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High rate psychrophilic anaerobic digestion of high solids (35%) dairy manure in sequence batch reactor

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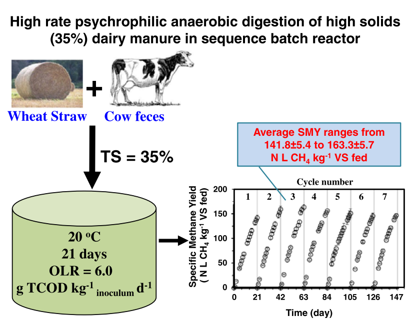
HIGHLIGHTS

- Psychrophilic dry anaerobic digestion (PDAD) of cow feces and wheat straw (CFWS).
- At OLR 6.0 g TCOD kg^{-1} d^{-1} and 21 days the yield is 163.3 ± 5.7 N L CH_4 kg^{-1} VS.
- PDAD of CFWS is feasible at 35% TS in feed and OLR of 6.0 g TCOD kg^{-1} d^{-1}.
- VS-based inoculum to substrate ratio of 2.13 ± 0.2.
- PDAD of CFWS (TS 35%) is as efficient as mesophilic DAD.

GRAPHICAL ABSTRACT



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ABSTRACT

Zero liquid discharge is increasingly adopted as an objective for waste treatment process. The objective of this study was to increase the feed total solids (TS) and the organic loading rate (OLR) fed to a novel psychrophilic (20 °C) dry anaerobic digestion (PDAD). Duplicate laboratory-scale bioreactors were fed cow feces and wheat straw (35% TS in feed) at OLR of 6.0 g TCOD kg^{-1} inoculum d^{-1} during long-term operation (147 days consisting of 7 successive cycles).

An overall average specific methane yield (SMY) of 151.8 ± 7.9 N L CH_4 kg^{-1} VS fed with an averaged volatile solids removal of 42.4 ± 4.3% were obtained at a volatile solids-based inoculum-to-substrate ratio (ISR) of 2.13 ± 0.2. The operation was stable as indicated by biogas and VFAs profiles and the results were reproducible in successive cycles; a maximum SMY of 163.3 ± 5.7 N L CH_4 kg^{-1} VS fed was obtained. Hydrolysis was the reaction limiting step. High rate PDAD of 35% TS dairy manure is possible in sequential batch reactor within 21 days treatment cycle length.

1. Introduction

The main waste by-product from livestock operations is manure containing biodegradable organic matter. The amount of manure has been increasing worldwide as a result of the livestock industry growth. Manure handling and disposal represent a substantial part of farm operation cost and also represent environmental, economic, and social challenges to livestock operations. Therefore, developing robust and cost effective technologies for on-farm manure-to-energy conversion can solve some of its environmental problems and improve the social acceptability of livestock operations. The generation of revenue will help to offset manure management cost.

Currently, anaerobic digestion is well-established and accepted on-farm manure treatment which generates combustible biogas containing methane. Dairy manure on livestock operations that use bedding is characterized by its high solids; depending on the amount of bedding used the total solids (TS) of manure may be as high as 40%. Wet anaerobic digestion (WAD; TS < 15%) has been

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used to treat manure; however, currently developing dry anaerobic digestion (DAD; TS > 15%) is gaining interest because it offers several advantages when compared with WAD. For example, DAD requires a digester of smaller size compared to wet anaerobic digestion (WAD); this translates in reduced capital and operational costs, and higher volumetric bioenergy yield (Luning et al., 2003).

The advantages of DAD have been demonstrated at mesophilic and thermophilic conditions for agricultural wastes and livestock manure (15–20% TS) (Ahn et al., 2010; Böske et al., 2015; Di Maria et al., 2012; Jha et al., 2013; Kusch et al., 2008; Wei et al., 2014; Zhu et al., 2014). However, most manure producing regions such as Canada, Europe, northern part of the USA and China are classified as cold regions. Therefore, psychrophilic (15–25 °C) operation would be more suitable for cold-climate regions if its feasibility is demonstrated because maintaining mesophilic and thermophilic conditions by heating the bioreactor reduces the net energy output. Kashyap et al. (2003) stated that developing a psychrophilic anaerobic digestion process to convert cattle manure to biogas is still a technological challenge. Since then, some technological advancement have been achieved; several on-farm psychrophilic WAD processes have been developed and deployed (Massé et al., 2010). Accommodating manure with high solids content (>15%) in psychrophilic operation is still a challenge that needs a technical solution. Presently, developing and optimizing a psychrophilic dry anaerobic digestion (PDAD) process is under extensive research worldwide.

