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Starting-up low temperature dry anaerobic digestion of cow feces and wheat straw

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ABSTRACT

Psychrophilic dry anaerobic digestion (PDAD) of animal manures and agriculture residues is of high interest in cold-climate regions. This paper reports the results of a start-up experiment (113 days) of PDAD of cow feces and wheat straw mixture (at two total solids (TS) of 18 and 21%) in laboratory scale sequence batch reactor (SBR) at 20 °C. An average specific methane yield (SMY) of 96.1 ± 5 L of CH_4 per kg of volatile solid (VS) corrected to standard pressure and temperature (101.3 kPa and 273 K) ($_N$L CH_4 kg^{-1} VS) has been achieved for a feed with TS of 18% along with an organic loading rate (OLR) 4.0 g total chemical oxygen demand (TCOD) kg^{-1} inoculum day^{-1} and a treatment cycle length (TCL) of 21 days. An average SMY of 149.9 ± 14 $_N$L CH_4 kg^{-1} VS with a maximum daily CH_4 production rate of 7.2 ± 0.7 $_N$L CH_4 kg^{-1} VS day^{-1} have been obtained for a feed with total solid of 21% along with an average daily inoculum OLR of 4.2 g TCOD kg^{-1} inoculum day^{-1} and TCL of 21 days. The rapid decrease in volatile fatty acids concentration after 7 days of treatment and their low concentration thereafter indicated that hydrolysis was the reaction limiting step. The results indicate that PDAD of cow feces and wheat straw is feasible at feed TS of 21%.

1. Introduction

Livestock manure is an abundant renewable source of substrate which can be converted into biofuel through anaerobic digestion (AD). Around 40–50% of the volatile solids (VS) in dairy manure is biodegradable. It is composed of lignocellulosic biomass of reduced carbon which can be converted to CH_4 [1]. Cow feces, for example, has total solids (TS) content around 10–13%, but using bedding materials increases its TS to as high as 25% [2]. Usually, such substrate must be primarily diluted in order to decrease its TS content for liquid handling and processing in liquid AD processes [3]. Moreover, diluting manure from TS of about 20% to between 1 and 5% increases the volume of the required bioreactor. Furthermore, on-farm wet anaerobic digestion (WAD) of dairy manure is usually performed at mesophilic and thermophilic conditions by using some of the biogas produced to heat the bioreactor continuously thus decreasing the net energy yield. For cold-weather region such as in Canada and the northern parts of the USA, heating the bioreactor reduces the net energy output. An anaerobic digestion process which can digest dairy manure of around 20% TS and operate at low temperature such as 20 °C would provide an alternative to the mesophilic and thermophilic wet and dry AD processes. Psychrophilic dry anaerobic digestion (PDAD) is getting more interest because the lower energy input for heating which increases specific volumetric energy output of the bioreactor compared to mesophilic and thermophilic WAD and DAD. The PDAD of cow manure (mixture of cow feces and beddings material such as wheat straw) has been developed recently at Agriculture and Agri-Food, Dairy and swine Research and Development Centre (DSRDC) in Sherbrooke, Quebec-Canada.

PDAD development built on the previous development of psychrophilic anaerobic digestion (PAD) in sequential batch reactor (SBR) [4,5], developed at DSRDC to stabilize agricultural wastes with TS contents lower than 12%, such as swine manure. Massé et al. [4–8] have demonstrated that low temperature wet anaerobic digestion provided a unique, very stable and cost effective process for liquid swine manure. PAD reduces odors, decreases the organic pollution load by more than 70% [5], produces high quality biogas, significantly diminishes pathogens survival [6], and improves the agronomic value of digestate [9]. The PAD process offers the competitive advantages of great stability, robustness, maximum performance, and minimum supervision [4]. Research is still

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needed to adapt this technology to agricultural wastes with high solids such as dairy manure with bedding.

The feasibility of mesophilic and thermophilic DAD of the organic fraction of municipal solid wastes (OFMSW) has been demonstrated [10,11]. However, psychrophilic DAD of livestock manure still needs more development and optimization studies prior being recommended for livestock wastes processing.

Mesophilic or thermophilic DAD of agricultural wastes with high solids content is a relatively new biotechnology [12,13]. Schäfer et al. [14] reviewed the suitability and economic feasibility of on-farm DAD for solid manure, crop residues, spoiled hay and silage, and energy crops [14]. They concluded that the ideal technologies have not been invented yet thus DAD has been found uncompetitive in terms of energy production compared to current slurry-based technologies. For the anaerobic digestion of the organic fraction of municipal solid waste (OFMSW), Luning et al. [15] indicated that the specific gas yields from DAD (25% TS) and WAD (5% TS) were identical (15 kton of biogas per 100 kton of organic material digested) at a hydraulic retention time of 18 days; similarly, the organic loading rates were close to each other, 6.8 and 7.7 kg VS m^{-3} d^{-1}, respectively.

