Waste Management 49 (2016) 372–377

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Enhancing recovery of ammonia from swine manure anaerobic digester effluent using gas-permeable membrane technology

P.J. Dube [a,*], M.B. Vanotti [a], A.A. Szogi [a], M.C. García-González [b]

[a] United States Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water and Plant Research Center, 2611 W. Lucas St, Florence, SC 29501, USA
[b] Agriculture Technological Institute of Castilla and Leon (ITACyL), Valladolid, Spain

ARTICLE INFO

Article history:
Received 19 October 2015
Revised 14 December 2015
Accepted 15 December 2015
Available online 28 December 2015

Keywords:
Anaerobic digestion
Waste management
Gas-permeable membranes
Swine manure
Ammonia recovery
Nutrient recovery

ABSTRACT

Gas-permeable membrane technology is useful to recover ammonia from manure. In this study, the technology was enhanced using aeration instead of alkali chemicals to increase pH and the ammonium (NH_4^+) recovery rate. Digested effluents from covered anaerobic swine lagoons containing 1465–2097 mg NH_4^+–N L^{-1} were treated using submerged membranes (0.13 cm^2 cm^{-3}), low-rate aeration (120 mL air L-manure^{-1} min^{-1}) and nitrification inhibitor (22 mg L^{-1}) to prevent nitrification. The experiment included a control without aeration. The pH of the manure with aeration rose from 8.6 to 9.2 while the manure without aeration decreased from 8.6 to 8.1. With aeration, 97–99% of the NH_4^+ was removed in about 5 days of operation with 96–98% recovery efficiency. In contrast, without aeration it took 25 days to treat the NH_4^+. Therefore, the recovery of NH_4^+ was five times faster with the low-rate aeration treatment. This enhancement could reduce costs by 70%.

Published by Elsevier Ltd.

1. Introduction

Ammonia (NH_3) emissions to the atmosphere are an environmental quality concern because they can contribute to eutrophication of surface waters, nitrate contamination of ground waters, and impair air quality (EPA, 2014). In the United States, the largest source of NH_3 is livestock farming; NH_3 emissions from animal husbandry operations (dairy, beef, poultry and swine) were estimated at 2.4 million tons/year in 2010 and 2.5 million tons/year in 2015 (EPA, 2014). In its volatile form, NH_3 is a cause of air pollution and can create health problems for neighboring residents (Wing and Wolf, 2000). Ammonia runoff and subsequent accumulation in water sources leads to eutrophication and destruction of marine habitats (Paerl, 2006). On the other hand, NH_3 is a valuable chemical for use in agricultural fertilizers and in the chemical industry. Current practices for NH_3 production are energy intensive and contribute to global warming (Funderburg, 2013; IFA, 2009); manufacturing one metric tonne of anhydrous NH_3 fertilizer requires 1043 m^3 of natural gas. Therefore, developing new methods for removal and recovery of NH_3 from swine manure is desirable for environmental and economical reasons.

Ammonia mitigation techniques for livestock farming typically focus on five areas: reduction of nitrogen (N) excretion through dietary modifications, reduction of volatile N, building designs and manure managements, land application strategies, and emission capture and treatment (Ndegwa et al., 2008). Among technologies that focus on NH_3 emission capture and treatment, some are focused on the recovery of the N for further use. These technologies include: (1) wet scrubber and stripping technologies (proposed for ammonia removal from swine manure wastewaters) (Bonmati and Flotats, 2003; Liao et al., 1995; Lin et al., 2014), (2) struvite precipitation with phosphate and magnesium (Nelson et al., 2000), (3) reverse osmosis using osmotic pressure (Masse et al., 2010), (4) ion exchange adsorption with zeolites (Milan et al., 1997), and (5) a gas-permeable membrane process at low pressure (Vanotti and Szogi, 2015).

The gas-permeable membrane process includes the passage of gaseous NH_3 through a microporous hydrophobic membrane and subsequent capture and concentration in an acidic stripping solution on the other side of the membrane (Fig. 1). The membrane manifolds are submerged in the liquid manure and the NH_3 is removed from the liquid before it escapes into the air (Vanotti and Szogi, 2011, 2015); the NH_3 permeates through the membrane pores reaching the acidic solution located on the other side of the membrane. Once in the acidic solution, NH_3 combines with free protons to form non-volatile ammonium (NH_4^+) ions that are converted into a valuable NH_4^+ salt fertilizer. The process is responsive to increased pH through addition of alkali chemicals (Garcia-Gonzalez and Vanotti, 2015), which leads to an increased release of NH_3 from the manure and capture by the membrane (Fig. 1).

