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Assessment of percolation through a solid leach bed in dry batch anaerobic digestion processes

Anil Shewani[a,b,c,f], Pierre Horgue[d,e], Sébastien Pommier[a,b,c], Gérald Debenest[d,e], Xavier Lefebvre[a,b,c], Emmanuel Gandon[f], Etienne Paul[a,b,c,*]

[a] Université de Toulouse, INSA, UPS, INP, LISBP, 135 Avenue de Rangueil, F-31077 Toulouse, France
[b] INRA, UMR792 Ingénierie des Systèmes Biologiques et des Procédés, F-31400 Toulouse, France
[c] CNRS, UMR5504, F-31400 Toulouse, France
[d] Université de Toulouse, INPT, UPS, IMFT (Institut de Mécanique des Fluides de Toulouse), Allée Camille Soula, 31400 Toulouse, France
[e] CNRS, IMFT, 31400 Toulouse, France
[f] Cofely INEO GDF Suez, 10 Impasse André Marestan BP 44795, F-31047 Toulouse Cedex 01, France

HIGHLIGHTS

- Percolation through solid cow manure was assessed.
- An experimental procedure was set up to calibrate a multiphase flow model.
- A percolation and drainage cycle was needed to reach water holding capacity.
- Micro/macro-porosity and permeability were obtained for two compaction levels.
- Numerical simulations successfully reproduced experimental dynamic water retention.

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ABSTRACT

This work aimed at assessing water percolation through a solid cow manure leach bed in dry batch AD processes. A laboratory-scale percolation column and an experimental methodology were set up. Water behaviour was modelled by a double porosity medium approach. An experimental procedure was proposed to determine the main hydrodynamic parameters of the multiphase flow model: the porosity, the permeability and the term for water exchange from macro- to micro-porosity. Micro- and macro-porosity values ranged from 0.42 to 0.70 $m^3\ m^{-3}$ and 0.18 to 0.50 $m^3\ m^{-3}$. Intrinsic permeability values for solid cow manure ranged from $5.55 \cdot 10^{-11}$ to $4.75 \cdot 10^{-9}\ m^2$. The term for water exchange was computed using a 2nd order model. The CFD tool developed was used to simulate successive percolation and drainage operations. These results will be used to design leachate recirculation strategies and predict biogas production in full-scale dry AD batch processes.

1. Introduction

Dry anaerobic digestion is an effective, sustainable method for the treatment of solid wastes from agriculture, allowing the recovery of both energy and nutrients. For small-size farms, more and more rustic easily-maintained dry anaerobic batch technologies are being developed to treat wastes such as solid cow manure. Nevertheless, these types of dry anaerobic batch reactors have several drawbacks: long degradation times that lead to a large bioreactor volume and hence a high investment cost; a low methane conversion yield; a high inoculation rate using stabilized digestate kept from previous batches (Schäfer et al., 2006); and high sensitivity to inhibition if the substrate is mostly composed of readily biodegradable organic matter and if the water content is low (Vavilin et al., 2008; Abbassi-Guendouz et al., 2012). Appropriate leachate percolation through the solid waste body (amount of recirculated leachate, leachate injection geometry, injection flow rate and recirculation frequency) is a key point to solve these major issues and to increase the overall process efficiency (Benbelkacem et al., 2010).

* Corresponding author at: Département GPE, INSA Toulouse, 135 Avenue de Rangueil, 31077 Toulouse Cedex 4, France. Tel.: +33 (0) 5 61559772; fax: +33 (0) 5 61559776.

E-mail address: paul@insa-toulouse.fr (E. Paul).

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Leachate helps to provide water, microorganisms, nutrients and to dilute intermediate anaerobic digestion products (mainly volatile fatty acids VFAs, NH_4^+ and H_2) and potential toxins (Bilgili et al., 2007; Vavilin et al., 2003; Xie et al., 2012). Water is a key component as it acts as a solvent and contributes to mass transfer, the diffusion of microorganisms and the colonization of the substrate reactive surface (Vavilin et al., 2003; Le Hyaric et al., 2011; Bollon et al., 2011). A minimum water content is necessary for biological activity (Lay et al., 1997; Pommier et al., 2007). In dry batch processes, the overall performance and reliability depend on the extent to which VFA accumulation can be controlled through their leaching using water recirculation (Kusch et al., 2011). The amount of free water determines the efficiency with which intermediate reaction products are extracted (mainly as VFAs). To better understand water distribution and quantify the optimal amount of leachate to be recirculated, it is necessary to study the physical properties of the solids involved.

Various laboratory methodologies to determine the physical properties of the solid medium have been reported for municipal solid waste samples (Stoltz et al., 2012, 2010a,b; Wu et al., 2012). Physical parameters such as water content, bulk density, porosity and permeability have been measured in static (Agnew and Leonard, 2003; Richard et al., 2004; Schaub-Szabo and Leonard, 1999) and dynamic (Huet et al., 2012) conditions. Agnew and Leonard (2003) have reported porosity values for solid cow manure ranging between 90% and 92% and solid particle dry densities between 1200 and 1800 kg m^{-3}. These research works have focused on landfilling and composting, and thus used static characterization with different initial water contents. However, in dry batch AD processes, the water content has been shown to vary in time and space. Therefore, hydrodynamic characterization is necessary to better understand the process of percolation through the solid leach bed.

