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Generalised modelling approach for anaerobic co-digestion of fermentable substrates

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HIGHLIGHTS

- Generalised approach for model implementation of soluble fermentable substrates.
- Fermentations channelled through sugars fermentation equivalent reactions.
- Fermentable substrates degraded by a generic group of fermenters.
- Model validated with soluble substrates in continuous pilot scale UASB–AF reactor.

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ABSTRACT

A general methodology to implement fermentable soluble substrates in the IWA Anaerobic Digestion Model No. 1 (ADM1) that extends its application to anaerobic co-digestion of multiple substrates is presented. The approach considers the fermentation of new soluble substrates, not originally described in ADM1, as channelled through mass- and electron-balanced sugar fermentation equivalent reactions, and that fermentable substrates are degraded by a generic group of fermenters instead of the original ADM1 sugar fermenters. Therefore, no additional microbial group state is required. An additional term that modifies the ADM1 sugar fermentation kinetics equation was included to account for the competition among multiple substrates to be degraded by a particular biomass group. The model was validated at pilot scale treating a blend of pig manure (soluble fraction), wine and gelatine at mesophilic conditions. Only the ADM1 acetoclastic ammonia inhibition parameter was calibrated to obtain consistent model prediction of gas and liquid composition.

1. Introduction

Anaerobic digestion (AD) has been traditionally associated with the treatment of agro industrial waste streams and of sewage sludge from aerobic wastewater treatment plants. The possibility of using blends of multiple substrates (co-digestion) has recently extended the applicability of anaerobic digestion, since it provides a number of environmental, technological and economic advantages. Anaerobic co-digestion can increase methane production depending on the operating conditions and the co-substrates used (Alvarez et al., 2010). This is achieved through synergies between blended substrates that complement each other in terms of C/N ratio, COD, dilution of inhibitors, alkalinity, dry matter, etc. (Hartmann et al., 2003).

Many organic wastes, which often cause a problem of disposal and at the same time represent potential energy sources, have been successfully treated by anaerobic co-digestion (AcoD); for example, the by-product containing glycerol generated in a biodiesel producing plant, the whey containing lactose generated in the cheese factories, or the vinasse wastewaters containing ethanol from wine distillery (Astals et al., 2012; Comino et al., 2012; Riaño et al., 2011). Achieving the correct blend of wastes in AcoD that leads to a stable operation is not trivial. It requires knowledge on the process since it involves a complex network of reactions to convert complex substrates into biogas. In this sense, models can early evaluate the viability of a particular blend of wastes treated in an AcoD system.

A few years ago, part of the research on AD started to focus on modelling in order to describe its mechanisms accurately

Abbreviations: AcoD, anaerobic co-digestion; AD, anaerobic digestion; ADM1, anaerobic digestion model no. 1; BMP, biochemical methane potential; C/N, carbon to nitrogen ratio; COD, chemical oxygen demand; CODs, soluble chemical oxygen demand; CODt, total chemical oxygen demand; HRT, hydraulic retention time; LCFA, long chain fatty acids; OLR, organic loading rate; SRT, solid retention time; TAN, total ammonia nitrogen; 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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(Angelidaki et al., 1993; Donoso-Bravo et al., 2011). The IWA Anaerobic Digestion Model No. 1 (ADM1) (Batstone et al., 2002) is a structured model that describes the main processes involved in AD to convert complex organic substrates into biogas: disintegration, hydrolysis, acidogenesis (or fermentation), acetogenesis and methanogenesis. The model defines state variables to describe the behaviour of soluble and particulate components along the reaction path and includes 7 groups of bacterial degraders, classified by their functions: degraders of sugars, amino acids, LCFA, valerate and butyrate, propionate, acetate and hydrogen. All organic species and molecular hydrogen are described in terms of COD, whereas inorganic carbon or inorganic nitrogen species are described in molar basis.

In recent years, there has been an increasing interest on AcoD modelling (Mata-Álvarez et al., 2011); In spite of the existing literature about AcoD modelling, it seems to lack generalised methodologies to implement soluble substrates into ADM1. Some authors incorporated fermentative reactions of soluble substrates such as phenol, ethanol, glycerol, or lactic acid to ADM1 following their own methodologies (Fezzani and Ben Cheikh, 2009; Rajinikanth et al., 2008; Galí et al., 2009; Hidaka et al., 2010); however, different pathways to degrade ethanol, glycerol or lactate can be found in the literature. According to Schink et al. (1985) ethanol can be degraded to organic acids through different pathways: butyrate formation, simultaneous acetate and propionate formation or acetate as sole acid, and concluded that ethanol was not exclusively metabolised via acetate. The same was observed by Seeliger et al. (2002) where ethanol could be degraded via acetate plus propionate. Glycerol degradation has been implemented in ADM1 through carbohydrates too (Galí et al., 2009; Biernacki et al., 2013), with default ADM1 catabolic products of sugars fermentation. According to Sørensen et al. (1991), lactate degradation pathways included: acetate formation; formation of acetate, hydrogen and carbon dioxide; formation of propionate, acetate and carbon dioxide; or fermentation to acetate, propionate and hydrogen. However, batch experiments conducted by Sørensen et al. (1991) encountered acetate as the major intermediate produced during batch assays. In general, the fermentation via propionate and acetate seems to be the most common pathways in the literature (Antonopoulou et al., 2012; Skiadas et al., 2000; Seeliger et al., 2002). Nevertheless, different acetate to propionate ratios together with different hydrogen pressures were found depending on the bacteria used according to experiments conducted by Seeliger et al. (2002). Therefore, the key issue is to find the catabolic yields (stoichiometry) of the organic acids (acetate, propionate and butyrate) from these fermentable substrates.