* Corresponding author.
E-mail address: Patrick.dube@ars.usda.gov (P.J. Dube).

http://dx.doi.org/10.1016/j.wasman.2015.12.011
0956-053X/Published by Elsevier Ltd.

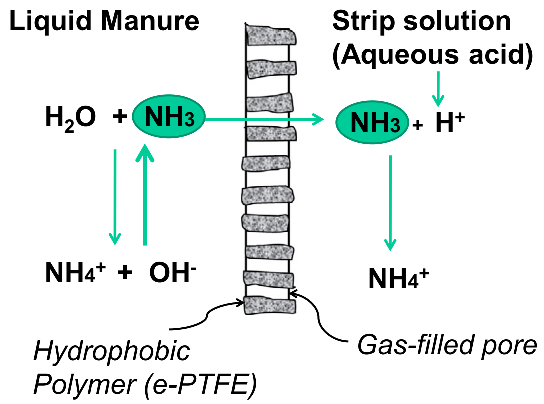

Fig. 1. Experimental device for NH_4^+ capture from manure using gas-permeable membranes and low-level aeration to increase manure pH.

Gas-permeable membranes have been shown to effectively recover more than 98% of NH_4^+ from liquid swine manure (Garcia-Gonzalez et al., 2015; Garcia-Gonzalez and Vanotti, 2015; Vanotti and Szogi, 2015). Zarebska et al. (2015) reviewed the pros and cons of six ammonia recovery methods including nanofiltration, reverse osmosis, gas-permeable membrane process (membrane distillation), air stripping, zeolite ion exchange, and struvite chemical precipitation and indicated the energy consumption for the gas-permeable membrane process was among the lowest (0.18 kW h kg NH_3^{-1}). For example, comparing gas-permeable membranes with air stripping, which both produce liquid ammonium sulfate, the energy consumption for the gas-permeable membrane process is 18 times lower than for air stripping. The main drawback from gas-permeable membrane systems is the cost of alkali chemicals to increase manure pH (Zarebska et al., 2015). Therefore, a strategy to reduce costs of the gas-permeable membrane process and improve farmer's adoption is to seek a simple and inexpensive alternative for raising the pH of the manure in a farm setting.

Vanotti and Szogi (2015) proposed the use of gas-permeable membranes with aeration instead of alkali chemicals to enhance the removal and recovery of NH_4^+ from livestock effluents. Such conditions applied to stored livestock effluents results in a pH increase of about 1 unit and increased NH_3 release. This effect has been demonstrated in experimentation involving the aeration of swine manure. In one study, passing air, 0.5% O_2 or 4.9% O_2 gas mixtures through slurry caused an increase in pH of about 1 unit in 1–2 days and about 2 units in 10 days (from 7 to between 8.5 and 9) (Stevens and Cornforth, 1974). Another study showed that aeration of swine lagoon wastewater without nitrification increased the pH of wastewater 1.5 units, from 7.5 to 9, in the first 18 h (Vanotti and Hunt, 2000). Others showed continuous aeration of manure increased pH almost 2 units (Zhu et al., 2001). In order to recover NH_3 using gas-permeable membranes with aeration, nitrification must be inhibited or else it will oxidize NH_3, decrease pH, and affect overall NH_4^+ recovery efficiency (Vanotti and Szogi, 2015). Nitrification inhibition can be achieved in various effective ways, for example: reducing aeration rates, reducing nitrifying biomass, increasing temperatures, or adding a commercial nitrification inhibitor (Vanotti and Szogi, 2015).

Using raw swine manure that contained high NH_4^+ concentration and high carbon (chemical oxygen demand 17 g L^{-1}), Garcia-Gonzalez et al., 2015 showed that 98% recovery of NH_4^+ can be obtained with gas-permeable membranes using low-rate aeration for increasing pH while reducing operational costs by 57% when compared to alkali chemical addition. The objective of this research was to determine if the aeration approach – with nitrification inhibition – is also effective to increase pH and recover NH_4^+ from anaerobically digested effluents containing high NH_4^+ concentration and low organic carbon (chemical oxygen demand < 2.5 g L^{-1}). We used anaerobically digested manure effluent from two swine farms with covered anaerobic lagoons in North Carolina, USA.