For agriculture residue, Mussoline et al. [16] reported a specific methane yield of 231 L CH_4 kg^{-1} VS of untreated rice straw in mesophilic dry (20% TS) pilot-scale digester (1 m^3) inoculated with pig wastewater and anaerobic sludge; however, the retention time was long (93 days) at OLR of 4.8 g VS kg^{-1} d^{-1}. Sun et al., 1987 concluded that specific methane yield (333–349 L CH_4 kg^{-1} VS of rice straw) from DAD (15–30% TS) was comparable to that (325 L CH_4 kg^{-1} VS of rice straw) from WAD (8% TS) in mesophilic operation (28 °C); however the retention time in DAD was 1.5–2.1 of that in WAD [17].

Literature published so far investigated mostly mesophilic DAD; however, no data exist for psychrophilic DAD whether for livestock manure, agriculture residue, or the OFMSW. Lack of research and development of on-farm DAD is behind its slow development; more work is needed to demonstrate its technical and economical feasibility [14]. The main objective of this study was to assess the technical feasibility of starting up psychrophilic (20 °C) dry anaerobic digestion of the dairy cow manure and wheat straw at feed TS of 18 and 21%.

2. Materials and methods

2.1. Experimental design

Six 40-L cylindrical barrel bioreactors were operated as sequential batch reactors (SBR) in a temperature controlled room (20 °C). The reactors were fitted with two gas lines; one for purging with nitrogen gas immediately after feeding the substrate to maintain the anaerobic condition, and the second to release and quantify the biogas produced. The experimental design is given in Table 1.

Cow feces and wheat straw were fed at total solids of 18 and 21% and digested in psychrophilic conditions during 113 days. A strategic objective was also to adapt the inoculum to ferment the substrate (cow feces and wheat straw) within a desired treatment cycle length of 21 days. The treatment cycle length (TCL) of the first cycle has been extended to multiples of 21 days (i.e., 42, 63, and 71 days) to allow the inoculum to adapt to the feed TS of 18%. In the second treatment cycle, the TS has been increased to 21% and the treatment cycle length has been extended from 21 to 42 days (=2 TCL).

The initial inoculum was obtained from a semi-industrial scale (11.4 m^3; TS = 5.7% and VS = 4.4) psychrophilic (20 °C) anaerobic reactor fed with fresh dairy manure (12% TS), and operated as a SBR. Fresh feces from dairy cows were collected at the experimental farm of the Dairy and Swine Research and Development Centre (DSRDC), Sherbrooke, Quebec. Feces was collected on wood boards, before getting in contact with urine and bedding, transferred into a plastic drum, stored at 4 °C, before being fed to the reactors. Cow feces has been used as it is; no attempt has been made to adjust its alkalinity or pH. Wheat straw was harvested at the DSRDC's experimental farm during fall 2011 and fall 2012 and chopped (3 mm) using a laboratory mill (Thomas Wiley Laboratory Mill Model 4, Arthur H. Thomas Company, Philadelphia, PA). Different masses of wheat straw and cow feces (Table 2) were mixed manually to obtain the desired feed TS content (18 and 21%) while maintaining the design organic loading rate (OLR) of around 4.0 g TCOD kg^{-1} inoculum day^{-1} based on a 21 days treatment cycle length.

The substrate and inoculum has been mixed manually for 5 min during feeding. Every week the content of the bioreactor is mixed manually for 5 min before sampling the content to ensure a homogenous and representative sample is taken. No mixing took place during other time of the treatment cycle; therefore, the process can be considered as a static dry anaerobic digestion.

2.2. Organic loading rate

The VS-based inoculum-to-substrate ratio (ISR) at the beginning of the cycles and the organic loading rate (OLR) are given in Table 2. The OLR has been calculated based on the masses of VS and total chemical oxygen demand (TCOD) and the composition of the substrate fed (Table 2). OLR was expressed in g of TCOD per kg of inoculum, and g of total VS per kg of inoculum per day.

2.3. Biogas measurement

Biogas volume produced was measured daily using calibrated wet tip gas meters while the biogas components (CH_4, H_2S, CO_2)

Table 1
Experimental design.

Cycle	Duration (days)	Substrate	TS (%)	Number of replicates
1	71	CF + WS	18	6
2	42	CF + WS	21	6

Note: CF = cow feces; WS = wheat straw.

Table 2
Composition of the feed and the organic loading rate.

Parameter	Cycle 1	Cycle 2
Inoculum (kg)	4	6
Cow feces (kg)	2	1.7
Straw (kg)	0.13	0.20
TCOD/VS ratio for:		
Cow feces	0.8	1.5
Straw	1.29	1.29
Feed	0.97	1.40
Mass fraction of cow feces in feed	0.94	0.89
Mass fraction of straw in feed	0.06	0.11
Feed TS (%)	18.3	21.4
ISR (VS-based)	0.96	0.96
Organic loading:		
TCOD fed (g)	339.5	525.5
VS fed (g)	350.5	375.0
Organic loading arte (OLR) (based on 21 days cycle):		
COD-based (g TCOD kg^{-1} inoculum d^{-1})	4.0	4.2
VS-based (g VS kg^{-1} inoculum d^{-1})	4.2	2.97

Note: ISR = inoculum-substrate ratio.