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Optimization and evaluation of an air-recirculated stripping for ammonia removal from the anaerobic digestate of pig manure

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ABSTRACT

An air-recirculated stripping involved two processes and did not require any pretreatment. First, stripping CO_2 decreased the buffer capacity of the anaerobic digestate, thereby reducing the amount of lime used to achieve a high pH. Second, lime was added to increase pH and remove ammonia from the anaerobic digestate of pig manure. pH increased from 8.03 to 8.86 by stripping CO_2 in the first process (gas-to-liquid ratio = 180) and further reached 12.38 in the second process (gas-to-liquid ratio = 300). During process optimization, the maximum ammonia removal efficiency reached 96.78% with a lime dose of 22.13 g. The value was close to 98.25%, which was the optimal result predicted by response surface methodology using the software Design-Expert 8.05b. All these results indicated that air-recirculated stripping coupled with absorption was a promising technology for the removal and recovery of nitrogen in the anaerobic digestate of pig manure.

Keywords: Anaerobic digestate of pig manure; Response surface methodology; Air-recirculated stripping

1. Introduction

Most livestock farms in China have insufficient lands for disposing large volumes of wastewater because the development of modern livestock industry has led to the separation of crop and animal production. Anaerobic digestion (AD) is a primary technology for excess animal waste. Although AD produces renewable energy and mitigates greenhouse gas emissions (Clemens et al., 2006), this technology also yields overloaded anaerobic digestate. The anaerobic digestate is rich in nitrogen, which can lead to water eutrophication (Zeng et al., 2003; Buosi et al., 2011), groundwater pollution (Hao and Chang, 2002), and air pollution. Nitrogen can be removed from anaerobic digestate using nitrification and denitrification (Deng et al., 2006), magnesium ammonium phosphate (Song et al., 2007; Liu et al., 2011), membrane filtration (Mondor et al., 2008), and ammonia stripping (Liao et al., 1995; Guštin and Marinšek-Logar, 2011; Laureni et al., 2013). The ratio of chemical oxygen demand (COD) to ammonium nitrogen (NH_4^+-N) of anaerobic digestate is low, and traditional biochemical treatments are unsuitable because of the poor biodegradability of this digestate (Liao and Maekawa, 1994; Bortone et al., 1994; Poo et al., 2004). Ammonia stripping is a physical-chemical procedure advanced for treatment of anaerobic digestate and it is unaffected by toxic compounds, that could disrupt the performance of a biological system. Yu et al. (2011) developed a multi-fluid model to analyze and optimize the mass transfer in the packed stripping tower. Laureni et al. (2013) indicated that the ammonia stripping/absorption process could be industrial implementation from an economic perspective. Jiang et al. (2014) optimized the ammonia stripping temperature and pH. They reported that the recovered ammonium sulfate can compensate the cost of chemical and electricity without considering the value of the upgraded quality of biogas.

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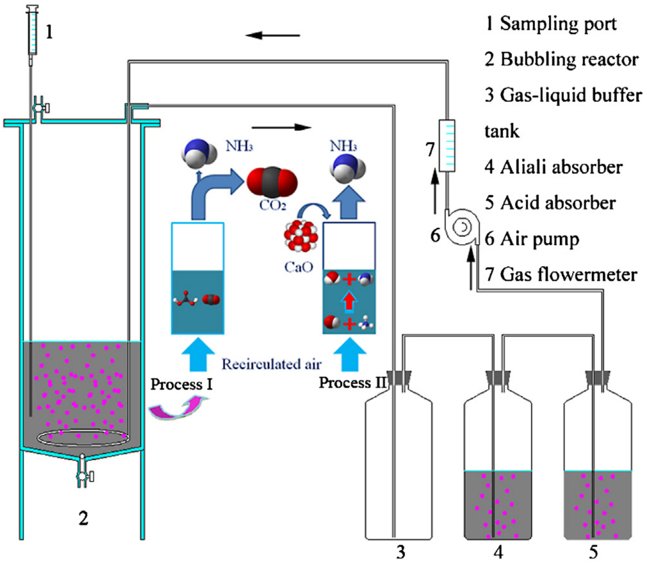

Fig. 1 – Schematic of the air-recirculated stripping experimental setup. Process I: CO_2 stripping. Process II: Ammonia stripping and recovery.

Ammonia stripping coupled with absorption is a proven suitable technical solution for the recovery of NH_4^+-N.

