass is suitable for its application in pyrolysis, as the risk of corrosion during the thermal process of the substance is minimised. The ash fusibility analysis provides key findings: the initial deformation temperature is 1336 °C, indicating that the ashes do not deform until very high temperatures are reached.

The yield of the solid, liquid and gas fractions is contingent on the experimental conditions of the pyrolysis process (i.e. temperature and heating rate). Pyrolysis processes have been carried out at a heating rate of 25 °C/min and at different temperatures (450, 500, 600 and 750) to verify that, at low temperatures, the majority fraction of bio-oils is obtained. The bio-char, bio-oil and gas yields as a function of temperature can be seen in **Fig. 1.** Once the optimal temperature for the experiment had been established, further tests were conducted in which the heating rate was modified. The results indicate that, at 500°C, a higher heating rate (25°C/min) favors a higher yield of the bio-oil fraction, **Fig. 2**.

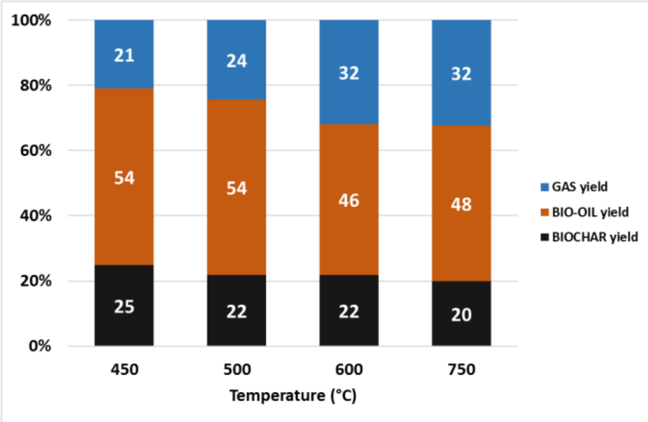

Fig. 1. Pyrolysis fraction yield. Effect of the temperature.

Conclusions

Ultimate and proximate analysis indicates that dairy sludge possesses good properties for use in pyrolysis processes to produce biofuels or biomaterials. The European Flexby Project has been conceived with the objective of developing heavy biofuels for the transport sector. As part of the project, the sludge from the dairy industry was subjected to conventional pyrolysis at different experimental variables in order to optimise the bio-oil yield. Through the strategic variation of the conventional pyrolysis process parameters (temperature and heating rate), it was determined that low temperatures (450 and 500 °C) and a moderate heating rate (25 °C/min) yield optimal bio-oil fractions, with up to 54% yield. These tests have confirmed that the biosludge has the ideal characteristics to be transformed into a high value-added product in the context of the circular bio-economy.

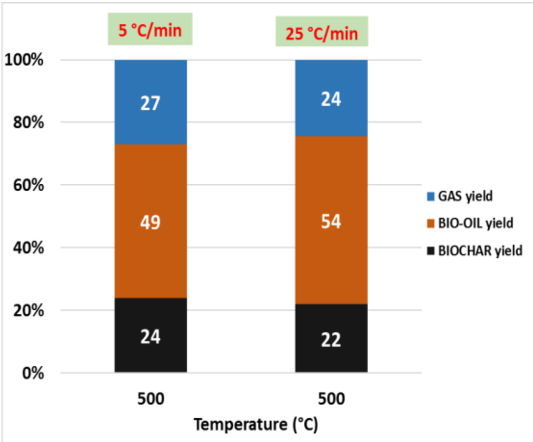

Fig. 2. Pyrolysis fraction yield. Effect of the heating rate at 500°C.

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