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Multiscale scheme for the optimal use of residues for the production of biogas across Castile and Leon

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ABSTRACT.

This work evaluates the exploitation of four different types of waste for the production of biogas and fertilizer using a feedback multiscale analysis approach. The yield of sludge, manure, municipal solid wastes (MSW) and lignocellulosic residues is evaluated and the kinetics of the anaerobic digestion of each of these residues is determined by performing a parameter estimation using experimental data. It turns out that hydrolysis is the limiting stage. Next, a techno-economic evaluation of a processing facility is carried out. Finally a supply network model is developed to evaluate the optimal use of the residues over a region in Spain. The network is formulated as a mixed integer linear programming problem selecting the type of residue, the number and size of the digesters and the location of the plants across 59 shires of a particular region in Spain for the available budget. MSW is the selected waste due to its wide availability and large yield to fertilizer. Lignocellulosic residues are the second best option. Only intra-shire transport is suggested. The shires selected for waste processing are rather scattered as a function of the resources available and the already installed facilities. However, the amount of residues available can provide more than three times the region demand for natural gas, but the budget required adds up to more than $4.4 \cdot 10^9$ €

1. Introduction

Developed societies generate large amounts of different types of waste. In the European Union, 0.5 t of waste are produced per person and year (Eurostat, 2017). Not only the large volume but also the composition becomes a challenge. Processing waste requires large and costly facilities, but it is required to avoid dangerous effects on the environment. Anaerobic digestion is a technology that is capable of both, processing and generating added value out of waste. Two main products are obtained, biogas, a mixture of methane and CO_2, and digestate, which can be used as fertilizer. This kind of facilities can be considered as part of the so-called circular economy (Circle Economy, 2016), aiming at the reuse of waste to add value to residues extending their lifespan (Lieder and Rashid, 2016).

European consumption of natural gas has been increasing since the 70's, resulting in the fact that approximately 60% of that demand is covered via imports. However, the actual potential for the production of methane from residues is not exploited yet. Currently, Germany is the country with the largest biogas production sector, approximately half of the biogas production facilities in Europe are installed there. The theoretical potential of primary energy production from biogas in 2020 is assumed to be 166 Mtoe. However, a more realistic value corresponds to 39.5 Mtoe (AEBIOM, 2016). Biogas is a flexible raw material since, apart from its value as a source of power (León and Martín, 2016), it can also be used for the production of chemicals via dry reforming (Hernández and Martín, 2016). The composition of the residues determines their possible use as biogas, as fuel or to obtain syngas for the production of chemicals such as methanol, ethanol, dimethyl ether (DME) or Fischer-Tropsch liquids. The selection of the type of waste used depends on the credit obtained from the digestate. The selling price of the digestate is a complex issue and the estimation method affects the type of waste selected (Hernández et al., 2017). Furthermore, the possibility of producing digestate, rich in nutrients, together with syngas allows the development of an integrated facility for the production of biodiesel. In this process both, the oil, which is produced by using digestate to provide nutrients to grow algae, and the biogas, which is dry reformed into syngas to produce the methanol

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required for the transesterification, are obtained from the anaerobic digestion of waste (Hernández and Martín, 2017).

Numerous studies on the production of biogas from various waste types are available to determine the yield, i.e. for fruit waste (Lattieff, 2016), to optimize that yield (Dahunsi et al., 2017) and to evaluate the kinetics (Weinrich and Nelles, 2015). It can be seen that each raw material presents a different kinetic rate due to its physical structure, leading to a trade-off between yield and tank size (for sludge i.e. Astals et al., 2013; for solid waste, i.e. García-Gen et al., 2015; for agricultural crops, i.e. Weinrich and Nelles, 2015). Literature on the use of waste comprises different types of studies. Some groups focused on general studies on biomass and waste availability and their potential towards biogas (Haider, 2011). Other studies evaluate the effects that waste processing can have on employment as a means to develop agricultural areas (Guenther-Lübbers et al., 2016). Stucki et al. (2012) determined the environmental impact of the production of biogas from various waste sources, while Ertem et al. (2017) compared the impact of biogas production using waste instead of energy crops. Moreover, some studies aim at planning the sustainable use of just one type of waste, i.e. municipal solid waste (Santibañez-Aguilar, 2013). However, to the best of our knowledge, there is no systematic study to evaluate the use of the various residues and the cost and selection of them. The proper selection of waste depends on the yield to biogas and to digestate, the local availability of the resources and its transportation, and the investment to build the processing facilities. The tank size and the digestion kinetics determine the actual yield of the facility from a particular raw material. The link between the reactor yield and the usage and selection of the type of waste requires the use of a multiscale analysis to evaluate the potential of each type of waste. Recently, Floudas et al. (2016) presented a review on the use of multiscale analysis. In that work, apart from the methodology, several examples were presented such as the case of CO_2 capture and utilization or thermo-chemical routes for biomass processing to chemicals and fuels. These cases of study comprise the evaluation of four scale levels: first the molecular level, to design the appropriate adsorbent materials, second, the scale of individual process units, a third scale at the level of the entire process design and, finally, the evaluation of the supply chain level.

