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Quantifying physical structure changes and non-uniform water flow in cattle manure during dry anaerobic digestion process at lab scale: Implication for biogas production

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HIGHLIGHTS

- Physical structure changes of manure were quantified during AD.
- Tracer experiments and modeling revealed non-uniform flow through the manure.
- The changes in the structure limited liquid percolation through the manure.
- Recirculation frequency improved the methane production only in first stages of AD.

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ABSTRACT

The aim of this study was to investigate and quantify non-uniform water flow during dry AD and its implication for biogas production. Laboratory tracer experiments were performed on cattle manure over the course of AD. The evolution of the permeability, the dry bulk density, the dry porosity, the total and volatile solid contents of cattle manure at different stages of AD, revealed waste structure changes, impacting water flow and methane production. Tracer experiments and numerical modeling performed by using a physical non-equilibrium model indicated non-uniform preferential flow patterns during degradation. According to literature, the increase of inoculum recirculation frequency improved methane production rate. However, these results demonstrated that this improvement occurs only at the beginning of manure degradation. After 19 days of degradation the inoculum recirculation and the flow patterns modification had no effect on methane production rate.

1. Introduction

Anaerobic digestion (AD) is a method engineered to decompose organic matter by a microbial consortium under oxygen-free conditions, into biogas (50–70% methane) and an organic residue with excellent agronomic qualities. This technology has been successfully implemented in the treatment of agricultural wastes, food wastes, and municipal wastes in order to produce renewable energy. Solid-state or dry digestion generally occurs at solid contents higher than 15% of total solids content in the reactor (Li et al., 2011; Raposo et al., 2011; Karthikeyan and Visvanathan, 2013). During the dry batch process, wastes are placed in hermetic reactors and a liquid phase (inoculum) is recirculated to accelerate AD.

In the dry process, the liquid phase is essential to facilitate the redistribution of substrates, nutrients and the spreading of micro-organisms in the medium, leading to an increase in the methane production rate. Thus, favorable conditions for dry AD are conditioned by uniform distribution of water content and this parameter may greatly affects biogas production (Lay et al., 1997). A great number of studies have pointed out the important role of liquid recirculation to optimize the waste degradation (El-Mashad et al., 2006; Karthikeyan and Visvanathan, 2013). They indicated that the waste decomposition can be improved by an increase of the water content (Mata-Alvarez et al., 2000). Abbassi-Guendouz et al. (2012) reported a decrease in methane production for substrates when total solids increase of 10–25%. Bollon et al. (2013) reported that the water content affects the

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transport of solutes by diffusion; the effective diffusion coefficient of iodide at 25% of TS was decreased by a factor 185 relative to pure water.

Solute transport is modified during anaerobic digestion by the microorganism growth leading to a biofilm accumulation. The biofilm formation may lead to a reduction of the pore space, thus impacting the hydrodynamic parameters of the porous media (Cunningham et al., 1991). Nevertheless, the thickness of biofilm controls the presence of acidogenic or methanogenic populations, needed to AD (Buffière et al., 1998). Le Hyaric et al. (2011) established a linear relationship between the water content and the methanogen activity. Dry AD is a complex process because of the presence of three phases interacting together: liquid (inoculum), gas (biogas) and solid (waste) phases.

The highly heterogeneous physical structure of the solid waste materials and their evolution during anaerobic digestion result in a heterogeneous distribution of water, inoculum and nutrients within the digester. This physical pore scale heterogeneity causes variations of fluid velocity, resulting in non-uniform flow. Many studies have been carried out emphasizing non-uniform flow and solute transport in structured soils (Lamy et al., 2009), reporting that solute transport is significantly affected by rapid flow through preferential pathways. The rapid convective solute transport through preferential flow paths is accompanied by diffusive mass transfer of solutes between the preferential flow domain and the matrix domain with slow water flow, or stagnant water. This phenomenon has been called physical non-equilibrium transport and may limit the predictability of flow and transport processes in structured soils. Even though non-equilibrium flow and transport has been widely studied in structured soil, few studies have been carried out to investigate the non-uniform flow field in municipal solid wastes (Rosqvist and Destouni, 2000; Woodman and Beaven, 2011). However, the transport characterization was studied to understand the behavior of the liquid and the solid phase in continuous dry process. Benbelkacem et al. (2013) used tracer procedure to study the liquid mixing and solid segregation in continuous dry AD process. Three types of spherical particles of the same diameter (8 mm-diameter), but made out of different materials, were chosen to test different densities: polypropylene ($\rho = 0.95$ kg/L), polyamide, ($\rho = 1.14$ kg/L) and glass beds ($\rho = 2.5$ kg/L. Only 9% of glass beads and 71% of polypropylene spheres were extracted of reactor demonstrating that the increase of particle density affects their segregation potential. Their study demonstrated that the solid segregation potential increased with the particle density. Recently Shewani et al. (2015) applied CFD (Computational Fluid Dynamics) modeling tool on cow manure to investigate macro- and micro-porosity percolation at lab scale in order to predict water distribution in cow manure.