Olivier and Gourc (2007) have studied the hydrodynamic behaviour in municipal solid waste in a 1 m^3 pilot-scale compression cell with leachate recirculation and have investigated the correlation between biological degradation and settlement in a landfilling process with leachate recirculation. They have also studied the effect of the degradation degree and the leachate flow rate on the variations of the effective porosity and permeability of the solid waste. Moreover, modelling approaches have been proposed to improve our understanding of water distribution and physical changes during percolation processes. Tinet et al. (2011) and Capelo and De Castro (2007) considered municipal solid waste as a double porosity medium so as to take better account of water transport and distribution inside the waste. In the double porosity medium theory, two types of heterogeneities are distinguished: macro-porosity, where two-phase (gas and liquid) flow transport occurs, and micro-porosity, where both the gas and liquid phases are static. The comparison of numerical simulations with experiments should help to determine the main physical changes (such as porosity and permeability variations) during the waste treatment as a whole and thus to better understand the physical processes involved and finally to optimize biogas production.

The aim of this work was to study water distribution through a solid bed of cow manure during the percolation and drainage processes. Firstly, a double medium porosity was defined and static and dynamic water saturations were determined. From experimental data, the main hydrodynamic parameters, i.e. micro-porosity, macro-porosity and permeability were identified. A water balance on the solid bed was established to estimate micro-saturation/macro-saturation values and to quantify water transport from macro-porosity to micro-porosity. These results were used to implement a CFD modelling tool running numerical simulations to predict water distribution in full-scale percolation processes.

2. Methods

2.1. Solid waste characterization

Cow manure solid waste was taken from an experimental farm of the French National Polytechnic Institute located in the area of Toulouse (Midi-Pyrénées, France). Samples were rapidly placed at 4 °C. To measure the initial gravimetric water content, a representative total mass of 1 kg of each sample was shredded to 1 cm and dried at 105 °C for 24 h. For percolation operations, no mechanical pretreatment was carried out. To assess the repeatability of the results, two experiments (M_1 and M_2) were performed using the same solid cow manure.

As solid cow manure is a highly heterogeneous medium, a double-medium porosity model was used to represent the physical heterogeneity of the solid waste. This model is based on a theoretical assessment similar to those used by Tinet et al. (2011) and Capelo and De Castro (2007) for municipal solid waste. The distinction between micro-pores and macro-pores was based on the assumption that the micro-porosity was completely filled with static water when the solid bed reached its water holding capacity (Stoltz et al., 2010a; Huet et al., 2012).

The solid fraction (φ_s) was defined as the ratio between the volume of dry mass and the total volume of the leach bed and was considered constant during the whole testing period. The different fractions satisfied the obvious relationship

$$\varphi_M + \varphi_s + \varphi_m = 1 \quad (1)$$

where φ_M and φ_m are the macro-porosity and micro-porosity fractions, respectively. The dry mass lost with the drained liquid (total amount of solubilized mineral matter and COD) made up less than 1% of the total dry mass fed into the percolation device, and was thus neglected. The initial characteristics of the solid waste beds are reported in Table 1.

2.2. Experimental set-up

The laboratory scale bed reactor consisted of a stainless steel column of 100 L total working volume, and 0.75 m maximum working height. The height was divided into three sections enclosed with rubber gaskets to ensure water tightness (Fig. 1). The water was injected by means of a peristaltic pump at the top of the vessel using an injector that divided the flow among twelve injection points distributed above the whole working surface. The applied surface hydraulic loads (SHLs) were 16, 48, 96, 128 and 176 L h^{-1} m^{-2}, corresponding to injection flow rates of 2, 6, 12, 16 and 22 L h^{-1}, respectively. To avoid side-effects at the vessel walls, a surface/volume ratio of 2.5 was chosen in agreement with Huet et al. (2012). Thus, 0.4 m of waste height was used. The leachate was recovered by five withdrawal nozzles as shown in Fig. 1 It fell into a reservoir placed on a precision balance for online acquisition of the drained leachate flow. To avoid migration of solid

Table 1
Initial characteristics of leach beds.

Initial characteristics	M_1	M_2
Solid bed total wet mass (kg)	16.7	17.8
Solid bed total dry mass (kg)	6.60	7.50
Bulk density (kg m^{-3})	313	337
Total height (m)	0.40	0.40
Total volume (L)	50.27	50.27
Initial gravimetric water content (kgH_2O kgW M^{-1})	0.58	0.58
Initial static water saturation (m^3 m^{-3})	0.18	0.20
Initial solid fraction φ_s (m^3 m^{-3})	0.08	0.08
Initial total porosity ($\varphi_m + \varphi_M$) (m^3 m^{-3})	0.92	0.92