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Effect of ammoniacal nitrogen on one-stage and two-stage anaerobic digestion of food waste

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ABSTRACT

This research compares the operation of one-stage and two-stage anaerobic continuously stirred tank reactor (CSTR) systems fed semi-continuously with food waste. The main purpose was to investigate the effects of ammoniacal nitrogen on the anaerobic digestion process. The two-stage system gave more reliable operation compared to one-stage due to: (i) a better pH self-adjusting capacity; (ii) a higher resistance to organic loading shocks; and (iii) a higher conversion rate of organic substrate to biomethane. Also a small amount of biohydrogen was detected from the first stage of the two-stage reactor making this system attractive for biohythane production. As the digestate contains ammoniacal nitrogen, re-circulating it provided the necessary alkalinity in the systems, thus preventing an eventual failure by volatile fatty acids (VFA) accumulation. However, re-circulation also resulted in an ammonium accumulation, yielding a lower biomethane production. Based on the batch experimental results the 50% inhibitory concentration of total ammoniacal nitrogen on the methanogenic activities was calculated as 3.8 g/L, corresponding to 146 mg/L free ammonia for the inoculum used for this research. The two-stage system was affected by the inhibition more than the one-stage system, as it requires less alkalinity and the physically separated methanogens are more sensitive to inhibitory factors, such as ammonium and propionic acid.

1. Introduction

The introduction of separated collection of different fractions of municipal solid waste (MSW) and subsidies for renewable energy production have been the main drivers for the development of the anaerobic digestion (AD) as a system to treat the organic fraction of municipal solid waste (OFMSW). Food waste (FW), the single largest fraction of MSW, has a high biomethane production potential (200–670 $mlCH_4/gVS_{added}$) (Ariunbaatar et al., 2014a,b; Kastner et al., 2012; Khalid et al., 2011; Xu et al., 2011; Zhang et al., 2013). Thus, treating FW through AD has become an exciting research field. Designing and optimizing the AD process using FW is nevertheless challenging (Kastner et al., 2012).

The performance of continuous anaerobic reactors fed with FW is initially good with increasing build-up of the acetic acid concentration, which reaches a peak after a few months (Banks et al., 2012). During a long-term operation, the acetic acid concentration declines and the propionic acid concentration builds up. Eventually the volatile fatty acids (VFA) accumulation can overcome the digester buffer capacity, leading to acidification and failure of the system. The alkalinity already present in the FW stream feeding the reactors as well as that produced from the biological process contributes to the anaerobic system with the buffer capacity and therefore, it is an essential parameter for a successful operation as compared to the direct measurement of pH (Ward et al., 2008). During the hydrolysis and fermentation stages of AD there is a consumption of alkalinity, while alkalinity is produced and acidification is compensated during the methanogenic stage. A higher buffer capacity allows AD to operate at higher organic loading rates (OLRs), thus resulting in a higher biomethane production without experiencing a pH drop and acidification.

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The total ammoniacal nitrogen (TAN) concentration in anaerobic reactors plays a significant role for maintaining the required alkalinity. In anaerobic aqueous solution, the ammonium ions (NH_4^+) and free unionized ammonia (NH_3) ions are in a chemical equilibrium forming the TAN. The equilibrium between ammonium and free ammonia (FA) depends on the temperature and pH of the system. The bioreactors perform best at TAN concentrations of 600–800 mg/L (at pH = 7.2–7.5 and mesophilic condition), and a higher TAN concentration can lead to an inhibition of the methanogens and an eventual failure of the reactor (Prochazka et al., 2012; Yenigun and Demirel, 2013; Kayhanian, 1999).

It was proposed by several researchers that higher ammonium (NH_4^+–N) concentrations reduce the activities of the propionic acid utilizing anaerobes, thus propionic acid starts to build up (Zhang et al., 2013; Banks et al., 2012; Angelidaki and Ahring, 1993). Propionic acid accumulation further inhibits the methanogens, and consequently all VFA concentrations increase causing an imbalance of the reactors (Banks et al., 2012; Kayhanian, 1999; Angelidaki and Ahring, 1993). On the other hand, Nakakubo et al. (2008) and Prochazka et al. (2012) suggested that higher ammonium concentrations directly inhibit the enzymatic activity of the methanogens causing a lower biomethane production (Prochazka et al., 2012; Chen et al., 2008). A high concentration of FA is also extremely inhibitory to methanogens (Chen et al., 2008; Nakakubo et al., 2008) as it can diffuse passively into the bacterial cells. FA inside the cells cause an imbalance of the intercellular pH while it equilibrates with the ammonium ion outside the cells, which further inhibits some enzymatic activities of the methanogens (Yenigun and Demirel, 2013; Nakakubo et al., 2008).

