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Optimisation of substrate blends in anaerobic co-digestion using adaptive linear programming

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HIGHLIGHTS

- Optimisation method to calculate feedings of anaerobic co-digestion processes.
- Method based on linear programming aiming at maximising methane production.
- Validated in a continuous co-digestion experiment at pilot scale (UASB-AF reactor).
- Results accurately predicted with an ADM1-based anaerobic co-digestion model.

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ABSTRACT

Anaerobic co-digestion of multiple substrates has the potential to enhance biogas productivity by making use of the complementary characteristics of different substrates. A blending strategy based on a linear programming optimisation method is proposed aiming at maximising COD conversion into methane, but simultaneously maintaining a digestate and biogas quality. The method incorporates experimental and heuristic information to define the objective function and the linear restrictions. The active constraints are continuously adapted (by relaxing the restriction boundaries) such that further optimisations in terms of methane productivity can be achieved. The feasibility of the blends calculated with this methodology was previously tested and accurately predicted with an ADM1-based co-digestion model. This was validated in a continuously operated pilot plant, treating for several months different mixtures of glycerine, gelatine and pig manure at organic loading rates from 1.50 to 4.93 gCOD/L d and hydraulic retention times between 32 and 40 days at mesophilic conditions.

1. Introduction

Anaerobic co-digestion (AcoD) stands for the simultaneous digestion of two or more substrates and its benefits rely on the enhanced performance of the process compared to anaerobic digestion (AD) due to potential synergies among the co-substrates. Thanks to their complementary characteristics, co-digestion can increase biogas production (Mata-Alvarez et al., 2011), and achieve other environmental, technological and economic advantages: a more efficient use of equipment and cost-sharing by processing multiple waste streams in a single facility (Alatriste-Mondragón et al., 2006), or lower greenhouse gas emissions and climate change impact in comparison to composting or anaerobic mono-digestion (Krupp et al., 2005).

As anaerobic digestion involves complex biological pathways, the efficiency of the overall process can be affected by different factors such as composition of substrates, temperature, pH, moisture, carbon to nitrogen ratio (C/N), organic loading rate (OLR) or microbial consortia (Khalid et al., 2011). Different studies suggest thresholds for the key parameters of AD in order to guarantee the stability of the operation, for instance, in terms of C/N ratio (Burton and Turner, 2003; Bouallagui et al., 2009), lipid concentration (Neves et al., 2009; Palatsi et al., 2009), moisture (Mata-Alvarez et al., 2000), alkalinity (Cuetos et al., 2008), salinity (Jard et al., 2012), volatile fatty acids (VFA) concentration (Ahring

Abbreviations: AcoD, anaerobic co-digestion; AD, anaerobic digestion; ADM1, Anaerobic Digestion Model No. 1; BMP, biochemical methane potential; C/N, carbon to nitrogen ratio; C/S, carbon to sulphur ratio; COD, chemical oxygen demand; CODs, soluble chemical oxygen demand; CODt, total chemical oxygen demand; F/M, feed to microorganism ratio; HRT, hydraulic retention time; OLR, organic loading rate; SRB, sulphate reducing bacteria; SRT, solids retention time; TKN, total Kjeldahl nitrogen; TS, total solids; UASB-AF, Upflow Anaerobic Sludge Blanket – Anaerobic Filter reactor; VFA, volatile fatty acids; VS, volatile solids; VSS, volatile suspended solids.

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et al., 1995; Nielsen et al., 2007) or sulphide in biogas (Peu et al., 2011).

Selecting the blend of substrates leading to a stable AcoD operation is not trivial as it requires knowledge and expertise on the process. The proportions of the substrates should be adequately balanced to ensure the key parameters of AD are within the ranges for stable operations. According to this, different optimisation methods can be found in the literature trying to achieve optimum blends. The conventional method consists of lab-scale batch assays with different proportions of co-substrates to evaluate the digestibility and methane potential of the different mixtures (Alatriste-Mondragón et al., 2006). Other optimisation methods include: (i) neural networks to increase the biogas production of full-scale digesters (Abu Qdais et al., 2010; Thorin et al., 2012), (ii) response surface methodologies to optimise feeding composition and C/N ratio (Wang et al., 2012), (iii) simplex-centroid mixture design and central composite design to optimise the feeding with higher methane potential (Wang et al., 2013), and (iv) linear programming approaches to obtain the optimum blend of co-substrates that maximises methane production (Alvarez et al., 2010).

Any optimum blends obtained with the different methods should be validated in continuous experiments, to confirm the long term feasibility of those mixtures. In this sense, and considering that continuous experiments are very time-consuming, models appear as a very useful tool to assess promptly the viability of different blends in continuous AcoD operations. The IWA Anaerobic Digestion Model No. 1 (ADM1) (Batstone et al., 2002), which describes the main processes involved in anaerobic digestion (disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis), has been widely used as standard model for AD systems and also adapted to simulate continuous AcoD processes (García-Gen et al., 2013; Mata-Alvarez et al., 2014).

