Bioresource Technology 187 (2015) 128–135

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

# High rate psychrophilic anaerobic digestion of undiluted dairy cow feces

Daniel I. Massé, Noori M. Cata Saady *

*Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, Sherbrooke, Quebec J1M 0C8, Canada*

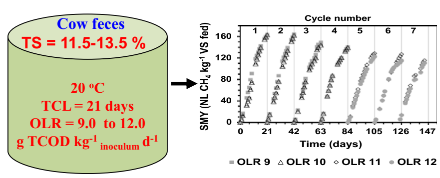
## HIGHLIGHTS

- Anaerobic digestion (DAD) of cow feces is feasible at 20 °C and 21 days.
- Psychrophilic DAD of cow feces (TS 11.5–13.5%) is as efficient as mesophilic DAD.
- Cow feces at OLR 9–12 g VS fed $kg^{-1}$ inoculum $d^{-1}$ yielded 154–116 NL $CH_4$ $kg^{-1}$ VS.
- The substrate to inoculum mass ratio (SIR) was 1.17–1.43.
- Cow feces quality affected the methane yield more than the OLR.

## GRAPHICAL ABSTRACT

**High rate psychrophilic anaerobic digestion of undiluted dairy cow feces**

| Organic loading rate (g TCOD $kg^{-1}$ inoculum $day^{-1}$) | 9.0 | 10.0 | 11.0 | 12.0 |
|---|---|---|---|---|
| Specific methane yield (N L $CH_4$ $kg^{-1}$ VS fed) | 154.0±11.7 | 152.1±12.2 | 126.0±2.8 | 116.0±6.1 |
| Substrate-to-inoculum ratio | 1.17±0.06 | 1.30±0.06 | 1.31±0.05 | 1.43±0.05 |




## ARTICLE INFO

*Article history:*
Received 11 February 2015
Received in revised form 23 March 2015
Accepted 24 March 2015
Available online 28 March 2015

*Keywords:*
Psychrophilic
High-solids
Dry anaerobic digestion
Cow manure
Wheat straw

## ABSTRACT

Novel high rate psychrophilic (20 °C) anaerobic digestion (PAD) of undiluted cow feces (11.5–13.5% total solids) was demonstrated using sequence batch reactor in long-term operation with successive cycles of 21 days treatment cycle length (TCL). At organic loading rates (OLR) 9.0, 10.0, 11.0 and 12.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$ average specific methane yield (SMY) was 154.0 ± 11.7, 152.1 ± 12.2, 126.0 ± 2.8 and 116.0 ± 6.1 NL $CH_4$ per kg of VS fed, respectively. Volatile solids removal averaged around 31.7 ± 3.3%, 32.2 ± 1.0%, 27.9 ± 2.2% and 23.4 ± 0.5%, respectively. Substrate-to-inoculum ratio (SIR; wet-mass basis) ranged between 1.17 ± 0.06 and 1.43 ± 0.05. Concentration of volatile fatty acids in the bioreactors during the TCL indicated that hydrolysis was the rate limiting reaction. High rate PAD of undiluted cow feces is possible at OLR (g TCOD $kg^{-1}$ inoculum $d^{-1}$) 9.0 and 10.0 with a TCL of 21 days; however, OLR of 11.0 and 12.0 are also possible but require longer TCL to maintain the SMY.



## 1. Introduction

Livestock manure is responsible for about 6.6% and 1.1% of total greenhouse gas (GHG) emissions in the United States and Canada, respectively (Baylis and Paulson, 2011). Similarly, dairy cow slurry storage in cold regions generates, for example, about 12% and 23% of the total $CH_4$ emission from livestock operation in Europe and the US, respectively (Hindrichsen et al., 2005; IPCC, 1996). These emissions could be reduced and green energy could be recovered if a cost-effective on-farm process is developed to digest livestock manure economically. So far, dilute manure (total solids (TS) < 10%) has been treated using wet mesophilic and thermophilic anaerobic digestion (AD). However, large reactor volume is required and heating and mixing reduce the net energy yield; farmers were generally reluctant to invest in wet anaerobic digestion (WAD) because of its high operating costs and long payback periods.

Currently, on-farm dry anaerobic digestion (DAD) of undiluted manure is under intensive research (Ahn et al., 2010; Boske et al., 2014; Böske et al., 2015; Di Maria et al., 2012; Kusch et al., 2008; Li et al., 2014; Massé and Saady, 2015) to introduce technological advancements which decrease the environmental impact, increase bioenergy yield, and reduce capital and operating costs. Increasing both the organic loading rate (OLR) and the substrate total solids fed to AD are important engineering design objectives to decrease

* Corresponding author. Tel.: +1 819 780 7304; fax: +1 819 564 5507.
*E-mail address:* noori.saady@agr.gc.ca (N.M.C. Saady).

http://dx.doi.org/10.1016/j.biortech.2015.03.110
0960-8524/

the bioreactor volume, increase the energy yield per bioreactor unit volume, and reduce its construction and operation costs (Massé and Saady, 2015). Further increase in energy yield would be achieved by adopting psychrophilic (<20 °C) rather mesophilic or thermophilic operation. Compared to mesophilic and thermophilic WAD, psychrophilic dry anaerobic digestion (PDAD) of undiluted cow feces offers more advantages such as less energy input for mixing and heating, and increases the specific volumetric energy output of bioreactor (Brown et al., 2012).

