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Simultaneous ammonia stripping and anaerobic digestion for efficient thermophilic conversion of dairy manure at high solids concentration

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ABSTRACT

A major challenge to take high rate advantage of thermophilic anaerobic digestion (AD) is overcoming ammonia inhibition without adding any significant cost to the process. A concept of thermophilic AD with simultaneous ammonia stripping was tested for treating dairy manure at high total solids concentration (TS%) as an attempt to address this challenge. The results showed that ammonia inhibition occurred at 1.8–2.4 g/L total ammonia nitrogen (TAN) concentration which corresponded to 10% TS as a threshold concentration. Thermophilic AD of dairy manure efficiency at the threshold TS% was significantly improved by simultaneously stripping ammonia with the optimum stripping rate of 1 L min^{-1}. The required time for reaching stable state was 4 days shorter than control, and the highest methane content (56.5–75.5%) was obtained. The ammonia stripping strategy maintained TAN level below the inhibition limit of 1.5 g/L throughout AD process. The maximum cumulative methane production of 192.3 L/kg-volatile solids (VS) was obtained, which was 2.3-fold the control. Therefore, simultaneous ammonia stripping overcame the ammonia inhibition on thermophilic AD of dairy manure at the threshold TS%. The proposed concept simplified the system by combining ammonia stripping and thermophilic AD within the same digester.

1. Introduction

Anaerobic digestion (AD) has been recommended as a primary process for treating livestock manure, because waste reduction, energy (biogas) production and mitigation of pollutant emissions (odor, greenhouse gases, and animal pathogens) can be all accomplished [1]. The increasing concerns about the environmental impact of animal feeding operations and the growing needs for renewable energy make AD an attractive alternative for managing animal manure [2].

Enhancing AD process performance is desirable for dropping the cost of operation. Temperature is a key factor affecting AD process performance. There are mainly three different types of AD processes based on the operating temperature: thermophilic (>45 °C), mesophilic (20–40 °C) and psychrophilic (<25 °C). Thermophilic AD has many inherent advantages over mesophilic and psychrophilic AD, including faster reaction rate, higher biogas production, less foaming occurrence, enhanced pathogen reduction, and facilitated the decomposition of coarse fibers in dairy manure [3,4]. However, as is well known, temperature affects the threshold of ammonia inhibition [5], and thermophilic AD tends to be unstable in processing the nitrogen-rich wastes such as manure mainly due to the fact that increasing temperature results in more accumulation of ammonia and then the severe ammonia toxicity to microbes [6]. The effects of ammonia inhibition on microbial consortia are reported to have a pronounced impact in later stages of AD, including the activity of acetate-utilizing (acetoclastic) methanogens or hydrogen/formate-utilizing (hydrogenotrophic) methanogens, and the acetoclastic methanogens (*Methanosaeta* sp. and certain *Methanosarcina* sp.) which are considered to be most sensitive to ammonia [7]. In addition, the elevated ammonia accumulation releases overload free ammonia (NH_3), which can cause

Abbreviations: AD, anaerobic digestion; SS-AD, solid-state anaerobic digestion; SSFW, source sorted food waste; TKN, Kjeldahl nitrogen; TAN, total ammonia nitrogen; NH_3, free ammonia; S/I, substrate-to-inoculum; sCOD, soluble chemical oxygen demand; CK, no urea treatment; VFAs, volatile fatty acids; TS, total solids; VS, volatile solids.

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intercellular pH variation, proton imbalance, potassium deficiency, and even cease the growth of methanogens by permeating the cells [8]. Most evidence has confirmed the high sensitivity of methanogens to NH_3 [9]. Protein-rich materials are common sources for sulfide formation, which is not only toxic for microbial populations but also forms complexes with metals, resulting in decreased bioavailability of trace elements for microbial activity [7,10].

Various attempts have been made to overcome ammonia inhibition to maximize the specific methane production and enhance the process stability of thermophilic AD of nitrogen-rich materials. The simplest operation is to dilute the organic waste with water to avoid ammonia inhibition. Apart from dilution, chemical precipitation like magnesium ammonium phosphate (MAP) process [11], zeolite and clay process [12,13], and the addition of phosphorite ore [14] have been used. Biological processes like nitrification/denitrification [15] and bipolar bioelectrodialysis [16] have been studied as a way to reduce the ammonia inhibition. Methanogenic consortia acclimation to elevated ammonia levels was effective to improve ammonia tolerance for enhancing methane production [17]. The process of acclimation usually takes a long time and the methane production remains relatively low [18]. Gas-permeable membrane technology is also used to recover NH_3 from liquid manures [19].

