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Electrical resistivity tomography to quantify in situ liquid content in a full-scale dry anaerobic digestion reactor

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HIGHLIGHTS

- ERT was implemented on a full scale dry anaerobic digestion reactor.
- PDP array was adapted with an infinite electrode at the bottom of the AD reactor.
- Resistivity values were correlated with methane potential, water and fiber content.
- Degradation zones, high methane potential zones, liquid repartition were localized.

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ABSTRACT

The electrical resistivity tomography (ERT) method is a non-intrusive method widely used in landfills to detect and locate liquid content. An experimental set-up was performed on a dry batch anaerobic digestion reactor to investigate liquid repartition in process and to map spatial distribution of inoculum. Two array electrodes were used: pole–dipole and gradient arrays. A technical adaptation of ERT method was necessary. Measured resistivity data were inverted and modeled by RES2DINV software to get resistivity sections. Continuous calibration along resistivity section was necessary to understand data involving sampling and physicochemical analysis. Samples were analyzed performing both biochemical methane potential and fiber quantification. Correlations were established between the protocol of reactor preparation, resistivity values, liquid content, methane potential and fiber content representing liquid repartition, high methane potential zones and degradations zones. ERT method showed a strong relevance to monitor and to optimize the dry batch anaerobic digestion process.

1. Introduction

Organic solid waste (>15% of total solid content) such as agricultural waste, food waste and industrial waste may be degraded by microorganism consortium to produce biogas containing 50–70% of methane and digestate with high agronomic qualities (Raposo et al., 2011; Li et al., 2011; Karthikeyan and Visvanathan, 2013). Several dry technologies are developed with different temperature process (mesophilic or thermophilic), reactor configurations (simple or multistage), batch or continuous feeding and with or without mixing systems (Karthikeyan and Visvanathan, 2013).

In dry process, a linear relationship between water content and methanogen activity has been established (Le Hyaric et al., 2011). The important role of water in this process is highlighted by several works (Klink and Ham, 1982; Bayard et al., 2005; François et al., 2006; El-Mashad et al., 2006; Filipkowska, 2008; Kusch et al., 2009; Shahriari et al., 2012). Liquid phase enhances biogas production by implementing distribution and spreading of microorganisms performing the methanogenesis, temperature favoring microorganism development, nutrients and moisture essential to microorganism growth (Lay et al., 1997). Liquid recirculation presents advantage to decrease lag time of biogas production, increasing both carbon conversion rate and cumulative biogas production (200 and 350 normal cubic meters of biogas (Nm^3_{biogas}) per ton of carbon total (t_{CT}) respectively without and with liquid recirculation at 120 mL kg^{-1} $week^{-1}$) (Bayard et al., 2005).

Major topics of dry anaerobic digestion are to characterize and manage water flow and hydrodynamic behavior of waste subjected to degradation. Most studies have been carried out at lab and pilot

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scales. André et al. (2015) investigated and quantified non-uniform water flow on 60 L pilot batch reactors during dry waste anaerobic digestion and its implication for biogas production. Shewani et al. (2015) investigated the macro, the micro porosity and the percolation applying CFD (Computational Fluid Dynamics) tool to 100 L columns. But these techniques are not appropriate for industrial size reactors. About the latter, it could be possible to implement methods that are commonly used in other fields such as soil or landfill.

Several methods exist to quantify and to determine water localization in landfills such as neutron probe, time domain reflectometry probe, gravimetric method, capacitive probe, optic fiber, gas tracer and electrical resistivity tomography (ERT) (Imhoff et al., 2007). To localize liquid phase in dry batch container (30 m^3) in the whole, the choice between techniques was made by confronting their advantages and disadvantages. Most of these methods are intrusive, their measurements are localized and implying an important probe number. ERT was chosen because it is a non-intrusive method, data acquiring and treatment are fast. ERT needs an expensive instrumentation, and moisture content may not be directly evaluated getting resistivity values (Imhoff et al., 2007). In situ, the knowledge of leachate electrical conductivity and temperature are sometimes difficult.

Several works use this method mainly in municipal solid waste (Rosqvist et al., 2005; Barina, 2005; Rosqvist et al., 2007; Abdulrahman et al., 2013). Grellier et al. (2008) monitored leachate injection in a bioreactor landfill (134,000 tons of waste) with ERT method. They established a relationship between resistivity and water content according to Archie's law. Moreira et al. (2014) used ERT method to detect biogas accumulation in a landfill. Biogas presence was correlated to high resistivity values, while low resistivity values corresponded to organic matter and water. In the majority of cases ERT method is implemented on long profile in landfill. In dry anaerobic digestion, data were not found with implementation of these techniques to detect and quantify liquid content. Commonly, gravimetric method is used to get total solid content. The development of methods and tools to monitor liquid repartition in full-scale dry AD process is essential.