2. Methods

2.1. Experimental procedure

Batch experiments were conducted in 2-L wastewater vessels made of polyethylene terephthalate (PET) with an effective volume of 1.5 L (Fig. 2). The acid tank used to concentrate the NH_4^+ consisted of 500-mL Erlenmeyer flasks with 250 mL of a 1 N sulfuric acid (H_2SO_4) stripping solution. This stripping solution was continuously recirculated using a peristaltic pump (Cole-Parmer, Masterflex L/S Digital Drive, Illinois, USA) at 4 mL min^{-1} through a tubular gas-permeable membrane submerged in the reactor. In the aerated treatments, air was delivered to the bottom of the manure vessel at a low-rate of 0.18 L-air min^{-1} (0.12 L-air L-manure^{-1} min^{-1}) using an aquarium pump, a shielded air flow meter with a precision valve (GF-9260, Gilmont Instruments, Illinois, USA) and an aquarium diffuser stone that provided fine bubbles. This low airflow rate was selected to effectively increase the pH of manure based on preliminary aeration tests and at the same time avoid nitrification of the NH_4^+ (that reduces pH in manure). Aeration rate was half the aeration rate used in the experiments of Garcia-Gonzalez et al. (2015) with raw swine manure (0.24 L-air L-manure^{-1} min^{-1}), and about 8 times lower than aeration rates used by Magrí et al. (2012), that greatly inhibited nitrite production activity in experiments of partial nitritation of swine wastewater (0.9 L-air L-liquid^{-1} min^{-1}). Another strategy to avoid nitrification was the addition of a commercial nitrification inhibitor (Vanotti and Szogi, 2015). In this study we used both low-aeration and a nitrification inhibitor (nitrapyrin) to stop NH_4^+ oxidation in the aerated treatments. The vessels were not sealed and had 5 ports in the lid: two ports for acid recirculation, one sampling port, one port for aeration and one port that remained open to allow air to escape.

Gas-permeable membrane made of expanded polytetrafluoroethylene (ePTFE) (Phillips Scientific Inc., Rock Hill, SC) with a length of 60 cm, outer diameter of 10.25 mm and wall thickness

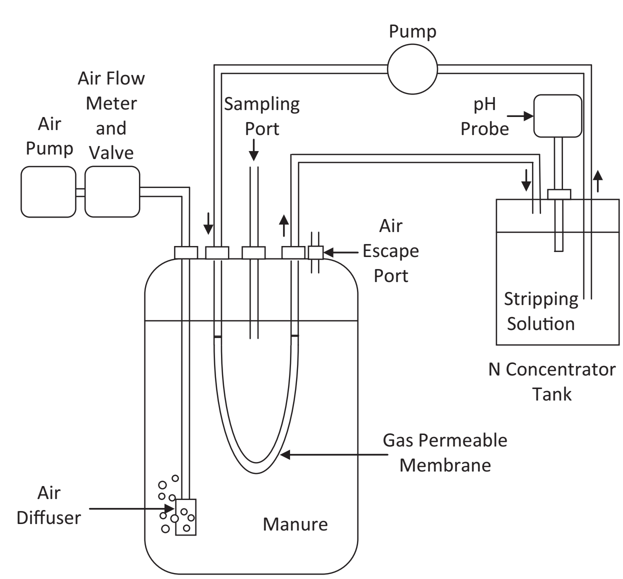

Fig. 2. Process diagram of gas-permeable membrane system for removal and recovery of anaerobically digested swine effluent.

of 0.75 mm was used for this experiment. The ePTFE membrane had an average pore size of 2.5 μm and bubble point of 210 kPa. The membrane was anchored to a glass rod inside the vessel to ensuring submersion throughout the experiment.

Four sets of experiments were carried out using the experimental device for NH_4^+ capture shown in Fig. 2. These experiments included two separate sources of liquid swine manure from covered lagoons effluents sampled from two farms in North Carolina. For each liquid source, aerated and non-aerated trials were carried out in duplicate. Aerated trials applied aeration to increase the pH and promote NH_4^+ removal, while non-aerated trials (control) did not include aeration. Nitrification inhibitor N-Serve (TCMP – 2-chloro-6 trichloromethyl pyridine, Hach, Loveland, CO, USA) was added to the aerated manure at a rate of 22.5 mg L^{-1}. All the experiments were done at a constant room temperature of 25 °C.

Small volume wastewater samples (2 mL) were drawn daily from the reaction vessels to test for alkalinity and NH_4^+ concentration. Samples from the stripping solution (0.2 mL) were also taken daily and tested for NH_4^+. The sampling decreased the initial volume of the manure and stripping solutions less than 5% and 1%, respectively. The pH was measured daily directly in the reaction vessels and stripping solutions. If the pH of the stripping solution rose above 2, concentrated H_2SO_4 was added to reduce the pH < 1. Initial and final samples for each trial were taken and analyzed for pH, alkalinity, NH_4–N, total Kjeldahl nitrogen (TKN) concentration, chemical oxygen demand (COD) and solids.

