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Anaerobic co-digestion of cheese whey and the screened liquid fraction of dairy manure in a single continuously stirred tank reactor process: Limits in co-substrate ratios and organic loading rate

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HIGHLIGHTS

- Cheese whey and liquid fraction of dairy manure continuous co-digestion operation.
- Cheese whey proportion and HRT influence on the process was investigated.
- Operation possible with 85% cheese whey fraction in the feed.
- Similar efficiencies observed within the range 15–85% cheese whey in the feed.
- 1.37 m^3 CH_4 m^{-3} d^{-1} reached with 65% whey in the feed at OLR of 5.9 kg VS m^{-3} d^{-1}.

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ABSTRACT

Mesophilic anaerobic co-digestion of cheese whey and the screened liquid fraction of dairy manure was investigated with the aim of determining the treatment limits in terms of the cheese whey fraction in feed and the organic loading rate. The results of a continuous stirred tank reactor that was operated with a hydraulic retention time of 15.6 days showed that the co-digestion process was possible with a cheese whey fraction as high as 85% in the feed. The efficiency of the process was similar within the range of the 15–85% cheese whey fraction. To study the effect of the increasing loading rate, the HRT was progressively shortened with the 65% cheese whey fraction in the feed. The reactor efficiency dropped as the HRT decreased but enabled a stable operation over 8.7 days of HRT. At these operating conditions, a volumetric methane production rate of 1.37 m^3 CH_4 m^{-3} d^{-1} was achieved.

1. Introduction

Cheese whey is the liquid remaining after the precipitation and removal of milk casein during cheese-making (Teixeira et al., 2010). From a valorization point of view, cheese whey is a nutrient-rich by-product that contains approximately 55% of the initial milk nutrients (Prazeres et al., 2012). Among the most abundant of these nutrients are lactose (4.5–5% w/v), soluble proteins (0.6–0.8% w/v), lipids (0.4–0.5% w/v) and mineral salts (8–10% of the dried extract) (Guimarães et al., 2010). Despite its nutritional value, large volumes of cheese whey are discharged into the environment every day (Saddoud et al., 2007). The problem occurs due to the high water content of cheese whey (92–95%), which increases the cost of transportation. In addition, the use of valorization technologies can make the use of cheese whey uneconomical, in particular for small- and medium-sized cheese producing units. When the costs associated with valorization technologies are not reasonable, the disposal of cheese whey becomes an environmental problem.

Cheese whey has a high organic load (up to 80 g COD L^{-1}) and a high biodegradability (Kalyuzhnyi et al., 1997; Mawson, 1994) that causes excess oxygen consumption if it is directly disposed of in water bodies. Given these characteristics, biological treatment processes are required when cheese whey needs to be managed as a waste effluent. Due to the high organic content of whey, aerobic treatment processes such as the activated sludge process are completely inappropriate (Gavala et al., 1999). Thus, anaerobic treatment is a particularly attractive solution for treating or pretreating this waste effluent because it offers an excellent solution

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in terms of both energy savings and pollution control (Ferreira et al., 2014; Ergüder et al., 2001).

However, some difficulties have been reported regarding the anaerobic digestion of cheese whey. The majority of these difficulties are due to the low alkalinity content and the rapid acidification of cheese whey that can exhaust the buffering capacity, leading to a drop in pH, volatile fatty acids (VFA) accumulation and subsequent reactor failure (Ergüder et al., 2001; Kalyuzhnyi et al., 1997). Another drawback for the anaerobic treatment of cheese whey is the difficulty in obtaining granulation and the tendency to produce an excess of viscous exopolymeric materials that severely reduces sludge settleability and can cause biomass washout in high-load anaerobic reactors (Malaspina et al., 1995).

To address the above difficulties, the co-digestion of cheese whey with animal manure in a CSTR digester has proven to be a solution because manure can provide the necessary buffer capacity to ensure the stability of the process (Gelegenis et al., 2007; Kavacik and Topaloglu, 2010). In addition, co-digestion of animal manure with different substrates may enhance the anaerobic digestion process due to a better carbon and nutrient balance, which results in a suitable option for improving biogas production (El-Mashad and Zhang, 2010; Risberg et al., 2013). It has been recognized that using animal manure alone, although convenient and feasible, may not represent the most efficient way to produce biogas due to its inherently low C/N ratio (Wu et al., 2010). The optimal C/N ratio for bacterial growth in anaerobic digestion systems has been reported to range from 20 to 30, although the optimal C/N ratio varies with the type of digested feedstock (Yan et al., 2015). In this regard, the characteristics of dairy manure and cheese whey are completely opposite. Dairy manure presents many suspended solids and fibrous material and only a small part of the organic matter content is in the soluble form. Dairy manure has enough alkalinity to develop the anaerobic process and its anaerobic biodegradability is approximately 45% (Rico et al., 2007). Hydrolysis is the rate-limiting step in the anaerobic digestion of dairy manure, whereas for cheese whey it is methanogenesis. The higher C/N ratio of cheese whey can also provide a more optimal C/N ratio and thus can have a positive synergetic effect on gas production. Dairy manure and cheese whey are totally antagonistic but complementary for the anaerobic co-digestion process. Indeed, anaerobic co-digestion of animal manure and by-products from the food industry demonstrates many advantages. Biogas plants can convert a disposal problem into a profit centre, allowing animal manures and food wastes to be converted into highly valuable fuel, reducing greenhouse gases emissions and replacing mineral fertilization with nutrient recovery (Agyeman and Tao, 2014; Holm-Nielsen et al., 2009).