Air-stripping systems can be categorized as packing columns (Ozyonar et al., 2012), bubble-aeration setups (Collivignarelli et al., 1998), and water-sparged reactors (Quan et al., 2009). Air-stripping systems are widely used in the removal of ammonia from landfill leachate (Elovitz et al., 2000), AD effluent (Guštin and Marinšek-Logar, 2011; Laureni et al., 2013), and coke wastewater (Ozyonar et al., 2012). Although ammonia stripping is well known to effectively purge out ammonia from wastewater, many difficulties still exist for an economically feasible operation. For example, the packing column is easy to block (Quan et al., 2009) and needs high energy to complete the stripping process (Basakcilardan-Kabakci et al., 2007). Another challenge is the cost of the alkali used to convert ammonium to ammonia.

In this study, an air-recirculated stripping process coupled with alkali and acid absorption was proposed to remove and recover CO_2 and NH_4^+-N from the anaerobic digestate of pig manure (ADPM). The process had the advantages of a simple structure, absence of gas discharge, and capability to reduce lime. A response surface methodology (RSM) optimization statistical model was used to optimize the process operation conditions, with focus on the effects of three controlling factors (gas flow rate (GFR), dose of lime (DL), and gas-to-liquid ratio (GLR)) on single-response NH_4^+-N removal efficiency. The objective was to improve the removal efficiency of NH_4^+-N and reduce operating costs.

2. Materials and methods

2.1. Experimental setup and operational conditions

A bubble column reactor (diameter, 16 cm; height, 40 cm; working volume, 8.0 L) with alkali and acid absorption was operated in this study, as shown in Fig. 1. All parts of the reactor were connected in series and isolated from the atmosphere. Air inside the system was pumped with an air pump and pushed into the bubble column reactor through some orifices ($\Phi = 0.5$ mm) on the tube set at the bottom of the reactor. The buffer tank was setup such that no foam could get into the alkali absorber. An alkaline solution was used to absorb CO_2 stripped out of the anaerobic digestate. The acid absorber contained 500 mL of sulfuric acid (0.5 mol/L) to trap and recover ammonia as ammonium sulfate ($(NH_4)_2SO_4$).

Table 1 – Variables and coded units of the Box–Behnken design used.

Factor	Coded unit	Level		
		−1	0	1
GFR (L/min)	A	6	8	10
DL (g)	B	16	20	24
GLR (–)	C	1500	2250	3000

Two processes were involved in one experimental run. First was stripping CO_2, which decreased the buffer capacity and increased the pH of ADPM. GLR was fixed at 180 for this process. Second was adding lime (analytical grade) into the bubble reactor immediately at the end of the first process and completing the rest of the run (GLR = 3000). Five milliliters of liquid was collected as sample per 500 GLR. All runs were conducted in a room with a constant temperature of 36 ± 1 °C. Prior to the experiment, 3 L of anaerobic digestate without precipitation or filtration was placed in a container overnight. In each run, the anaerobic digestate with a temperature of 36 ± 1 °C was thoroughly mixed, and 2 L of digestate was added to the bubble reactor. Air inside the system was recirculated with an air pump and controlled with a gas flowmeter.

2.2. Experimental procedure

RSM uses second-order polynomial regression to approximately fit a mathematical model. This method was used to evaluate the effects of multiple parameters and their interactions in this study. The three parameters GFR, DL, and GLR were represented as A, B, and C, respectively. The coded levels of the variables are illustrated in Table 1.

A polynomial model was used to identify all possible interactions of the selected factors with the response function as Eq. (1).

$$Y = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + b_{13}AC + b_{23}BC \quad (1)$$

where Y is the response of ammonia removal efficiency; b_0 is the ordinate at the origin; b_1, b_2, and b_3 are the regression coefficients for linear effects; b_{11}, b_{22}, and b_{33} are the regression coefficients for quadratic effects; and b_{12}, b_{13}, and b_{23} are the regression coefficients for interaction effects. Fifteen batch experiments were subjected to the Box–Behnken design using the software Design-Expert 8.05b.

2.3. Material and analytical methods

The main characteristics of the ADPM obtained from a biogas plant (the reactor type was upflow solid reactor) in Beijing are outlined in Table 2. NH_4^+-N concentration and pH were measured in the factorial experiments. Total solids, volatile solids, NH_4^+-N, *ortho*-phosphorus (PO_4^{3-}), total phosphorus, and pH were measured according to the "Monitoring and analysis method of water and waste water" (Fourth Edition). COD and soluble chemical oxygen demand were determined by

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