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Kinetics evaluation of a semi-continuously fed anaerobic digester treating pig manure at two mesophilic temperatures

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ARTICLE INFO

Article history:
Received 17 March 2013
Received in revised form
26 June 2013
Accepted 27 June 2013
Available online 16 July 2013

Keywords:
Anaerobic digestion
Kinetics
Pig manure
Temperature
Biomass yield

ABSTRACT

Anaerobic digestion of animal waste at a low range of mesophilic conditions has not been well described to date. In this study, laboratory-scale semi-continuously fed anaerobic digesters treating pig manure were operated at 28 and 38 °C with organic loading rates ranging from 1.3 to 4.3 g ODM L^{-1} d^{-1}. The estimated biomass yield was higher at 28 °C (0.065 g VSS g^{-1} $COD_{removed}$) than at 38 °C (0.016 g VSS g^{-1} $COD_{removed}$). The resulting calculated biomass concentration range at 28 and 38 °C was 1.2–2.4 and 0.3–0.6g VSS L^{-1}, respectively, which fitted well with a Michaelis–Menten type function. These VSS results are one or two orders of magnitude lower than previously reported for manure-fed digesters. Although maximum specific substrate utilisation rate at 38 °C is five-fold that at 28 °C, higher biomass yield in the digester at 28 °C seemed to compensate for the adverse effects of lower temperature on digester performance.

1. Introduction

Animal waste is a valuable biomass resource, which can be utilized as a renewable source of energy. The most commonly applied animal waste management option is anaerobic digestion. In China, more than 30 000 medium-scale (300–500 m^3) and large-scale (>500 m^3) agricultural biogas plants were in operation in 2010 (Ministry of Agriculture, 2011). Most of these biogas plants are medium-scale and are located on pig farms. The sole substrate is pig excrement with a large amount of wastewater. However, many of the biogas units are run either at low organic loading rates (OLR) or in the lower range of mesophilic conditions because of lack of insulation and insufficient heating, resulting in low volumetric biogas production. The poor manure treatment performance results in a heavy nutrient load to subsequent wastewater treatment facilities or land. Therefore, process optimisation of agricultural biogas plants has received growing attention in China in recent years.

Temperature is one of the most important factors affecting the anaerobic digestion process. Anaerobic digestion can proceed under psychrophilic (<25 °C), mesophilic (25–40 °C) and thermophilic (>45 °C) conditions (El-Mashad et al., 2004). Mesophilic temperatures (35–37 °C) are commonly considered optimum for maintaining the stability of bacterial activity and biogas production from animal excrement (Sakar et al., 2009). However, for most of agricultural biogas plants in China, a minimum temperature of around 20 °C prevails during winter,

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0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2013.06.054

while in summer the temperature in the plant depends on the ambient temperature and can be up to around 30 °C. Thus understanding of the performance of anaerobic process under low range of mesophilic conditions is important for Chinese biogas plants. This mode of operation is different from that of biogas plants in Europe, which are mostly large-scale, run at high OLR, and most commonly have their temperature maintained at around 37–39 °C throughout the year. The biogas produce in such large-scale units is generally used in a combined heat and power plant (CHP) to produce electricity and heat. However, the high investment costs for a CHP system are unacceptable for the owners of medium- or small-scale biogas plants.

Kinetic modelling of the anaerobic degradation of complex wastes is essential for a better understanding of the performance of anaerobic processes. The development of mathematical models to describe the anaerobic digestion of animal waste began in the 1960s (Lawrence and McCarty, 1965). Numerous different types of animal waste digestion models, including un-structured non-segregated models (Chen, 1983; Chen and Hashimoto, 1980), un-structured segregated models (Hill, 1983), Structured kinetic models (Batstone et al., 2002) and empirical model (Hashimoto et al., 1981), have been developed and reported in the literature.