To date, very few attempts have been made for the co-digestion of dairy manure and cheese whey in a continuous-mode operation (Bertin et al., 2013; Comino et al., 2012; Kavacik and Topaloglu, 2010; Lo et al., 1988). In the present work, the anaerobic co-digestion of cheese whey and the screened liquid fraction of dairy manure has been investigated in a single continuously stirred tank reactor (CSTR) process at 35 °C. More specifically, the aim was to reach the treatment limits in terms of: (a) cheese whey fraction in the feed under a constant hydraulic retention time (HRT) and (b) organic loading rate (OLR) by decreasing the HRT operating with a constant cheese whey fraction in the feed.

2. Methods

2.1. Substrates

Cheese whey (CW) was supplied by Queserías la Fuente, a dairy milk processor located in Heras (Cantabria, Spain). The CW was transported to the laboratory and stored at 4 °C prior to use. The CW characteristics (Table 1) were quite uniform during the experimentation process as indicated by the relative low SD in the CW characteristics.

The screened liquid fraction (SLF) of dairy manure used as a co-substrate was obtained from a pilot plant located in the ''La Granja'' agricultural secondary school (Heras, Cantabria). Dairy manure was collected from the manure pit of a 500-free stall dairy cow farm equipped with scrape systems. The manure was extracted from the dung pit by a tractor equipped with a vacuum tank system and transported to the pilot plant.

The raw manure was separated by means of a screw press separator (Doda MS5CE, 0.8 mm mesh). The SLF was processed and collected from the pilot plant, delivered to lab installations and stored at 4 °C prior to use. The SLF characteristics were not uniform due to the manure pit management and weather conditions but were reasonably consistent during the experimental period to ensure the reliability of the experiments. The mean characteristics of both substrates during experimentation are shown in Table 1.

2.2. Experimental setup scheme

The experimental setup scheme of the developed process is shown in Fig. 1. The manure separation processes to obtain SLF were conducted at the pilot scale. More details about the pilot installation and the separation process can be found in Rico et al. (2011). The CSTR was operated at the lab scale.

2.3. CSTR digester

The CSTR digester was cylindrical (vertical type), made of PVC and 36 cm in internal diameter and 24 cm high with an operating volume of 21 L. A vertical mechanical stirrer (40 rpm) was used for mixing and homogenization of the digester content and to avoid stratifications inside the reactor. It was programmed to work fifteen minutes per hour. The digester was fed manually once a day. The anaerobic effluent left the reactor when the digester was fed by means of an exit tube with a hydraulic closing system to prevent the entrance of air.

The CSTR was equipped with a temperature probe. A stable reactor temperature was maintained at 35 °C by means of the continuous flow of heated water through a helical coiled tube heat exchanger inside the reactor.

Biogas was released from the reactor by its own pressure through a tube in the dome. The volume of biogas generated in the CSTR was measured by means of a home-made biogas meter device constructed using two coaxial chambers made of acrylic cylinders which were interconnected by means of two small holes in the lower zone of the internal chamber. The internal chamber was closed on the top and arranged with a piping connection to a three-way solenoid valve with biogas from the CSTR inlet and exhaust. A pre-set magnetic level sensor regulated the operation

Table 1
Characteristics of the cheese whey and the screened liquid fraction of manure used in the present study (mean ± SD).

Parameter	CW	SLF
TS ($g L^{-1}$)	55.1 ± 1.9	43.2 ± 4.8
VS ($g L^{-1}$)	47.8 ± 1.8	31.6 ± 3.7
COD ($g L^{-1}$)	57.5 ± 1.7	53.2 ± 4.5
COD_{VFA} ($g L^{-1}$)	0	7.8 ± 1.9
TKN-N ($g N L^{-1}$)	1.2 ± 0.2	2.4 ± 0.2
NH_4^+-N ($g N L^{-1}$)	0.2 ± 0.1	1.0 ± 0.2
C/N	22.1 ± 0.8	9.1 ± 1.5
P_T ($g P L^{-1}$)	0.2 ± 0.1	0.7 ± 0.1
BA ($meq L^{-1}$)	0	159 ± 67
BMP ($L CH_4 kg^{-1}$)	17.1 ± 0.4	8.6 ± 1.2