2.2. Origin of manure

Anaerobically digested liquid swine manure was collected from two separate sources of digested swine manure in North Carolina. It was collected from the effluent of covered anaerobic lagoons on typical swine finishing farms. Three 15-L plastic containers were filled using a pump, transported to USDA-ARS laboratory in Florence, SC and stored at 4 °C until used. The stored liquid manure was thoroughly mixed before use in the experiments. Chemical characteristics of the manure are shown in Table 1 for each farm.

2.3. Analytical methods

Alkalinity was determined by measuring the amount of 0.01 N hydrochloric acid required to reach pH of 4.5 and was reported as mg $CaCO_3$ L^{-1} and pH was monitored using a pH meter (Orion Star A111, Thermo Scientific). Determination of total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and ammonium (NH_4^+) in the initial and treated manure samples were performed using the APHA Standard Methods (1989). Total Kjeldahl N (TKN) was determined using acid digestion (Gallaher et al., 1976) and the salicylate methods (Standard Method 4500-Norg D) adapted to digested extracts (Technicon Instruments Corp., 1977). The NH_4^+ analysis was done by colorimetry (Standard Method 4500-NH_3 G). Data results were analyzed by means and standard deviation. Removal and recovery efficiencies of NH_4^+ were determined using mass NH_4^+ balances that considered the manure liquid volume and NH_4^+ concentration before and after treatment as well as the mass of N recovered in the acid tank.

3. Results and discussion

3.1. Nitrogen removal by gas membrane system: aeration vs. non-aeration

In this experiment, the recovery of NH_4^+ from anaerobically digested swine effluent was tested using gas-permeable membranes with and without aeration. As shown in Fig. 3, the test with effluent from Farm 1 and aeration removed 97% of NH_4^+ from the swine manure, reducing the NH_4^+ concentration from 2089 ± 101 mg N L^{-1} to 64 ± 20 mg N L^{-1} and reaching maximum NH_4^+ recovery in 4 days. The test with Farm 2 effluent and aeration saw a similar performance, reaching maximum NH_4^+ recovery in 5 days and decreasing NH_4^+ concentration from 1554 ± 19 mg N L^{-1} to 23 ± 5 mg N L^{-1} for a removal efficiency of 99%. Using gas-permeable membranes without aeration, NH_4^+ from Farm 1 was effectively reduced but at a much lower rate, it went from 2105 ± 88 mg N L^{-1} to 47 ± 13 mg N L^{-1} over 25 days. Similarly, without aeration the NH_4^+ from Farm 2 effluent decreased from 1375 ± 37 mg N L^{-1} to 103 ± 48 mg N L^{-1} over 28 days. Results show the addition of low-rate aeration to a gas-permeable membrane system removes NH_4^+ about 5 times as faster than the same system without aeration.

In addition to improved NH_4^+ removal, NH_4^+ recovery efficiency obtained was also consistently high. Table 2 shows recovery of 98% and 96% of N in the acid stripping solution from Farm 1 and Farm 2 respectively, with aeration versus 95% and 76% recovery without aeration. The aerated trial quickly recovered NH_4^+ with average recovery rates of 596 mg N day^{-1} with manure from Farm 1 and 441 mg N day^{-1} with manure from Farm 2. Corresponding average NH_4^+ recovery rates without aeration were consistently lower: 117 and 52 mg N day^{-1}.

The stripping solution was not changed throughout the course of the experiment and as a result, NH_4^+ concentration increased to over 5 times the concentration of the influent manure. Maximum NH_4^+ concentrations of 11,916 ± 7 and 8814 ± 175 mg N L^{-1} were reached in the aerated trial for Farm 1 and Farm 2, respectively, over 5 times the concentration of the influent manure (2089 ± 101 and 1554 ± 19 mg N L^{-1} for Farm 1 and Farm 2, respectively) (Fig. 3).

3.2. The effect of aeration on pH

During aeration of the manure, carbonate alkalinity is consumed and OH^- is instantly released, subsequently raising the pH of the manure according to Eq. (1).

$$HCO_3^- + \text{air} \rightarrow OH^- + CO_2 \qquad (1)$$

Table 1
Characteristics of manure before and after experiments[a].