Cow feces contains soluble and particulate organic materials such as carbohydrates (cellulosic and hemicellulosic fibers), volatile fatty acids (VFAs), lipids and fats, and proteins. Around 40–50% of the volatile solids (VS) in dairy manure is biodegradable lignocellulosic biomass which can be converted to $CH_4$ through AD (Abbassi-Guendouz et al., 2012). Recently, there has been increasing interest in PDAD of cow manure (Li and Jha, 2014; Massé and Saady, 2015; Zhu et al., 2014). The PDAD in sequential batch reactor (SBR), to digest undiluted cow feces with TS contents lower than 16%, has been developed lately at Agriculture and Agri-Food, Dairy and Swine Research and Development Centre (DSRDC) in Sherbrooke, Quebec–Canada (Massé and Saady, 2015). They have shown that PDAD of cow feces (12–16% total solids) is feasible in SBR. In addition, they demonstrated that PDAD of undiluted cow feces at OLR of 3.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$ was as efficient as mesophilic and thermophilic WAD of dilute cow manure (TS < 5.0%).

For wet process, SBR operation consists of four successive steps: fill, react, settle, and draw. For a dry process with no liquid–solid phase separation, the settle step is eliminated and digestate rather than decant is withdrawn as effluent in the draw step. The SBR is fed cow feces during the fill step. Treatment cycle length (TCL) should provide sufficient time to the reaction step to achieve pre-determined treatment objectives such as specific methane yield, VS and TCOD removal, etc. During the draw step, some of the digestate is reused as inoculum for the next cycle while some is disposed as effluent.

Most of the recently published studies on psychrophilic AD of undiluted cow manure were in batch (Li and Jha, 2014; Zhu and Jha, 2013) or at low organic loading rate (OLR) (3.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$) (Massé and Saady, 2015). To the author's best knowledge, no previous reports are available in the accessible literature on high rate PDAD. This is the first report on successful high rate psychrophilic (20 °C) dry anaerobic digestion (PDAD) of cow feces over long-term operation in sequence batch reactor. The principal objective of this study was to demonstrate feasibility and assess the performance of PDAD of dairy undiluted cow feces (TS 11.5–13.5%) in long-term operation using sequence batch bioreactor at high OLR (9.0–12.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$).

## 2. Methods

### 2.1. Experimental setup

A total of 7 treatment cycles have been conducted. Cycles 1, 2, 3 and 4 were operated at OLR of 9.0 and 10.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$ while cycles 5, 6 and 7 were operated at OLR of 11.0 and 12.0 g TCOD $kg^{-1}$ inoculum $d^{-1}$.

### 2.2. Bioreactor

Two sets of duplicate 40-L cylindrical (0.312 m in diameter × 0.520 m in height) plastic barrels were set-up and operated as batch reactors (PSBR) at a TCL of 21 days (measured from feeding the reactor to the next feeding) 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 the biogas produced from the bioreactor to the wet tip gas meter. The barrel was kept upside down after it has been filled so that the wet content works as a water seal in addition to the seal of the barrel's lid to ensure gas tightness.

### 2.3. Wet tip tank gas meter

The wet tip tank gas meter was manufactured at the workshop of DSRDC of transparent acrylic box, and consisted of a pivoting plastic container which is comprised of two equal-size compartments facing downwards to a port that releases biogas under the pivoting point. The biogas accumulates under the compartment which faces the gas port. The tipping container was placed submerged inside the acrylic box which is filled with water. When biogas released into one compartment reaches a certain known volume, the container tips (the compartment filled with gas pivots upward) due to the buoyancy of the gas and releases the biogas which bubbles upwards to escape from water and leaves the box. Upon tipping (pivoting) the second compartment on the other side of the container moves downward and biogas released from the port starts to accumulate inside it, and so on. Each tip was counted using a magnetic sensor which sends an electrical pulse to an electronic digital counter (manufacturer: OmRon; model number: H7EC-NV-B). The tip counts were monitored daily and used to calculate the volume of the biogas produced. The wet tip tank gas meter calibration was checked weekly. After feeding the reactor was held upside down so that the inoculum–substrate mixture provides sealing in addition to the locked lid of the barrel.

### 2.4. Inoculum and substrate

Fresh feces from dairy cows was collected at the experimental farm of the DSRDC. Feces were 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. Physico-chemical characteristics of the cow feces fed during the successive cycles are given in Table 1.

The initial inoculum which has been used to initiate the reaction in the first cycle was obtained from a laboratory scale (40 L; TS = 9%) psychrophilic (20 °C) anaerobic reactor fed with fresh dairy manure (11–16% TS), and operated as a SBR. Starting from the second cycle forwards, each reactor received 6 kg of the digestate from the previous cycle as inoculum for the next cycle. The mass of inoculum and cow feces fed to each bioreactor at beginning of each of the successive cycles and the corresponding OLR are given in Table 2.

At the end of each cycle, the effluent (digestate) has been withdrawn manually using a scoop. The remaining contents of the duplicate reactors have been mixed, homogenized, and each empty reactor received 6 kg of the digestate as inoculum for the next cycle.

The substrate and inoculum has been mixed manually for 5 min during feeding. Every week the content of the bioreactor is mixed manually for 3–5 min before sampling the content to ensure a homogenous and representative sample is taken. No mixing took place during other time of incubation; therefore, the process is considered as a static dry anaerobic digestion.

### 2.5. Organic loading rate

Organic loading rate (OLR) has been calculated based on the masses of TCOD and VS of the substrate fed (Table 2). OLR was expressed in g of VS fed per kg inoculum VS per day and g of TCOD fed per kg of inoculum VS per day. The average of