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Impact of organic loading rate on the performance of psychrophilic dry anaerobic digestion of dairy manure and wheat straw: Long-term operation

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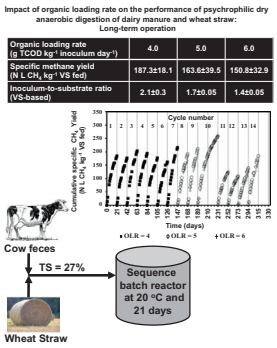
HIGHLIGHTS

- Psychrophilic dry anaerobic digestion (PDAD) of cow feces and wheat straw (CFWS).
- PDAD of CFWS (27% TS) is feasible at OLR of 4.0, 5.0 and 6.0 g TCOD kg^{-1} d^{-1}.
- PDAD of CFWS (TS 27%) is as efficient as mesophilic DAD.
- At OLR 6.0 g TCOD kg^{-1} d^{-1} and 21 days TCL yielded max 175 ± 12 N L CH_4 kg^{-1} VS.
- VS-based substrate to inoculum ratio of 0.71 is possible at OLR 6.0 g TCOD kg^{-1} d^{-1}.

GRAPHICAL ABSTRACT



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ABSTRACT

Development of efficient processes for valorising animal wastes would be a major advancement in cold-climate regions. This paper reports the results of long term (315 days experiment) of novel psychrophilic (20 °C) dry anaerobic digestion (PDAD) of cow feces and wheat straw in laboratory scale sequence batch reactor operated at increasing organic loading rate.

The PDAD process fed with a mixture of feces and straw (TS of 27%) over a treatment cycle length of 21 days at organic loading rate (OLR) 4.0, 5.0 and 6.0 g TCOD kg^{-1} inoculum d^{-1} (of 2.9 ± 0.1, 3.7 ± 0.1, and 4.4 ± 0.1 g VS kg^{-1} inoculum d^{-1}, respectively) resulted in average specific methane yield (SMY) of 187.3 ± 18.1, 163.6 ± 39.5, 150.8 ± 32.9 N L CH_4 kg^{-1} VS fed, respectively. PDAD of cow feces and wheat straw is possible with VS-based inoculum-to-substrate ratio of 1.4 at OLR of 6.0 g TCOD kg^{-1} inoculum d^{-1}. Hydrolysis was the limiting step reaction.

1. Introduction

Livestock industry produces large amount of manure that needs to be treated and stabilized. In Canada and USA, cattle generate about 75% and 86% of the manure produced by livestock (Hofmann and Beaulieu, 2001; Wen et al., 2004). Although fresh cow feces has a total solids (TS) content of about 12–14% bedding materials such as straw increase the total solids to about 25% (Demirer and Chen, 2008). Around 40–50% of the volatile solids (VS) in dairy manure is biodegradable lignocellulosics biomass which can be converted to CH_4 (Abbassi-Guendouz et al., 2012). Obviously, wet anaerobic digestion (WAD) is not the best bioprocess to stabilize solid wastes since the dilution required to decrease manure's total solids concentration for liquid handling will result in large volume of the reactors.

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Table 1
Experimental design.

Cycle	Treatment cycle length (days)	Substrate	TS (%)	OLR (g TCOD kg^{-1} inoculum d^{-1})	Number of replicates
1–7	21	CF + WS	27	4	3
8–14	21	CF + WS	27	5	4
8–14	21	CF + WS	27	6	2

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

Dry anaerobic digestion (DAD) is relatively a new alternative biotechnology which has been demonstrated at mesophilic and thermophilic conditions for the organic fraction of municipal solid wastes (OFMSW; 15% TS) (Challen Urbanic et al., 2011; Li et al., 2011b; Ramasamy and Abbasi, 2000) and for agricultural wastes and livestock manure (15–20% TS) (Ahn et al., 2010; Di Maria et al., 2012; Kusch et al., 2008). Schäfer et al. (2006) assessed the suitability and economic feasibility of on-farm DAD for solid manure, crop residues, spoiled hay and silage, and energy crops. They concluded that although DAD is suitable for on-farm conditions the ideal technologies have not been invented yet thus DAD has been found uncompetitive in terms of energy production to current slurry-based technologies. Specific methane yield of rice straw was higher in DAD compared to a WAD process (specific methane yield of 423 and 350 L CH_4 kg^{-1} VS for initial total solids of 8% and 30% digested in batch reactors at 28 °C, respectively) (Sun et al., 1987). Luning et al. (2003) indicated that the specific gas yields from the organic fraction of municipal solid waste in DAD and WAD were identical (15 kton of biogas per 100 kton of organic material digested); similarly, the organic loading rates (OLR) were close to each other, 6.8 and 7.7 kg VS m^{-3} d^{-1}, respectively. Brown et al. (2012) concluded that volumetric productivity of DAD (18% TS) is 2- to 7- times greater compared to WAD (5% TS) for lignocellulosic substrates based on 30 days batch incubation. Massé et al. (2011, 2010, 1997) and Massé and Droste (2000) have demonstrated that low temperature wet anaerobic digestion provided a unique, very stable and cost effective process for liquid animal manure.