In this paper the use of four types of residues, namely, sludge, manure, lignocellulosic residues and municipal solid waste (MSW), for the production of biogas and digestate is evaluated as an alternative to treat waste, generating further value out of it and determining the actual potential of the residues available. However, the various compositions of the residues require the proper digester design, resulting in trade-offs between the yield to biogas and the degradation kinetics. Thus, first the kinetics of the four types of waste is evaluated to determine the proper reactor design and yield. Next, a techno-economic evaluation of a facility that processes waste into digestate and biogas is carried out. Finally, a supply chain approach is presented to study the use of the residues across a region in Spain, Castile and Leon, with 94,223 km^2 and 2.478 million inhabitants, and characterized by its agricultural economy. The rest of the paper is structured as follows. In section 2 the multiscale scheme for the analysis of the potential of the waste within a region is presented, including the modelling effort at reactor, plant and supply chain scales. Section 3 shows the results of the kinetics for each of the four residues evaluated, the techno-economic analysis of a plant, the location of the processing facilities and the selection of the type of waste. Section 4 comments on some final remarks.

2. Methodology

The use of various residue types depends not only on their availability but also on the yield towards valuable products, biogas and digestate. Thus, the design and operation of such systems have to be evaluated within a multiscale framework, from the process unit to the supply chain. Due to the strong link between the various scales, a feedback analysis is required. Processing data and costs are required at supply level, but waste usage and investment decisions can only be made by solving the problem at supply chain level. First, the operation of the plant for each of the residues that can be processed, namely, sludge, lignocellulosic residues, MSW and manure is evaluated. The residence time in the reactor is a direct function of the residues physical structure. Therefore, for the same reactor size, typically standardized, the yield is different as a function of the kinetics. Next, a full production facility is evaluated including a techno-economic evaluation to determine the investment and production costs. The processing plants may be located at different shires within the area of study. Finally, at a macroeconomic level, a supply chain study is developed to determine the actual use of the residues and the size and number of facilities to be installed, considering availability, transportation cost and feasibility depending on the yield to products of each raw material.

Thus, this section is divided into three parts. First, the flowsheet of the process that processes the various residues is described. The performance of the anaerobic digester is evaluated developing a kinetic model for each of the residue types. A parameter estimation approach using experimental data from the literature is used. Subsequently, an economic evaluation of the facility is carried out. Finally, those results are used to build a supply chain network model that provides information on the most efficient use of the residues for a limited budget.

2.1. Process description

Wastes such as manure, sludge, urban residues or lignocellulosic crop residues are processed in an anaerobic digester. However, the reaction must take place under certain conditions so that the yield computed is achieved. The solids in the digester must not surpass 10% by weight in water (Shi et al., 2017). Thus, a mixer is added to the process, M-01, and a heat exchanger, IC-01, to prepare the feed for the digester, R-01. Each residue has a characteristic residence time to reach the plateau of the conversion. For each residue, the residence time is assumed to be that corresponding to 95% of the maximum methane production, to avoid longer residence times for a small increase in the production capacity. The digester operates isothermally by means of an external heat exchanger, IC-03, to maintain the temperature over time due to the endothermic reactions taking place. pH is controlled above 6.8. The gas is cleaned up from ammonia using a scrubber, and from H_2S and CO_2, using a multibed pressure swing adsorption (PSA) system (Miltner et al., 2017). Before feeding the gas to the scrubber, it has to be compressed to 4.5 bar, C-01, and cooled down to 298 K at IC-02. The digestate is filtered recovering water, F-01, that is recycled and reused in the scrubber. The cake recovered at F-01 is stored to be sold as fertilizer. The water is, after proper treatment, M-02 and F-02, reused. It is out of the scope of this work to evaluate the water treatment to remove the ammonia dissolved. Fig. 1 shows the flowsheet of the facility. The number of digesters is given by the trade-off between the investment, the availability of the type of waste and the added value of the biogas and fertilizer produced.

The economic evaluation of the facility is carried out using the factorial method (Sinnot, 1999) that computes the investment cost of a facility as a function of the equipment cost. The costs of the heat exchangers and the vessels are estimated using the information in Almena and Martín (2016) that relates the units