It is widely recognised that the physiology of the anaerobic microbes, origin of inoculum, substrate characteristics and operational conditions affect the inhibitory level of both ionized and unionized forms of ammonia (Braun et al., 1981). Hence, a wide range (1.7–14 gTAN/L) of inhibitory concentrations have been reported in the literature (Chen et al., 2008). In general, earlier research reported that a TAN concentration of 1700–2000 mgTAN/L is toxic to unacclimated microbes (Van Velsen, 1979; Koster and Lettinga, 1984), whereas the 50% inhibition for acclimated methanogens could reach up to 12,000–14,000 mgTAN/L (Chen et al., 2008; Koster and Lettinga, 1984).

To the best of our knowledge, the buffering and inhibitory effects of TAN on the AD of FW have not yet been studied in detail, whereas it has been widely studied for AD of swine manure (Kayhanian, 1999; Nakakubo et al., 2008; Braun et al., 1981) and waste activated sludge (WAS) (Van Velsen, 1979; Koster and Lettinga, 1984, 1988). Therefore, this research aims at investigating the effect of TAN on the AD of synthetic FW through batch and semi-continuous reactors. The buffering as well as inhibitory effects of ammonium were investigated in batch experiments as well as in one-stage (R1) and two-stage (R2) continuously stirred tank reactors (CSTR) treating synthetic FW at mesophilic conditions.

2. Materials and methods

2.1. Substrate and inoculum

As the FW composition can change depending on the season, region and the ways it is collected it might have a varying impact on the performance of the AD process. Hence, a synthetic FW was used for both batch and semi-continuous experiments in this study. The synthetic FW was prepared weekly following (Ariunbaatar et al., 2014b), and it was stored in the fridge (4 °C) when not in use. The FW was added directly to the bottles for batch experiments, whereas it was mixed with water prior to feeding to the semi-continuous reactors. The inoculum used for the experiments was from a full-scale AD plant (treating buffalo manure and cheese whey) located in Capaccio–Salerno (Italy).

2.2. Batch experiments

The inhibitory effect of TAN on the AD of FW was studied through batch experiments to determine the biomethane potential (BMP) by adding a gradient series (0.5, 0.8, 1.67, 1.67, 1.67, 0.8, 0.8, 1.67, 1.67 g/L) of ammonium chloride (NH_4Cl) to the BMP bottles (marked as N series) and compared with the control (BMP bottle with no addition of NH_4Cl). The substrate to inoculum (S/I) ratio was 0.5 gVS/gVS. BMP tests were conducted in a 1 L glass bottle, sealed with silicone filled stopper. The bottles were placed on a shaker to provide continuous mixing, and all tests were conducted in duplicate at mesophilic conditions (30–34 °C) as described by Esposito et al. (2011). The biomethane production was measured with the liquid displacement method using a sodium hydroxide (120 gNaOH/L) solution to trap the carbon dioxide (CO_2) (Esposito et al., 2011).

2.3. Semi-continuous reactors

The effect of TAN on the buffer capacity was studied through a semi-continuous one-stage (R1) and two-stage (R2) CSTR at a mesophilic (32–37 °C) condition. R2 consisted of two separate CSTRs connected with a tube, and the working volumes were 220 ml and 1980 ml for the first and second stage, respectively, making the total working volume (2.2 L) the same as R1. The stirring speed of all the CSTRs was 150 rpm.

Three independent runs of the reactors were carried out. The detailed operational parameters of each run are shown in Table 1. To investigate the effect of TAN on the buffering capacity as well as the robustness of the reactors, Run 1 was performed for 60 days by applying an organic loading shock with no additional buffer addition or re-circulating the liquid fraction of the digestate (LFD). During Run 1, the hydraulic retention time (HRT = V/Q) and the organic loading rate (OLR = C/HRT) were 20 d and 1.2 gVS/L·d, respectively. The main purpose of Run 2 was to study the effect of the LFD re-circulation on the buffer capacity and/or toxicity of TAN (in both R1 and R2); although to secure a prolonged stable operation, the HRT was increased to 40 d and the OLR was also reduced to 0.3 gVS/L·d by reducing the VS concentration in the feed (Table 1). The digestate was centrifuged at 3000 rpm for 5 min to separate the liquid and solid fractions. The LFD was used to prepare the feed for the reactors, thus the re-circulation was performed manually. However, the volume of the LFD was only sufficient for 75–80% of the feed volume, hence tap water was added. Run 2 lasted for 59 days and due to operational hitches, the reactors were stopped

Table 1
Operational parameters of R1 and R2.

Parameters	One-stage CSTR (R1)	Two-stage CSTR (R2)	
		First stage	Second stage
Run 1			
pH	6.6–7.2	3.2–5.5	6.7–7.2
OLR (gVS/L·d)	1.2	1.2	1.2
HRT (d)	20	2	18
Run 2			
pH	7.2–7.4	5.2–6.1	7.2–7.6
OLR (gVS/L·d)	0.3	0.3	0.3
HRT (d)	40	4	36
Run 3			
pH	7.2–7.4	4.0–5.1	7.4–7.6
OLR (gVS/L·d)	0.4–0.9	0.4–0.9	0.4–0.9
HRT (d)	40	4	36