	Initial effluent		Treated effluent			
	Farm 1 initial	Farm 2 initial	Farm 1 aerated	Farm 2 aerated	Farm 1 non aerated	Farm 2 non aerated
pH	8.71 (0)	8.47 (0.01)	9.26 (0.09)	9.17 (0.09)	8.13 (0.11)	7.99 (0.1)
COD (mg L^{-1})	1695 (35)	2485 (92)	1720 (113)	1885 (35)	1675 (21)	1825 (35)
TS (g L^{-1})	8.5 (0.17)	6.42 (0.07)	8.7 (0.02)	6.68 (0.06)	8.9 (0.11)	6.49 (0.24)
VS (g L^{-1})	1.5 (0.17)	1.80 (0.05)	1.4 (0.01)	1.82 (0.05)	1.3 (0.13)	1.60 (0.16)
TKN (mg N L^{-1})	2459 (165)	1752 (16)	102 (24)	120 (14)	162 (12)	181 (36)
NH_4^+ (mg N L^{-1})	2097 (78)	1465 (106)	64 (20)	23 (5)	47 (13)	103.1 (48)
Alkalinity (mg $CaCO_3$ L^{-1})	11,337 (10)	7369 (37)	3033 (58)	2083 (25)	3319 (80)	2763 (205)

[a] For initial effluent, data are average of 4 replicates. For treated effluent, data are average of 2 replicates. Values in parenthesis are standard deviation of the mean.

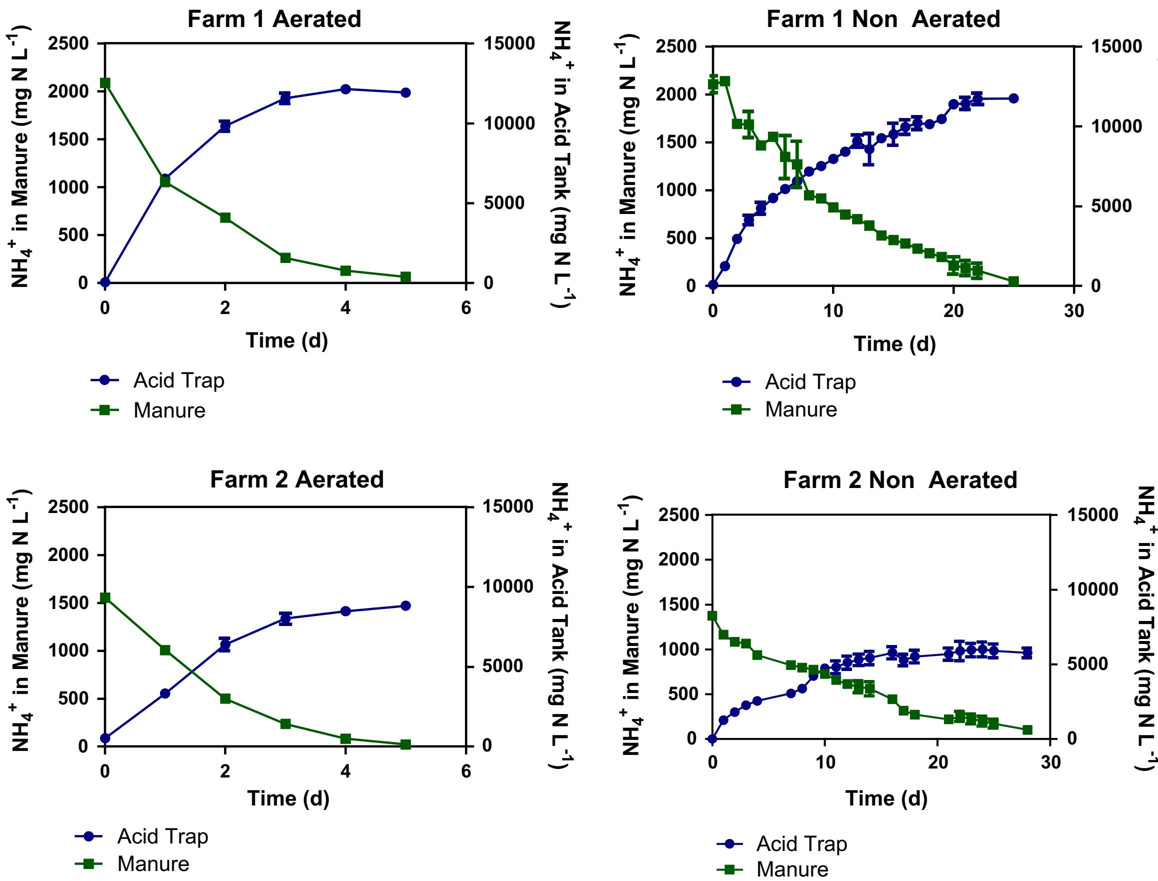

Fig. 3. Effect of aeration on the removal and recovery of NH_4^+ from digested swine effluent in two farms in North Carolina. The error bars are standard deviation of duplicate experiments.

Table 2
Mass balances of the recovery of ammonia from digested swine effluent in two farms using gas-permeable membrane module with and without aeration treatment[a].