The purpose of this work is to present a generalised methodology to easily incorporate fermentable soluble substrates into ADM1 and to extend the model for AcoD application. The proposed model was implemented in an Excel-Matlab/Simulink platform (Rodríguez et al., 2009) and the experimental validation study was conducted at pilot scale, in a highly instrumented hybrid Upflow anaerobic sludge blanket – anaerobic filter reactor (UASB–AF reactor) treating a blend of three substrates (namely wine, gelatine and pig manure) in continuous operation under mesophilic conditions.

2. Methods

2.1. ADM1-based AcoD Model

In order to simulate co-digestion processes, the ADM1-based model was implemented on Excel-Matlab/Simulink platform (Rodríguez et al., 2009) and adapted to run both batch and continuous operations. The model calculates the blend flow and the composition of the influent to the digester. The ordinary differential equations of all states were coded and implemented using Matlab and integrated with the ODE113 solver.

To validate the model, simulations were conducted under the same operating conditions as those in a pilot plant treating a blend of three soluble substrates at mesophilic conditions. All ADM1 parameters remained at their default values except the acetoclastic ammonia inhibition parameter, $K_{I,NH3}$, as sole calibrated parameter to fit experimental results.

2.2. Experimental set-up for continuous experiment

A continuous AcoD experiment was conducted in a fully instrumented pilot plant consisting of a hybrid UASB–AF reactor of 1 m^3 of liquid volume (Ruiz, 2005). The high recycling flow applied to the reactor guaranteed quasi-complete mixed reactor behaviour in the liquid phase. The on-line measurement devices connected to the plant include pH meter (Siemens, SIPAN pH/ORP 7MA 1010), gas flow meter (Brooks®, 5860E), continuous CH_4, CO_2, H_2S analyser (ABB, AO2020) and a hydrogen gas analyser (Sensotrans, Sensotox 420). A data acquisition programme developed in Visual Basic allowed the data acquisition and monitoring of the pilot plant. PLCs (Siemens, series S7-200) managed the signals coming from the different sensors and analysers connected to the pilot plant (Molina et al., 2007). Fig. 1 shows a schematic of the experimental set-up. The model simulated the same system in terms of process layout with a reactor modelled as perfectly mixed with biomass retention to mimic the UASB–AF as it is conventionally done.

The reactor was inoculated with sludge from an industrial internal circulator reactor in a brewery factory and operated for 5 months treating a blend of three soluble substrates (soluble fraction of pig manure, wine and gelatine) at OLR of 2.5 g COD/L·d, HRT of 11 days and 13 g VSS/L under mesophilic conditions. The characteristics of the different substrates are summarised in Table 1. In addition, water was added to the feeding (37.2% feed volume) to simulate a vinasse stream from wine, to reduce nitrogen and sulphate contents of the blend and to achieve an influent alkalinity around 3 g $CaCO_3$/L.

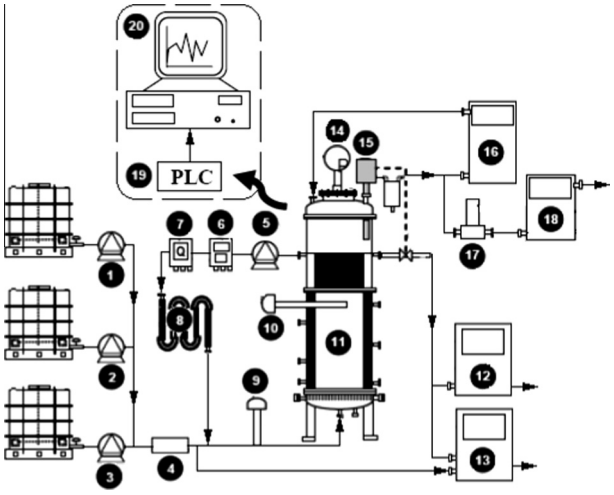

Fig. 1. Layout of the pilot plant: (1–3) feeding pumps of pig manure, gelatine and wine. (4) Static mixer. (5) Recirculation pump. (6) Flow meter. (7) Effluent pH meter. (8) Heat exchanger. (9) Influent temperature probe. (10) Reactor temperature probe. (11) UASB–AF reactor. (12) On-line alkalinity and VFA analyser (not used). (13) Total organic carbon analyser (not used). (14) Pressure probe. (15) Level switch. (16) CH_4 and CO_2 analyser. (17) Gas flow meter. (18) Hydrogen gas analyser. (19) Rack of PLCs, (20) PC provided with a data acquisition system to monitor the process (adapted from Ruiz (2005)).