Recently, a patent-granted bioprocess for psychrophilic DAD of cow manure (mixture of cow feces and beddings material such as wheat straw) has been developed at Agriculture and Agri-Food, Dairy and Swine Research and Development Centre (DSRDC) in Sherbrooke, Quebec-Canada to stabilize cow manure and convert its reduced carbon into methane. The process has been demonstrated successful in digesting cow feces (TS = 13–16%) at OLR of 3.0–6.0 g TCOD kg^{-1} inoculum d^{-1} during long-term study (252 days) (Massé and Saady, 2014). Moreover, it has been demonstrated for cow feces and wheat straw mixture at TS of 27% and OLR of 3.0 g TCOD kg^{-1} inoculum d^{-1} during long-term study (273 days) (Massé et al., 2014). Increasing the OLR fed to a bioreactor is a basic engineering design objective to decrease the bioreactor volume (Luning et al., 2003), and reduce its construction costs.

Hashimoto (1989) showed that the ultimate methane yield from straw decreased drastically from around 0.30–0.02 mL CH_4 - g^{-1} VS at VS-based inoculum/substrate ratio (ISR) of 0.25 and less than 0.25, respectively, in 150 days batch incubation; however, increasing the ISR from 0.07 to 2.0 increased the methane yield at a decreasing rate up to ISR $\geqslant$ 2.0 where the yield remained relatively constant. In addition, the increase in ISR decreases the time required to convert the organic substrate completely to methane in batch experiment (Hashimoto, 1989). Nevertheless, not many studies are published on the effect of OLR on the performance of dry anaerobic digestion. The principal objective of this study was to assess the effect of increasing the substrate OLR and decreasing the ISR on long-term performance of psychrophilic (20 °C) dry anaerobic digestion of dairy cow manure and wheat straw at 27%. Feed total solids of 27% was targeted because cattle in sheds with straw bed produce manure of around 27% TS (Demirer and Chen, 2008).

2. Methods

2.1. Experimental setup

The experimental design is described in Table 1. Several 40-L cylindrical barrels bioreactors have been operated as sequential batch reactors (PSBR) at a treatment cycle length (TCL) of 21 days in a temperature-controlled room (20 °C). The working volume ranged between 7.2 and 8.5 L based on the volumes of the feed and inoculum used. Each reactor was fitted with two gas lines;

Table 2
Composition of the feed and its Organic loading rate.

Cycle	Feces (kg)	Straw (kg)	ISR (VS-based)	Feed TCOD/VS ratio	Organic loading			
					TCOD fed (g)	VS fed (g)	g TCOD kg^{-1} inoculum d^{-1}	g VS fed kg^{-1} inoculum d^{-1}
1	1.212	0.272	2.0	1.34	503	374	4.0	2.97
2	1.212	0.272	1.9	1.34	503	374	4.0	2.97
3	1.212	0.272	1.9	1.34	503	374	4.0	2.97
4	1.212	0.272	1.9	1.34	503	374	4.0	2.97
5	1.178	0.266	1.9	1.38	504	365	4.0	2.89
6	1.241	0.210	2.5	1.55	500	325	4.0	2.58
7	1.241	0.210	2.5	1.55	504	356	4.0	2.83
8	1.550	0.263	1.7	1.42	630	445	5.0	3.53
9	1.527	0.308	1.6	1.38	630	456	5.0	3.62
10	1.527	0.308	1.6	1.38	630	456	5.0	3.62
11	1.550	0.362	1.7	1.32	630	478	5.0	3.80
12	1.550	0.362	1.7	1.32	630	478	5.0	3.80
13	1.452	0.343	1.7	1.34	630	470	5.0	3.73
14	1.452	0.343	1.7	1.34	630	470	5.0	3.73
8	1.860	0.315	1.4	1.42	756	534	6.0	4.24
9	1.830	0.370	1.4	1.38	756	547	6.0	4.34
10	1.830	0.370	1.4	1.38	756	547	6.0	4.34
11	1.860	0.435	1.5	1.32	756	574	6.0	4.56
12	1.860	0.435	1.5	1.32	756	574	6.0	4.56
13	1.743	0.410	1.4	1.37	756	550	6.0	4.36
14	1.743	0.410	1.4	1.37	756	550	6.0	4.36

Note: In all cycles the reactors have been inoculated with 6 kg of inoculum which has been transferred from the previous cycle. The feed TS has been kept at 27% in all cycles.