Treatments	Time	Time to maximum recovery	Initial NH_4^+ in manure	Remaining NH_4^+ in manure	NH_4^+ removed from manure[b]	NH_4^+ potentially volatilized in air[c]	NH_4^+ recovered in acidic solution	NH_4–N removal efficiency[d]	NH_4–N recovery efficiency[e]	Maximum NH_4^+ recovery rate	Average NH_4^+ recovery rate[f]
	(days)		(mg N)					(%)		(mg NH_4–N day^{-1})	
Farm 1 aerated	5	4	3133 (151)	96 (29)	3037	58	2979 (2)	97	98	1621	596
Farm 1 non aerated	25	25	3157 (132)	71 (19)	3086	150	2936 (40)	98	95	424	117
Farm 2 aerated	5	5	2332 (28)	34 (8)	2298	94	2204 (44)	99	96	768	441
Farm 2 non aerated	28	24	2062 (56)	155 (72)	1907	465	1442 (83)	92	76	538	52

[a] 1.5 L manure in a 2 L vessel, using 250 mL 1 N H_2SO_4 of acidic solution in the concentrator tank (recirculation rate of 4 mL min^{-1}) and membrane tubing length = 0.6 m (area = 194 cm^2). Aeration rate = 180 mL min^{-1} (0.12 L-air $L\text{-manure}^{-1}$ min^{-1}). Data are average and std. dev. of duplicate reactors.
[b] NH_4^+ removed from manure = initial NH_4^+ in manure − remaining NH_4^+ in manure.
[c] NH_4^+ potentially volatilized in the air = initial NH_4^+ in manure − remaining NH_4^+ in manure − NH_4^+ recovered in the acidic solution.
[d] NH_4^+ removal efficiency = (NH_4^+ removed from manure/initial NH_4^+ in manure) × 100.
[e] NH_4^+ recovery efficiency = (NH_4^+ recovered in the acidic solution/NH_4^+ removed from manure) × 100.
[f] Average NH_4^+ recovery rate = mass NH_4–N recovered in the acidic solution/days in experiment.

This rise in pH due to aeration affects the formation of NH_3 as defined in Eq. (2).

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O \quad (2)$$

In the experiment, these reactions significantly enhanced NH_3 availability and uptake via the gas-permeable membrane (Table 2 and Fig. 3). The starting pH for the manure from Farm 1 was 8.71 ± 0 and the starting pH for Farm 2 was 8.47 ± 0.01. As shown in Fig. 4, in the aerated trials, the pH of the manure rapidly increased over 5 days reaching a final pH of 9.26 ± 0.10 and 9.17 ± 0.09 in the digested swine effluents from Farm 1 and 2, respectively. Aeration resulted in a higher pH along with 5–6 times as fast recovery of NH_4^+ (Table 2).

In the non-aerated trials, the manure pH consistently decreased in both farm effluents as a result of the NH_4^+ being removed by the gas-permeable membrane system: in Farm 1 effluent, the pH decreased from 8.71 ± 0.0 to 8.13 ± 0.11 after 25 days, whereas in Farm 2 effluent, it decreased from 8.47 ± 0.01 to 7.99 ± 0.11. The

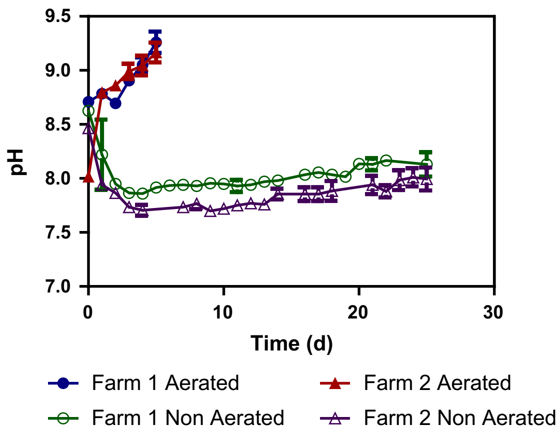

Fig. 4. Effect of aeration on manure pH during recovery of ammonia using gas-permeable membranes. The error bars are standard deviation of duplicate experiments.

removal of NH_4^+ by the gas-permeable membrane increases the acidity in the liquid manure as represented in Eq. (3).

$$NH_4^+ \leftrightarrow NH_3 + H^+ \tag{3}$$

Ammonia is then readily absorbed into the stripping solution of the gas-permeable membrane system, leaving H^+ behind and in the case of the non-aerated system, lowering the pH of the manure and slowing down the uptake of NH_3. Therefore, pH correction is needed for efficient N uptake by the gas-permeable process. This is consistent with the findings observed by Vanotti and Szogi (2011), in which they saw 10 times as high of a NH_4^+ recovery rate by gas-permeable membranes at pH 10 using alkali chemicals when compared to pH 8.3. Garcia-Gonzalez et al. (2015) showed the positive effect of the low-rate aeration on the NH_4^+ recovery rate by the gas-permeable membrane process was equivalent to adding 2.14 g NaOH L^{-1} of manure. Our results showed that alkalinity destruction using low-rate aeration is an effective approach to increase the pH of the manure and could substitute significant alkali chemical to achieve quick N recovery efficiency.