Process modelling based on kinetic models permits the effects of the most important process variables (substrate concentration in the influent and effluent, temperature, organic loading rate, etc.) on system performance to be predicted. Thus, development of adequate models and their parameterisation by fitting model equations to experimental results, obtained in specific assays is a very important task (Fdez-Güelfo et al., 2011). However, determination of kinetic parameters in the anaerobic process treating animal manure is a tedious exercise (Karim et al., 2007). Volatile suspended solid (VSS) is usually a very important parameter in biomass balance calculations. In the studies treating organic wastewater, biomass concentration is usually measured as VSS. However, VSS is not a good indicator of biomass concentration in a non-soluble waste e.g. manure-based digester feedstock (Ghaly et al., 2000). In additional, the effects of low-range mesophilic temperatures on the kinetic parameters in anaerobic digestion of animal waste have been less well studied than the effects of mesophilic or thermophilic temperatures.

The objectives of this study were thus: (1) to evaluate the effect of temperature (28 and 38 °C) on the biomass concentration in digesters treating pig manure using mass calculation, and to derive a Michaelis–Menten type function to predict the biomass concentration and (2) to evaluate the effect of temperature on kinetic parameters using a modified Stover-Kincannon model. The maximum substrate utilisation rate (U_{max}) and maximum specific substrate utilisation rate (k) at the two temperatures were compared.

Table 1 – Properties of farm-yard pig manure used for this study.

Parameter	Mean value ± st. dev.
pH	6.7–7.2
DM (%)	24.90 ± 0.03
ODM (of DM %)	83.19 ± 0.15
Total Kjeldahl nitrogen (%)	1.12 ± 0.03
Total phosphorus (%)	0.46 ± 0.04
Crude protein (dry basis %)	15.72 ± 2.28
Crude cellulose (dry basis %)	18.58 ± 0.68
Crude fat (dry basis %)	5.97 ± 0.07

2. Materials and methods

2.1. Feedstock and inoculum

Pig slurry (dry matter (DM):1.9%; organic dry matter (ODM): 1.4%) was used only to start up the biogas process and farm-yard manure (FYM) diluted with water was used at the subsequent loadings. Both substrates were collected from the Frankenforst University Experimental Farm, Bonn, Germany, and stored at 4 °C prior to use. The characteristics of the FYM are presented in Table 1. Because of the long-term nature of the experiments (nearly one year), the ODM of the FYM was determined once a week in order to ensure precise control of OLR. To start the biogas process, the digesters were inoculated with sewage sludge (DM: 1.2%, ODM: 0.75%) from a wastewater treatment plant in Bonn, Germany.

2.2. Digester

Six completely stirred anaerobic digesters with a volume of 10 L (diameter 19 cm, height 37.5 cm) and an effective slurry volume of 8 L were used. Each digester was sealed by a Plexiglas cap with a stirrer in the middle of the cap and a biogas

Table 2 – Steady-state performance results for different OLRs at 38 °C and 28 °C.

T °C	OLR g ODM L^{-1} d^{-1}	ODM concentration in influent g L^{-1}	ODM concentration in effluent g L^{-1}	Volumetric methane production L L^{-1} d^{-1}	VFA/TIC ratio	TAN g L^{-1}
38	1.3	32.5	14.8 ± 3.2	0.41 ± 0.02	0.15 ± 0.03	1.6
	2.3	57.5	29.1 ± 3.9	0.70 ± 0.02	0.19 ± 0.02	2.7
	3.3	82.5	49.3 ± 3.2	0.77 ± 0.03	0.22 ± 0.04	2.5
	4.3	107.5	64.5 ± 6.4	0.94 ± 0.03	0.25 ± 0.02	3.2
28	1.3	32.5	16.3 ± 2.1	0.40 ± 0.02	0.16 ± 0.02	1.6
	2.3	57.5	31.7 ± 1.5	0.60 ± 0.03	0.31 ± 0.02	1.6
	3.3	82.5	49.9 ± 2.4	0.73 ± 0.03	0.39 ± 0.04	1.9
	4.3	107.5	62.0 ± 4.9	0.91 ± 0.05	0.54 ± 0.04	2.0