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Blending based optimisation and pretreatment strategies to enhance anaerobic digestion of poultry manure

Ivan Rodriguez-Verde *, Leticia Regueiro, Juan M. Lema, Marta Carballa

Department of Chemical Engineering, Institute of Technology, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Spain

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ABSTRACT

Anaerobic digestion of poultry manure is limited by the excessive levels of nitrogen and the high concentration of dry matter. These limitations are usually overcome either by applying procedures to remove nitrogen or by employing pretreatments that allows to solubilise organic matter. In this work, the treatment of poultry manure was enhanced by co-digestion with pig manure through the methodological determination of optimal mixtures combined together with a thermochemical pretreatment coupled to ammonia stripping. The optimum poultry-pig mixture, resulting in a 24%:76% (volume basis) poultry-pig manure, was determined by applying a methodology based on linear programming which calculates the proportions of the blend which returns the maximum methane production while keeping a stable process. Pretreatment batch experiments, consisting of increasing both temperature and pH simultaneously with ammonia stripping process was optimised for a temperature of 90 °C and a pH of 10 resulting in a nitrogen removal efficiency of 72% and a 1.2-fold higher methane production in comparison to the unpretreated mixture. Continuous anaerobic co-digestion of pretreated optimum mixture enhanced the COD removal efficiency by 37% when compared with the treatment of unpretreated feedstock (37% vs 27%, respectively). This study indicates that combining blending optimisation of substrates, thermochemical pretreatments and ammonia stripping procedures prior to anaerobic co-digestion becomes a good strategy to overtake the limitations offered by solid- and nitrogen-rich substrates, such as poultry manure.

1. Introduction

In European Union 113 millions of tons of poultry manure are yearly generated (Foged et al., 2012). This residue was traditionally applied on land as agricultural amendment due to the valuable nutrient content (Thangarajan et al., 2013). Nevertheless, the direct application of manure on land may provoke severe effects to the environment such as greenhouse gas emissions, odour related issues, eutrophication or releasing of pathogens in the groundwater, among others (ten Hoeve et al., 2014). This barrier is successfully overtaken by applying efficient treatments to manure such as anaerobic digestion (AD) (Nasir et al., 2012; Rodriguez-Verde et al., 2014a; Sakar et al., 2009). Organic wastes with high and readily biodegradable organic matter content are preferably treated by AD because higher biogas production are expected, thus improving both economic and environmental profiles (Rodriguez-Verde et al., 2014a). Poultry manure (PoM) presents high levels of organic matter (>300 g O_2/kg); however, the total solid content (>25%) and the nitrogen concentration, up to 30 g N-TKN/kg, most as urea (Kelleher et al., 2002; Tiquia and Tam, 2000) are the two main factors hampering the anaerobic digestion of PoM. The high dry matter content limits the processing in conventional digestion systems (Chamy et al., 2012) which is further aggravated due to the reduction of the methane potential caused by the high lignocellulosic fraction coming from the bedding material (sawdust and straw) (Ahring et al., 2015; Güngör-Demirci and Demirer, 2004; Sun et al., 2016). Moreover, the high protein content may conduct to the formation of free ammonia during AD, which was already demonstrated to be an inhibitor for the process (Regueiro et al., 2012; Yenigün and Demirel, 2013).

To overcome these limitations, several strategies to enhance PoM treatment were evaluated, such as anaerobic co-digestion (ACoD) or pretreatments prior AD. ACoD compensates the lack of appropriate characteristics of PoM for AD, such as the humidity content and the C/N ratio (Abouelenien et al., 2014; Li et al., 2014; Sun et al., 2016). Within the agroindustrial waste treatment framework, pig manure (PM) is a very suitable substrate for ACoD due to its high humidity and excellent buffering capacity (Regueiro et al., 2012). Nevertheless, the proportions of the substrates should

* Corresponding author.
E-mail address: ivan.rodriguez@usc.es (I. Rodriguez-Verde).

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be adequately balanced to ensure the stable operation and also to provide the highest methane production. In order to define the optimal mixture of substrates for ACoD, several procedures have been applied: blending of substrates based on trial-and-error with different proportions of co-substrates in batch experiments (Alatriste-Mondragón et al., 2006), response surface methodologies (Wang et al., 2012) or linear programming to maximize methane production (Álvarez et al., 2010). The latter was further improved by García-Gen et al. (2015) combining both optimization and control principles in order to establish blends that maximise methane production while keeping a suitable reactor performance. Pretreatment of slowly biodegradable substrates prior to AD or ACoD is often encouraged in order to speed up and/or increase their methane potential either by making accessible some organic material or removing toxic compounds for the anaerobic process (Monlau et al., 2012). Accordingly, different methods were employed to improve the degradation of PoM such as a) thermochemical pretreatment (Costa et al., 2012), consisting of applying a temperature of 90 °C, an alkali dose of 0.2 g_{lime}/g TS_{waste} and a pressure of 1.27 bar; b) chemical pretreatment (Ardic and Taner, 2005) by the addition of NaOH (20% of the total solid content) at high temperature (boiling temperature of water); and c) biological co-treatment (Costa et al., 2012) by the bioaugmentation with *C. cellulollyticum*, *C. thermocellum* and *C. saccharolyticus*. The different methods applied to PoM resulted in the improvement of the organic matter solubilisation of PoM, however,the nitrogen concentration remained at high levels probably limiting the methane yield improvement, thus being necessary complementary or alternative methods to diminish ammonium content (Zhang et al., 2012). In this line, several strategies have been used in literature such as struvite precipitation or ammonia stripping (Rajagopal et al., 2013). The former achieves an appropriate performance when liquid streams are considered and when a high fraction of phosphorus is present, such as leachates, urine or swine wastewater (Kumar and Pal, 2015). Similarly, ammonia stripping was successfully proved (ammonia removal efficiencies higher than 80%), but mainly with low solid concentration streams either prior to anaerobic digestion (Bonmatı and Flotats, 2003; Laureni et al., 2013) or during AD process (Abouelenien et al., 2009). However, enhancing the anaerobic digestion of complex substrates such as poultry manure leads to the application of methods combining ammonia removal, co-substrates blending optimisation and solubilisation of organic matter.

