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Integrated approach to sustain biogas production in anaerobic digestion of chicken manure under recycled utilization of liquid digestate: Dynamics of ammonium accumulation and mitigation control

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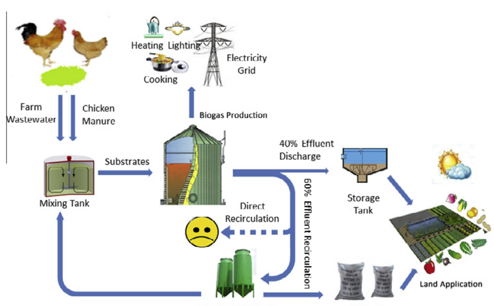
HIGHLIGHTS

- Ammonium dynamics and control in anaerobic digestion of chicken manure was investigated.
- Organic and inorganic compounds significantly accumulated after direct slurry recirculation.
- Accumulated VFAs and ammonium resulted in decrease of biogas production of 43%.
- Integration of air stripping before recirculation shows to be effective for ammonium mitigation.

GRAPHICAL ABSTRACT



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ABSTRACT

The dynamics of ammonium accumulation and mitigation control in anaerobic digestion of chicken manure under the recycled utilization of liquid digested slurry were investigated by using an integrated approach in two laboratory-scale semi-continuously stirred tank reactors. In the reactor with direct recycled utilization of the anaerobic digested liquid slurry, total volatilized fatty acids (in CH_3COOH) and NH_4^+-N increased from 1600 mg/L to 8000 mg/L and from 2600 mg/L to 5000 mg/L, respectively. The daily volumetric biogas production decreased from 1.4 ± 0.1 L/(L·d) to 0.8 ± 0.1 L/(L·d) with a reduction efficiency of 43 ± 4%. Air stripping was integrated for ammonium mitigation of recycled liquid digested slurry and was shown to effectively reduce the ammonium to 3000 mg/L. Correspondingly, the biogas production was recovered back to 1.4 ± 0.1 L/(L·d). This indicated the potential of the integration of air stripping for ammonium mitigation in an anaerobic digestion process with liquid digested slurry recirculation.

1. Introduction

With the rise of intensive animal farming, large amounts of waste are produced in China. By the end of 2012, the amount of animal manure was estimated to be approximately 243 million tons (Song et al., 2014). This large amount of livestock bio-waste can certainly lead to many unpleasant environmental consequences when it is directly disposed of into the environment. Biogas technology can effectively turn manure into bio-methane as renewable energy and digestate with nutrients as bio-fertilizer (Pöschl et al., 2010). Because of these two positive outcomes, biogas technology is being aggressively promoted by the Chinese government to both meet the growing energy demands of rural areas as well as protect the environment. At the end of 2013, the total number of biogas plants being fed with agricultural bio-wastes,

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including both household- and scaled-digesters, was 91,614 having a total volume of 14 million m^3 and an annual biogas production capacity of 1.7 billion m^3 (Statistics, 2013).

These anaerobic digesters have several advantages including substantially producing biogas for renewable energy (approximately 65% CH_4 and 35% CO_2), reducing direct and indirect greenhouse gas emissions (Nasir et al., 2012), and generating a large amount of anaerobic digested slurry. Traditionally, after mechanical solid–liquid separation of this anaerobic digested slurry, the solid part can be easily transported to markets or fields for reutilization as fertilizer, either directly or after composting (Pöschl et al., 2010). The liquid fraction, commonly referred to as the liquid digestate, has also been shown to be a good liquid bio-fertilizer or soil conditioner for crop production due to its high nutrient content (Cheng et al., 2014). However, this progress has often been limited due to the environmental impact and the consideration of the carrying capacity of nutrients to the surrounding land. Particularly in China, most of the surrounding farm lands are not owned by the biogas plant operators but are divided into many small pieces and owned by individual farmers. The land application of these liquid digested slurries is very hard to negotiate between the individual farmers. Furthermore, when compared to traditional chemical fertilizers, transportation of these liquid digestates is uneconomical due to their low fertilizer efficiency and high water content (Möller and Müller, 2012). Therefore, much of the anaerobic liquid digestate from intensive-scale anaerobic digesters can only be partially used in Chinese farm fields. Besides, the stored digestate will also have some greenhouse gases emissions into the atmosphere which would cause atmosphere pollution. Therefore, how to treat and/or reuse these large quantities of liquid digestate in an affordable and environmentally-friendly way has been a challenge for most scaled biogas plants in China, and even across the world (Gong et al., 2013).