3.3. The effect of N removal on alkalinity

The initial carbonate alkalinity of Farm 1 effluent was 11,337 ± 10 mg $CaCO_3\ L^{-1}$ and finished at 3033 ± 58 and 3319 ± 80 mg $CaCO_3\ L^{-1}$ for the aerated and non-aerated trials, respectively (Fig. 5). Farm 2 effluent also had a decrease in alkalinity with the gas-permeable membrane system in place, starting at 7369 ± 37 mg $CaCO_3\ L^{-1}$ and finishing at 2083 ± 25 and 2763 ± 205 mg $CaCO_3\ L^{-1}$ for the aerated and non-aerated trials, respectively. Alkalinity was readily consumed in the system as NH_4^+ removal increased, counteracting manure acidification. Lower alkalinity can be valuable when looking forward to further treatment of the manure. Phosphorus removal could also benefit as lower alkalinity requires lower amount of chemicals needed to precipitate phosphorus (Vanotti et al., 2005).

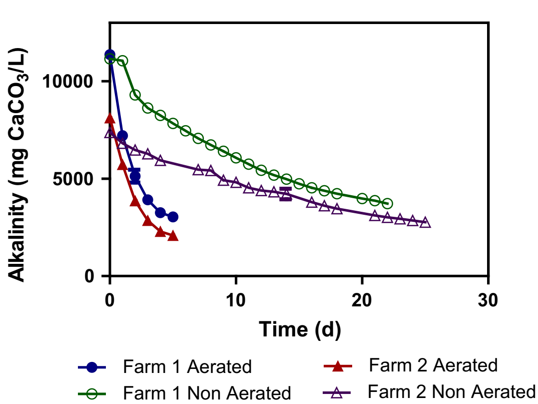

Fig. 5. Effect of aeration on swine wastewater alkalinity during capture of ammonia with gas-permeable membranes. The error bars are standard deviation of duplicate experiments.

3.4. Economic considerations

The annualized cost of NH_4^+ recovery with the gas-permeable membrane system was calculated on the basis of treating the anaerobic digestion effluent from a typical 4000-head swine finishing farm in North Carolina growing pigs from 22.7 to 100 kg (50–220 lb) with a 540,000 lb steady state live weight (SSLW). Treatment parameter and target values used in these calculations are based on this study along with the following conditions:

- Raw swine manure is produced at a rate of 21.8 $m^3\ d^{-1}$ and contains 2007 mg TKN L^{-1} (Vanotti et al., 2009).
- After anaerobic digestion, 80% of the TKN in raw manure is available as NH_4^+ for recovery by the system.
- NH_4^+ recovery efficiency using gas permeable membrane is 98% (this study).
- NH_4^+ removal rate of a membrane module with 32.3 m^2 surface area (e-PTFE tubing area/length = 0.0323 m^2/m) is 1.29 kg N d^{-1} with aeration and 0.21 kg N d^{-1} without aeration (this study).
- Amount of H_2SO_4 needed to absorb the NH_3 calculated from mole ratio, equivalent to 3.5 kg of acid per kg of N recovered.
- Annualized costs of equipment calculated using 8% interest and 10-year useful life (Rothrock et al., 2013).

The amount of NH_4^+ available after anaerobic digestion for the 4000-head swine operation is 35.1 kg N day^{-1}. With aeration, a membrane surface of 872 m^2 is required to remove the daily NH_4^+ generated in the effluent. Equipment cost estimates include 27 membrane modules at $4280 each plus additional components shown in Fig. 2 (feed pump, acid pump and controls, tanks, blower and piping) for a total annualized cost of equipment of $21,059 ($141,310 initial investment). With an average recovery efficiency of 98%, the amount of N recovered per year from this operation is 12,547 kg. The dosage of H_2SO_4 to absorb this N is 120 kg d^{-1} and the annual cost of acid is $14,053 (unit cost = $0.32 kg^{-1}). For nitrification inhibitor, using nitrapyrin (commonly used for farming) at 22.5 mg L^{-1} concentration, the dosage is 0.5 kg d^{-1}. The resulting cost of nitrification inhibitor is $1794 per year (unit cost = $10 kg^{-1}). Power consumption for the blower is 13.7 kW h/d, and for influent and module pumps is 26.4 kW h/d that amount to a total power consumption of 40.1 kW h/d, resulting in an annual electrical cost of $1020 (unit cost = $0.0698 kW h^{-1}, U.S. Energy Information Administration). Therefore, using the aeration approach, the estimated total annual cost (equipment + chemicals + power) for a gas-permeable membrane system in a 4000-head swine farm that uses anaerobic digestion is $37,926 or $70.23 per 1000 lb SSLW per year.