Therefore, the aim of this study was to enhance anaerobic treatment of poultry manure through co-digestion with pig manure: i) by determining the optimum poultry-pig mixture by linear programming methods, and ii) by applying a thermochemical pretreatment based on the application of both high temperature and pH combined with ammonia stripping to enhance anaerobic biodegradability and remove nitrogen.

2. Materials and methods

2.1. Wastes and inoculum

PoM was collected from a poultry farm with a 4-replacement cycle ratio per year of 20,000 chickens and it consisted of a mixture of manure and bedding material, composed by sawdust and straw. After collection, PoM was stored at 4 °C throughout the experimental period. PM was taken from a pig fattener farm with a total herd of 3000 heads. Several batches of PM, which were stored at 4 °C, were needed throughout the experimental period.

Both wastes were characterised in triplicate in terms of total (TS, g TS/kg) and volatile (VS, g VS/kg) solids content, total and soluble chemical oxygen demand (COD_t and COD_s, g O_2/kg), total Kjeldahl nitrogen (TKN, g N-TKN/kg), total ammonium nitrogen (TAN, g N-TAN/kg), pH, alkalinity (g $CaCO_3$/kg) and biomethane potential (L CH_4/kg_{VS} and L CH_4/kg_{waste}). Furthermore, the lignocellulosic content of the PoM was determined in terms of lignin, hemicellulose and cellulose concentrations.

The inoculum used in both biochemical methane potential (BMP) tests and anaerobic reactors was flocculent biomass (15 g VS/kg) coming from a mesophilic digester treating sewage sludge of a municipal wastewater treatment plant.

2.2. Determination of optimum mixture and operational conditions

In order to determine the optimum PM:PoM mixture and operational conditions, the ACoD of pig and poultry manure was simulated using the Optiblender tool developed at University of Santiago de Compostela (ES2156615, 2014), which consists of three steps: determination of optimum mixture (Blender) according to the procedure developed by García-Gen et al. (2014), the simulation of the co-digestion process (virtual plant) using the "ADM1-based ACoD model" developed by García-Gen et al. (2015) and the optimization of the process based on two diagnosis variables (Optimiser).

The blending protocol (Blender) is based on a linear programming optimisation software, which calculates the mixture that maximises methane production and the optimum hydraulic retention time (HRT) mantaining a stable operation according to a set of linear restrictions based on the heuristic knowledge of the process. From the feeding composition and the HRT, the organic load rate (OLR) is determined. In addition, blender also informs about the active restriction, that is, the boundary that limits the optimisation towards a new potential optimum.

The anaerobic co-digestion of this mixture is then simulated in the Virtual Plant and the results are evaluated. For diagnosis in Optimiser, two variables are used: reactor stability, which is determined by alkalinity ratio (relation between intermediate alkalinity, associated with volatile fatty acids (VFAs), and the total alkalinity) and methane yield. The values given by the virtual plant are compared to the target values (set-point), 0.3 and 15 L CH_4/L d for alkalinity ratio and methane productivity (García-Gen et al., 2015), respectively, and the result of this comparison will allow reformulating the boundaries of the active restrictions, deriving in the calculation of a new optimum mixture, HRT and OLR.

In summary, a closed loop is proposed: blending formulation, simulation of the co-digestion process and diagnosis, modification of active restriction boundaries and again blending formulation. The inputs required for the application of Optiblender are the physico-chemical characterisation and the BMP of wastes, the initial restrictions (Table 1) and a simulation time (200 days were considered in this study). The outcome is a mixture producing the highest methane possible under safe conditions, which was referred as max(PM:PoM) mixture, and the optimum HRT.

Table 1
Initial set of linear restrictions considered for the Optiblender.

Linear restriction	Minimum	Maximum
OLR (g COD/L d)	0	1
HRT (d)	20	30
TKN (g N-TKN/L)	0.2	4
TS (vol%)	0	8
Alkalinity (g $CaCO_3$/L)	2	10
Na^+ (g/L)	0	3
K^+ (g/L)	0	3
Biogas quality (ppm H_2S)	0	10,000
Digestate quality[a] (g COD/L)	0	6

[a] Expressed as volatile fatty acids concentration.

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