Non-uniform water flow through a digester influences the biodegradation process adversely, causing non-uniform waste degradation within the biological reactor. Relevant quantification of the water and solute movement through preferential pathways may be important information in order to improve predictions of dry digestion performance.

The aim of this study was to quantify both physical structure changes and non-uniform water flow in solid agricultural wastes and their effect on methane production. Physical and hydraulic parameters were continuously estimated over the course of waste degradation. Substrate characterization included the permeability, the total and volatile solid content, the dry bulk density and porosity. Solute tracer experiments were carried out under steady state flow conditions to investigate water flow at different stages of AD. Sodium chloride was used as water tracer, restricting this study to physical non-equilibrium mechanisms. To account for preferential flow and solute transport in such heterogeneous porous media, a non-equilibrium model known as the MIM (M-mobile/IM-immobile water) transport model was used to model tracer experimental elution and to quantify non-uniform water flow. The effect of two frequencies of inoculum recirculation on non-uniform water flow and methane production was also investigated.

2. Methods

2.1. Cattle manure characterizations

Cattle manure, which is the most common agricultural waste in French farms, was issued from the farm of the Institute LaSalle Beauvais, France. Waste sampling was performed according to the sampling plan described by Gy (1988).

2.1.1. Physical measurements

Total solid content, volatile solid content, dry bulk density, total porosity and specific density of fresh manure, and at different fermentation stages were measured. Samples were placed at 105 °C during 12 h according to standard methods (APHA, 1988) to determine the total solid (TS) content. The volatile solid (VS) content was obtained by drying the samples at 500 °C during 4 h (AFNOR NF U44-160, 1985). TS of 22.0 ± 0.5% and VS of 89.4 ± 0.6%$_{\mathrm{TS}}$ were obtained for cattle manure.

The dry bulk density, ρ_d, was estimated by the following equation:

$$\rho_d = M_{\mathrm{DS}}/V_{\mathrm{C}} \tag{1}$$

where M_{DS} is the weight of dry sample (g) and V_{C} is the volume of the column (cm^3). The ρ_d was estimated at 0.09 g cm^{-3} for cattle manure. The total dry porosity (ε) was estimated by dividing the saturated water by the weight total following:

$$\varepsilon = W_{\mathrm{SW}}/W_{\mathrm{T}} \tag{2}$$

where W_{sw} is the necessary weight of water to fully saturate the column (g) and W_{T} corresponds to the total weight made up of dry sample (M_{DS}) and water (W_{sw}) (g). The ε reached 91.1% for cattle manure. The total dry porosity was also calculated from the dry bulk density as following:

$$\varepsilon = 1 - \rho_d/\rho_g \tag{3}$$

where ρ_g is the specific grain density of the porous material. Similar porosity values were obtained from both methods. The specific density of the cattle manure was estimated by performing density analysis by helium pycnometry (Micromeritics AccuPyc 1330). The pycnometer determines the sample volume by measuring the pressure difference between an empty sample cell and the cell containing the sample to be analyzed. The increase in pressure is directly related to the volume of gas displaced. The solid specific density was therefore obtained by dividing the sample weight by the estimated volume. The density of the sample, of 1.69 g cm^3 for the cattle manure, was calculated as the average of ten measurements performed automatically by the pycnometer.

2.1.2. Hydraulic characterization

Permeability tests were also carried out with fresh manure, and for different fermentation stages (Table 1). Falling head permeability test, which is a common laboratory test for porous materials with intermediate and low permeability, was performed to estimate the substrate permeability. The hydraulic characteristics of the cattle manure were obtained through a smaller scale laboratory experiments (around 1 kg). Samples were placed in a permeability cell (22 cm in length and 3.8 cm in diameter, column section: 47.75 cm^2), connected to a standpipe (standpipe section: 0.785 cm^2) which provides the water head and also allows