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High-solids anaerobic digestion model for homogenized reactors

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ABSTRACT

During high-solids anaerobic digestion (HS-AD) of the organic fraction of municipal solid waste (OFMSW), an important total solid (TS) removal occurs, leading to the modification of the reactor content mass/volume, in contrast to 'wet' anaerobic digestion (AD). Therefore, HS-AD mathematical simulations need to be approached differently than 'wet' AD simulations. This study aimed to develop a modelling tool based on the anaerobic digestion model 1 (ADM1) capable of simulating the TS and the reactor mass/volume dynamics in HS-AD of OFMSW. Four hypotheses were used, including the effects of apparent concentrations at high TS. The model simulated adequately HS-AD of OFMSW in batch and continuous mode, particularly the evolution of TS, reactor mass, ammonia and volatile fatty acids. By adequately simulating the reactor content mass/volume and the TS, the HS-AD model might bring further insight about potentially inhibitory mechanisms (i.e. NH_3 buildup and/or acidification) occurring in HS-AD of OFMSW.

1. Introduction

Anaerobic digestion (AD) is a biochemical treatment technology for organic waste valorization yielding a high-methane-content biogas and a partially stabilized organic material with potential applications as soil amendment (Mata-Alvarez, 2003). High-solids anaerobic digestion (HS-AD) is a particular case of AD operated at a total solid (TS) content $\geq$ 10%, in contrast to 'wet' AD applications (i.e. TS < 10%) (Abbassi-Guendouz et al., 2012). Thus, HS-AD has the advantage of minimizing the reactor volume, as well as the need for water addition. On the other hand, HS-AD is normally associated with an important reduction of the total (TS) and volatile (VS) solid content, during the biological degradation of the organic matter. For example, HS-AD of the organic fraction of municipal solid waste (OFMSW) might lead to a TS removal of 30–80% (Cecchi et al., 2002; Mata-Alvarez, 2003; Pavan et al., 2000). However, some drawbacks limit the applicability of HS-AD as, for example, the reduced kinetics expected as a consequence of the hampered mass transfer, and the high risk of acidification due to organic overloading (Benbelkacem et al., 2015; De Baere, 2000).

Among the solid wastes used in HS-AD, the OFMSW is particularly suited for anaerobic treatment due to its elevated TS content (i.e. 25–30%), biodegradation potential and possibility to recover nutrients (i.e. nitrogen and phosphorous) from its composition (De Baere and Mattheeuws, 2013; Mata-Alvarez, 2003). However, HS-AD of OFMSW is normally associated with a high risk of inhibition due to the high protein content, leading to free ammonia nitrogen (NH_3), as one of the most important inhibitors (Chen et al., 2008; Kayhanian, 1999; Rajagopal et al., 2013).

Understanding the biochemical and physicochemical dynamics in HS-AD is crucial to ease the design and operation of HS-AD reactors, minimizing the risk of acidification/inhibition. Particularly important is the knowledge about the interactions between the main four phases – microorganisms, solids, liquids and gases – in HS-AD, since it might allow to increase the waste treatment capabilities and methane yield (Mata-Alvarez, 2003; Vavilin et al., 2004; Xu et al., 2015). In this line, an adapted mathematical model is required for the operational analysis and technology development of HS-AD, as some of the main applications for 'wet' AD of the anaerobic digestion model No.1 (ADM1) (Batstone, 2006; Batstone et al. 2002, 2015; Xu et al., 2015).

ADM1 is a structured model gathering together the main biochemical and physicochemical processes of AD (Batstone et al.

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2002, 2015). Biochemical processes include the disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis of complex substrates composed of carbohydrates, proteins and lipids in chemical oxygen demand (COD) units. Physicochemical processes include the gas transfer and the equilibrium of the ionic species of the main inorganic compounds in AD (i.e. CO_2 and NH_3). However, the CSTR implementation of ADM1 was primarily conceived for 'wet' AD applications (i.e. TS $\ll$ 10%), while a more complex hydraulic and particulate component modelling is required for HS-AD (Batstone et al. 2002, 2015; Xu et al., 2015). Thus, modelling HS-AD might be particularly challenging due to the intrinsic complexity of the process (Batstone et al., 2015; Mata-Alvarez et al., 2000; Vavilin et al., 2004; Xu et al., 2015). For example, the (semi-)solid matrix might define the soluble/gaseous transport processes, as well as the capabilities of anaerobic biomass to access the substrates (Bollon et al., 2013; Vavilin and Angelidaki, 2005).