To achieve the required organic loading of the digesters, the mixing of recycled liquid digestate with solid animal manure has been well-implemented in most Chinese scaled biogas plants since it not only reduces the generation of liquid digestate, but also partially substitutes water consumption. Even though slurry recirculation can increase a little bit energy consumption (about <2% of the total energy requirement) because of the pump operation, it is still wildly accepted. However, during anaerobic digestion, anaerobic microbes convert biodegradable organic matter into CO_2 and CH_4. However, nutrients, salts, and metals in anaerobic digesters cannot be removed effectively, and these can even heavily accumulate during long-term recycled utilization of liquid digestate. Inhibition of ammonium in the anaerobic digestion process of chicken manure, which is a high ammonium-containing bio-waste, has been well-investigated by several authors with batch experiments (Abouelenien et al., 2009; Wang et al., 2012). However, the dynamics of how ammonium accumulates during the digestion of chicken manure under long-term recycled unitization of liquid digestate as well as its influence on microorganism activity and biogas production are still not comprehensively understood. It should also be determined whether or not the use of ammonium removal technology, such as ammonia stripping, on the liquid digestate before its recycled utilization can effectively perform ammonium mitigation.

In this study, two laboratory-scale, semi-continuously stirred tank reactors were used to perform mesophilic anaerobic digestion of chicken manure with recycled utilization of liquid digestate being implemented in one reactor. The effects of liquid digestate recirculation on biogas production and fermentation characteristics (e.g. alkalinity, TS content, viscosity and ammonium) are discussed. The integration approach of "recirculation + air stripping" for ammonium mitigation of liquid digestate before recycled utilization was investigated in order to eliminate the adverse effect of ammonium inhibition and maintain a sustainable biogas production.

2. Methods

2.1. Chicken manure and seed sludge for methane production

The chicken manure used in this investigation was collected from deposits under chicken cages of a large-scale chicken farm located in Beijing, China. The sludge inoculum (TS content 1% w/w) obtained after mesophilic anaerobic digestion of excess activated sludge was used as a seed sludge to initiate anaerobic digestion of the chicken manure. The detailed characteristics of the chicken manure and sludge inoculum used are given in Table 1.

2.2. Experimental set-up and procedure

Two laboratory-scale semi-continuously stirred tank reactors with a nominal working volume of 20 L were run at a temperature of 37 °C and a stirrer speed of 140 rad min^{-1} (Gómez et al., 2006; Ishida et al., 1985) The normal operation of each reactor consisted of one daily feeding of 800 mL of a freshly prepared substrate mixture and discharging of an equivalent volume before each new feeding in order to maintain a constant working volume. The hydraulic retention time (HRT) was 25 days. The whole experiment lasted for about 200 days with four different experimental phases: phase I (0–35 day), phase II (35–65 day), phase III (65–125 day), and phase IV (125–200 day). The main strategic operational conditions of each experimental reactor are shown in Fig. 1. The organic loading rate (OLR) for both reactors started at 2 g VS L^{-1} d^{-1} in period I as start-up experimental period, and was increased to 3 g VS L^{-1} d^{-1} in period II. Starting at period III, the digested effluent of 800 mL from Reactor 2 (R2) was firstly settled, and then 500 mL of supernatant was recycled to prepare the fresh substrate mixture. The recirculation ratio of this reactor was 0.6 as calculated by the definition of the fraction of the recycled volume to the total volume of the fresh feeding substrate. During the experimental period IV, ammonia stripping was integrated to mitigate ammonium from the digested effluent of Reactor II before its centrifugation and recirculation. The stripping process consisted of firstly raising the pH of the digested effluent to 11.0 by adding $Ca(OH)_2$, and then, the ammonium concentration of the initial digested slurry was reduced to approximately 200 ± 25 mg L^{-1} by stripping with air for about 4 h. For Reactor 1 (R1), the same operating conditions as those used during period II and III were maintained. This included using an OLR of 3 g VS L^{-1} d^{-1} and not performing effluent digested slurry recycled utilization.

2.3. Analytical methods and calculations

The percentages of total solids (TS) (method 2540G) and volatized solids (VS) (method 2504D) in all samples and inoculum were determined according to standard methods (APHA, 2005). The samples were heated at 105 °C for 24 h and 550 °C for 4 h for TS and VS respectively (Zhang et al., 2014). The pH was determined using a digital pH meter (FE20, METTLER TOLEDO, Switzerland)

Table 1
Characteristics of chicken manure and sludge inoculum.

Materials	TS (%)	VS (% TS)	C (% TS)	N (% TS)	H (% TS)	S (% TS)
Chicken manure	90.98	71.87	33.08	4.91	4.28	4.28
Sludge inoculum	0.93	45	–	–	–	–