Recently, a PDAD process of cow feces with and without wheat straw in sequential batch reactor (SBR) at 20 °C, has been developed at the Dairy and Swine Research and Development Centre (DSRDC) of Agriculture and Agri-Food Canada, in Sherbrooke, Quebec-Canada (Massé et al., 2015). The process has been demonstrated in long term operation (> 450 days) at TS of 27% and organic loading rate of 3 g TCOD kg^{-1} inoculum d^{-1} (Massé and Saady, 2015).

The upper threshold limit for the total solids at which successful dry anaerobic digestion can be conducted is not well determined. Recently, Motte et al. (2013) concluded that wheat straw mesophilic conversion to volatile fatty acids (VFAs) decreased with the increase in its TS from 10% to 33% with no changes in the volatile fatty acids profiles until a clear limit at 28% TS supposedly because of the decrease of free water in the media. No information exists regarding the threshold limit of the TS content for a substrate composed of cow feces and wheat straw digested at psychrophilic condition.

This study is a step on developing PDAD by increasing the total solids content of the feed by 30% (from TS of 27% to 35%) while doubling the organic loading rate (from 3.0 to 6.0 g TCOD kg^{-1} inoculum d^{-1}) fed to sequence batch reactor. The principal objectives of this study were to answer the question: is it possible to have a high rate PDAD of high total solids (35%) dairy manure at relatively short treatment cycle length (21 days). To the authors' best knowledge, this is the first reports on successful long-term operation (147 days consisting of 7 successive treatment cycles) of PDAD at 35% TS in feed and OLR of 6.0 g TCOD kg^{-1} inoculum d^{-1}.

2. Methods

2.1. Experimental setup

The experiments assessed the effect of the organic loading rate (6.0 g TCOD kg^{-1} inoculum day^{-1}) on CH_4 production and process stability of psychrophilic anaerobic digestion of cow feces and wheat straw. The substrate total solids (TS) have been kept at 35%. The 147 days of operation comprised of seven successive cycles. The treatment cycle length (TCL) was 21 days measured between successive feedings of the reactor. The cycle includes the following steps: day 1: loading the reactor with inoculum, feeding the substrate, and mixing the inoculum and substrate; day 1–21: reaction; and day 21: unloading the digestate and starting the next cycle.

2.2. Bioreactor

Duplicate 40-L cylindrical (0.312 m in diameter × 0.520 m in height) plastic barrels bioreactors have been operated as sequential batch reactors (SBR) at a treatment cycle length (TCL) of 21 days in a temperature-controlled room (20 °C). The average mass of combined feed and inoculum in the reactor was about 7.74 ± 0.03 kg based on the masses of the cow feces, wheat straw and inoculum used. The reactors were fitted with two gas lines; one for purging the nitrogen gas immediately after feeding/ loading the substrate to expel O_2 and initiate an anaerobic environment inside reactor; and the second to release and measure the biogas produced. The biogas was sampled and its composition was analyzed once a week (Fig. 1). 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 (Beal, 1998) was manufactured at the workshop of the DSRDC. It is a transparent box made of acrylic contains a pivoting plastic tipping bucket (two equal-size compartments) and faced downwards just vertically above to a port that releases biogas under the pivoting point. The tipping container was placed submerged inside the water-filled acrylic box. 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 reed switch 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

The initial inoculum was obtained from a laboratory scale (40 L) psychrophilic (20 °C) anaerobic sequence batch reactor fed with fresh dairy manure and wheat straw (35% TS); the performance of the seeding inoculum has been reported previously (Saady and

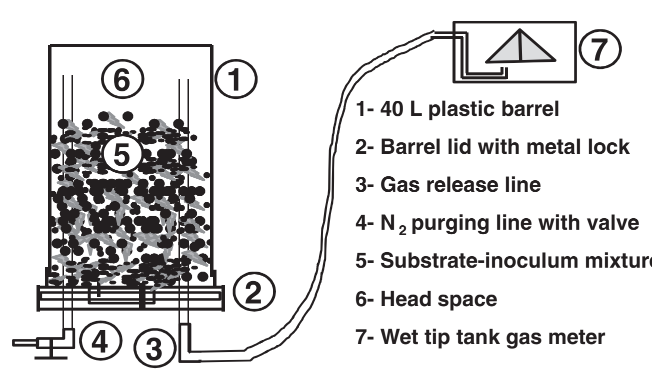

Fig. 1. Schematic diagram of the dry anaerobic digester.