The mass balance modification, regarding the continuously stirred tank reactor (CSTR) implementation of ADM1 (Batstone et al., 2002), is required to account for the reactor content mass (M_{Global}) removal and the specific weight (ρ_{Global}) dynamics in HS-AD (Batstone et al., 2015; Kayhanian and Hardy, 1994; Richards et al., 1991; Vavilin et al., 2004). Noteworthy, the reactor content volume (V_{Global}) might describe important fluctuations during HS-AD, depending mainly on the substrate TS and biodegradability, in contrast to 'wet' AD. Furthermore, a given degree of gaseous porosity (ε) might be present in the HS-AD matrix, particularly at TS contents $\geq$ 25% (Batstone et al., 2015; Benbelkacem et al., 2013; Bollon et al., 2013; Vavilin et al., 2003). ADM1 was originally expressed in volumetric units (i.e. kg COD/m^3). Meanwhile, the most common measurements in HS-AD are normally expressed in mass units (i.e. kg COD/kg), since accounting for the specific weight of (semi-)solid samples – but also the specific weight dynamics in HS-AD – involves the complexity of the analytical techniques (Benbelkacem et al., 2013; Bollon et al., 2013; Kayhanian and Tchobanoglous, 1996). For example, the specific weight of a (semi-)solid sample can be approximated by the use of a water pycnometer, where the sample must be appropriately pretreated (i.e. dried/ground), the distilled water fully degassed and analyses performed under temperature-controlled conditions (ASTM, 2002). With all the above, HS-AD simulations need to be approached differently than in 'wet' AD, where ρ_{Global} and V_{Global} are normally assumed constant, as summarized in Fig. 1.

This study aimed at developing a mathematical tool based on the ADM1 biochemical framework, capable of simulating the solids and reactor content mass/volume dynamics in HS-AD of OFMSW, including the interrelationship between TS (and VS) removal and biogas production. By simulating adequately the global mass/volume and TS dynamics, the presented model might serve as a link between 'wet' AD and HS-AD, while it might help to explore potential inhibitory/acidification mechanisms occurring during HS-AD of OFMSW. Meanwhile, the proposed model was aimed to be as general as possible, since different HS-AD applications (i.e. organic substrate and/or reactor configuration) could be simulated, provided that the main hypotheses presented in the methodology section are fulfilled. Furthermore, the eventual model user is encouraged to further calibrate the model parameters and/or modify the model structure, in order to adapt the HS-AD model for any specific need.

2. Materials and methods

2.1. High-solids model implementation

The main basis for the dynamic model presented in this study was ADM1 (Batstone et al., 2002), including the modifications suggested by Blumensaat and Keller (2005) for closing nitrogen and carbon balances. The simulation of HS-AD for OFMSW treatment required four preliminary hypotheses in order to reduce the complexity of the model. Firstly, HS-AD was assumed to take place in a homogenized (i.e. completely mixed) reactor [Hypothesis 1]. Secondly, the effect of porosity and transport processes was assumed to be negligible [Hypothesis 2]. Then, the specific weight of solids and solvent was considered constant [Hypothesis 3]. Finally, the biochemical reactions were assumed to occur predominantly in water [Hypothesis 4].

With these hypotheses, ADM1 required some particular modifications in order to simulate the TS and mass/volume dynamics in HS-AD, while allowing the calibration of the proposed model. The main modifications implemented in ADM1 in order to simulate HS-AD were the inclusion of mass balances modifying the reactor mass and volume (needed to account for the organic solid removal in HS-AD) and the inclusion of apparent concentrations (as a link between 'wet' and high-solids applications).

2.1.1. Mass balances in high-solids anaerobic digestion reactors

The simulation of the reactor mass and TS/VS content of homogenized HS-AD reactors required the implementation of the global (M_{Global}) [Equation (1)], solid material (M_{Solids}) [Equation (2)], liquid-solvent content ($M_{Solvent}$) [Equation (3)] and inert material (M_{Inerts}) [Equation (4)] mass balances. In this study, the solvent was considered as only water, while the solid material included all the organic and inorganic compounds (i.e. particulates and soluble compounds, VFA, microorganisms) inside the reactor, except water. In mass balances, the mass content (M_i) – global or partial – dynamics were related to the corresponding mass fluxes (m_i), particularly the gases flowing out of the reactor as a consequence of methanogenesis. The implementation of reactor mass balances is crucial in HS-AD, since it accounts for the importance of mass and water removal due to biogas production, in contrast to 'wet' AD (Henze et al., 1997; Kayhanian and Tchobanoglous, 1996; Richards et al., 1991).

$$\frac{dM_{Global}}{dt} = m_{Influent,Global} - m_{Effluent,Global} - m_{Biogas} \quad (1)$$

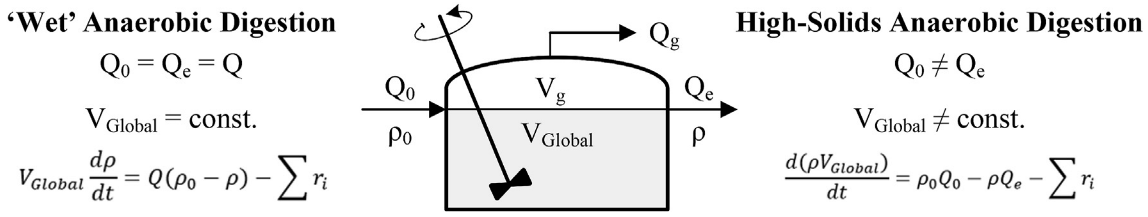

Fig. 1. High-solids vs. 'wet' anaerobic digestion.