The aim of this study was to implement ERT method for a 30 m^3 container reactor using an Isman and Ducellier-like dry process. Agricultural waste was loaded and a liquid phase was recirculated to accelerate waste degradation under mesophilic conditions. Liquid content distribution is essential to get an optimal methane production. Three ERT campaigns were achieved to define optimal conditions for ERT method in order to map resistivity values and consequently the distribution of liquid content in the container. Also samplings were performed to characterize physico-chemical parameters (total solid, volatile solid, pH, and conductivity), fiber content and methane potential, aiming to establish relationships between resistivity, liquid content, degraded waste and methane potential zones.

2. Methods

2.1. Reactor design: AD of agricultural waste

The metallic container was 6 m long, 2.5 m height and 2.5 m width, around 30 m^3 working volume. Anaerobic digestion was carried out on about 20 tons of agricultural waste (mainly cattle manure, straw, silage of corn). Waste was inoculated with 6 m^3 of liquid phase called inoculum coming from a previous anaerobic digestion cycle. The container was closed with roof and temperature was maintained at 37 °C to have optimal mesophilic anaerobic conditions. Leachate was re-circulated 500 L per hour during the batch process. Methane content of biogas was measured by a gas sensor (Dynament, UK) and biogas production was recorded by a gas meter (Gallus G4, Itron, USA).

2.2. Electrical resistivity tomography

2.2.1. General protocol

ERT is an electrical method based on the measurement of the apparent resistivity, ρ_a (ohm m), that implies injection of an electric current of an intensity (I) between two current electrodes (*A* and *B*), inserted on media surface. A second set of electrodes (*M* and *N*) measures the electrical potential (Fig. 1(A)). The electrodes were introduced in the container along a profile line (around 6 m) with defined spacing and connected by electric cables to recorder data of apparent resistivity. It is calculated by the following equation:

$$\rho a = k * (\Delta V_{MN}/I_{AB}) \quad (1)$$

where k is the geometrical factor, ΔV_{MN} is the voltage difference and I_{AB} is the intensity of current between A and B.

$$k = 2\pi\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} - \frac{1}{NB}\right]^{-1} \quad (2)$$

The apparent resistivity is a qualitative parameter which it is related to the depth and is estimated from surface measurement representing the approximate mean resistivity value of soil investigated.

The apparent resistivity is a qualitative parameter which is related to a depth level. It represents the approximate mean resistivity value of the investigated media between the measurement surface and the depth level. The apparent resistivity pseudo-sections must be inverted to obtain the resistivity sections which can be then interpreted.

The Terrameter Lund Imaging System (ABEM, Sweden) was used for the measurements. The current intensity of injection was adjusted automatically between 10 mA and 200 mA and reciprocal measurements were taken to check for reproducibility of data. For average reciprocal errors above 1%, four reciprocal data were measured.

Several protocols using different electrodes locations exist to probe media at different depths and resolution (Fig. 1). The apparent resistivity pseudo-sections were inverted with the standard Gauss–Newton code Res2dinv using software package RES2DINV (Geotomo Software in procession of Instituto Andaluz de Geofisica, Spain) (Loke and Barker, 1996; Loke et al., 2003) to reach a model of the media resistivity in 2D vertical section. The subsurface is divided into a number of rectangular blocks.

The root-mean-square (RMS) corresponds to difference between calculated and measured apparent resistivity values by adjusting resistivity of model blocks to optimize method by the following equation:

$$\mathrm{RMS} = \sqrt{\frac{1}{n^2}\sum_{i=1}^{n}\left(\frac{\log(\rho_{meas_i}) - \log(\rho_{cal_i})}{\log(\rho_{cal_i})}\right)} \quad (3)$$

where ρ_{meas_i} is the measured apparent resistivity at the ith data point, ρ_{cal_i} is the calculated apparent resistivity from the resistivity section at the ith data point and n is the number of measurement points.

Iteration number was 5 in this study. Two arrays were applied: gradient (GRD) array (Fig. 1(B)) and pole-dipole (PDP) array (Fig. 1(C)). PDP array increases the investigation depth using an infinite