Removing ammonia from thermophilic AD process through stripping is thought to be a feasible approach, especially for treating organic wastes with high ammonia content, such as source sorted food waste (SSFW) digestate [20], chicken manure [21], and poultry litter leachate [22]. During the process, free ammonia is stripped out from the organic wastes and entered the gas phase, which caused the reduction of ammonia content in the liquid phase. Ammonia stripping generates no extra sludge, and the reagents cost is relatively low. Ammonia stripping has been proved to be useful in recovering ammonia from liquid waste such as AD effluent and poultry litter leachate [22,23]. Some studies have also reported the application of ammonia stripping for dehydrated waste of activated sludge and dairy manure with high TS% [18,24]. Conventional ammonia stripping requires NaOH, CaOH, or KOH addition to increase pH within 10–11 [25]. However, after ammonia stripping, AD could be inhibited by the toxicity of residual Na^+, Ca^+, and K^+ [26]. 1.5, 2.5 and 2.5 g/L of Na^+, Ca^+, and K^+ concentrations, respectively, are known to begin inhibition effect on microorganisms [27]. In addition, the chemicals addition can enhance the sludge precipitates, cause mechanical problems, and form pipe scale [28]. For these studies, ammonia stripping is deployed as a separate stage followed by thermophilic AD.

A feasible option to efficiently treat nitrogen-rich materials with low cost, may be thermophilic AD coupled with ammonia stripping. The related studies are limited and only focused on chicken manure, piggery wastewater and poultry litter leachate so far [21,22,26]. However, there was no work done on dairy manure, so mechanism of the response of process performance and methane production to the stripping rate and the ammonia inhibition remain unclear. The characteristics of different nitrogen-rich materials are different, which influence the effectiveness of ammonia stripping. Therefore, it is necessary to investigate thermophilic AD of dairy manure coupled with ammonia stripping in order to enhance the knowledge base in the field of simultaneous ammonia stripping.

In the present study, a thermophilic AD system coupled with ammonia stripping was proposed to treat dairy manure. Compared with conventional ammonia stripping, there are some advantages: first, ammonia stripping and thermophilic AD were realized in a single stage; second, in order to eliminate the negative effect of chemicals addition on microbial activity as aforementioned, no chemicals were added to adjust pH, so the feedstock remains native; third, this proposed approach simultaneously eliminated the inhibitory effect on microbial activity caused by ammonia accumulation along with the thermophilic AD process, so this method can improve the economic feasibility and the applicability. Based on the above points, the threshold total solids concentration (TS%) that led to ammonia inhibition on thermophilic AD of dairy manure was firstly identified to examine the feasibility of simultaneous ammonia stripping on the removal of ammonia inhibition, and then the improvement of methane production was verified based on the threshold TS%. Additionally, the effect of stripping rate on the removal of ammonia inhibition, the process performance, and the methane production was investigated. The AD process was finally optimized to maximize the methane production.

2. Materials and methods

2.1. Feedstock and inoculum

Dairy manure was collected from Washington State University Dairy Center in Pullman, WA, USA and stored at 4 °C prior to use. The inoculum was sampled from a mesophilic anaerobic digester at Wastewater Treatment facility in Pullman, WA, USA. The characteristics of dairy manure and inoculum are shown in Table 1.

2.2. Anaerobic digestion design

2.2.1. Thermophilic anaerobic digestion of dairy manure at different high solids concentrations

The required amount of dairy manure and inoculum for each digester were 400 g and 100 g, respectively, based on the wet weight. The TS and VS for each digester were 51.93 g and 42 g, respectively. Deionized water was added to match the requirement of certain TS%. At 6% and 8% TS, 365.5 g and 140 g of deionized water were used, correspondingly. At 10% TS, no deionized water was added. This test was conducted in batch mode at laboratory scale and the volume for each digester was 1 L. The headspace of digesters was flushed with nitrogen gas for about 5 min to obtain anaerobic condition, after which digesters were capped tightly with rubber stoppers and incubated at 55 °C and shaken at a speed of 120 rpm [29,30]. Digestion experiments were conducted in triplicate for each condition.

2.2.2. Simultaneous ammonia stripping for thermophilic anaerobic digestion of dairy manure at the bottleneck solids concentration

Simultaneous ammonia stripping was conducted in a 3.0 L reactor. The selected TS% for stripping was the bottleneck TS% obtained from the previous experiments. Nitrogen gas, as the stripping gas, was introduced into the liquid phase from the bottom of the reactor via an aquatic air stone, and it helped to stir the mixed liquor in the reactor. The soft pipe connected with the aquatic air stone was introduced through the rubber cap and connected to nitrogen gas cylinder. The nitrogen flow rate was controlled at 1.0 L min^{-1}, 3.0 L $min^{-1,}$ and 5.0 L min^{-1} by a flow meter. The flow

Table 1
Characteristics of dairy manure and inoculum.

Parameter	Dairy manure	Inoculum
Total solids (%)	12.5 ± 0.4	1.9 ± 0.0
Volatile solids (% of total solids)	80.9 ± 0.1	74.4 ± 0.1
pH	8.4 ± 0.0	7.6 ± 0.0
Total carbon (%)	40.7 ± 0.1	35.5 ± 0.0
Total nitrogen (%)	1.8 ± 0.0	5.5 ± 0.0
Total hydrogen (%)	5.7 ± 0.0	5.3 ± 0.0
Total ammonia nitrogen (g N/l)	1.4 ± 0.0	0.6 ± 0.0