The main purpose of this work is to develop an optimisation method based on linear programming for the feeding of AcoD systems in order to obtain higher methane productivities, achieve higher COD removal efficiencies, meet the required biogas quality and ensure the stability of the operation.

The optimum blends calculated with the proposed methodology were initially tested with the ADM1-based AcoD model (García-Gen et al., 2013) and then validated with a continuous AcoD experiment performed at pilot scale, treating different blends of three substrates (glycerine waste, gelatine and pig manure) at different organic loading rates (OLR) and hydraulic retention times (HRT) at mesophilic conditions.

2. Methods

2.1. Linear programming optimisation method

To set up a linear programming problem, an objective function and a set of linear restrictions should be defined. In this study, both objective function and restrictions are calculated based on the physicochemical characteristics and the biochemical methane potential (BMP) of each substrate. The objective function is the methane production expected in a continuous AcoD system treating a mixture of substrates and the linear restrictions include the typical characteristics of AD systems (defined based on heuristic knowledge). Finally, the set of equations and the values of the restrictions can be adapted to each particular case (e.g. end use of the biogas, or characteristics of the soil where the digestate is applied). The methodology not only solves the proportions of the substrates in the blend (Alvarez et al., 2010) but also provides the HRT, a key operational parameter for continuous systems.

The method was implemented in MATLAB and makes use of two default functions, '*linprog*' to calculate the blend of substrates maximising the objective function at each HRT applied, and '*fminbnd*' to find the best HRT that optimises the methane productivity. Moreover, the linear programming optimisation informs about the restrictions that are actively limiting and that could be modified to move the operation towards a new potential optimum with a higher methane production. '*Linprog*' function returns the values of the Lagrange multipliers related to each restriction (different from 0 when they are active) that can be used to estimate what constraint mostly limits the value of the objective function. For instance, for a system with two active restrictions, the gradient of the objective function can be written as: $\nabla \boldsymbol{f} = \lambda \nabla \boldsymbol{g} + \mu \nabla \boldsymbol{h}$, where vector $\boldsymbol{f}$ stands for the objective function; vectors $\boldsymbol{g}$ and $\boldsymbol{h}$, refer to the active restrictions; and λ, μ are the Lagrange multipliers related to each restriction. In the proposed optimisation method, the information of these multipliers will be used to assess the importance of each restriction in obtaining a new value of the objective function. The constraint with a higher Lagrange multiplier will be considered the most limiting restriction.

2.1.1. Objective function

The assembly of the objective function is presented in Fig. 1. Experimental information from BMP assays is used together with substrate COD content to define the objective function, the methane production, expressed in OLR units (gCOD/L d).

The HRT of the system is calculated from the BMP tests of all substrates. This approach considers that the expected methanation of each individual substrate treated in a continuously-operated reactor working at a particular HRT would be similar to the methanation obtained in a BMP assay at a time equal to the HRT applied.

The method calculates the optimum blend and the value of the objective function at each time point of the batch tests with the '*linprog*' function. Then, '*fminbnd*' finds the time (HRT) at which the highest value of the objective function is obtained.

Therefore, the objective methane production depends on the volumetric fraction of each substrate in the blend (x_i), on their total COD contents (CODt) and the percentages of methanation (pMet) from the BMP tests of all substrates at a time equal to the selected HRT. Finally, in order to express the productivity of methane in OLR units (gCOD/L d), the equation is divided by the HRT, which it is the same value for all the substrates, so that the equation remains linear.

2.1.2. Linear restrictions

The set of linear restrictions is established based on the knowledge of the AD process and are defined based on typically available substrate characteristics. As AcoD systems can be performed at different operating conditions (OLR, temperature), at different stages (start-up, dynamic or steady-state operations), treating a wide variety of substrates or pursuing different objectives (end uses of the biogas and digestate), the set of restrictions applied to the linear programming problem should be appropriately selected according to the case.

Particularly in this study, maximum and minimum values for the following parameters were defined: (i) organic loading rate (OLR); (ii) total Kjeldahl nitrogen (TKN); (iii) moisture or liquid fraction; (iv) lipid content; (v) total alkalinity; salinity as (vi) Na^+ concentration and (vii) K^+ concentration; (viii) H_2S content in biogas; (ix) effluent COD content. Table 1 shows the intervals of all restrictions considered at the startup and they can be modified along the operation.

The maximum OLR might appear as somehow restrictive but it was selected in accordance with the typical values used in the start-up stages of AD operations. The maximum TKN allowed in the blend is 4 g-N/L (Chen et al., 2008) in order to prevent inhibitory concentration of ammonia. With regard to liquid fraction restriction, a high liquid fraction was required to operate this par-