Without aeration, a much higher membrane surface is required (5491 m^2) to remove the same amount of NH_4^+ generated daily by the 4000 head operation (35.1 kg N day^{-1}). Equipment cost estimates include 170 membrane modules and a total annualized cost of equipment of $112,070. The cost of acid is the same ($14,053 per year), but nitrification inhibitor is not required, and without the blower, the power consumption is reduced to 26.4 kW h/d ($672 per year). Thus, the estimated total annual cost (equipment + chemicals + power) without the aeration is $126,794, compared with $37,926 cost with aeration. Therefore, combining a gas permeable membrane system with low-rate aeration for N removal could result in a 70% cost reduction when compared with a gas-permeable membrane system without aeration.

The ammonium sulfate potentially recovered during one year operation of the N recovery system (12,547 kg N) has an equivalent fertilizer value of $34,002 assuming a value of $2.71 per kg N as ammonium sulfate ($522/ton, USDA-ERS, 2013). Considering the value of recovered N, the net cost is $3924 per year ($37,926–$34,002) when the aeration approach is used. Water quality credits are expected to become an important benefit to farmers adopting new manure treatment technologies in the future (EPA, 2015; Ribaudo et al., 2007). For current credit prices of $12.34 kg^{-1} N (Connecticut Department of Energy and Environmental Protection, 2014) and trading ratios for nonpoint sources of 2:1, the potential benefit from removing the N from the farm is $77,427.

A complete economic analysis of the technology would need to consider labor costs and unexpected expenses (recovered NH_4^+ storage reservoir, operator training, lab analysis, etc.) as well as other benefits such as reduction of greenhouse gas emissions due to reduction of direct and indirect N_2O emissions (Vanotti et al., 2008), and the significant reduction of land area required on the farm to dispose the treated effluents.

4. Conclusions

Ammonia recovery of anaerobically digested liquid swine manure using gas-permeable membranes was enhanced using low-rate aeration. The low-rate aeration reacted with the natural carbonates in wastewater and increased pH, which accelerated NH_3 uptake in the gas-permeable membrane system without the use of alkali chemicals. Utilizing aeration, more than 96% of NH_4^+ was able to be recovered in about 4 days' time which significantly improves on the 25 days required to remove NH_3 without aeration. Completing NH_4^+ removal more than 5 times faster represented a 70% reduction in costs.

Acknowledgements

This article is part of USDA-ARS Project 6082-13630-005-00D "Innovative Bioresource Management Technologies for Enhanced Environmental Quality and value Optimization." We acknowledge the field and laboratory assistance of William Brigman and Chris Brown, USDA-ARS, Florence, SC, and the field sampling assistance of Mark Rice, North Carolina State University, Raleigh, NC. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

References

APHA, 1989. Standard Methods for the Examination of Water and Wastewater, 17th ed. American Public Health Association, Washington, DC.
Bonmati, A., Flotats, X., 2003. Air stripping of ammonia from pig slurry: characterization and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion. Waste Manage. 23, 261–272.
Connecticut Department of Energy & Environmental Protection, 2014. Connecticut's Nitrogen Trading Program. Retrieved from <http://www.ct.gov/deep/lib/deep/water/municipal_wastewater/9_17_14_pres_futureplans_ntp.pdf>.
EPA, 2014. National Emission Inventory-Ammonia Emissions from Animal Husbandry Operations. U.S. Environmental Protection Agency. Retrieved from <www.epa.gov/ttnchie1/ap42/ch09/related/nh3inventorydraft_jan2004.pdf>.
EPA, 2015. Water Quality Trading. U.S. Environmental Protection Agency. Retrieved from <http://water.epa.gov/type/watersheds/trading.cfm>.
Funderburg, E., 2013. Why are nitrogen prices so high? The Samuel Roberts Noble Foundation Agriculture News and Views 2001. <www.noble.org/ag/soils/nitrogenprices/>.
Gallaher, R.N., Weldon, C.O., Boswell, F.C., 1976. A semiautomated procedure for total nitrogen in plant and soil samples. Soil Sci. Soc. Am. J. 40, 887–889.
Garcia-Gonzalez, M.C., Vanotti, M.B., 2015. Recovery of ammonia from swine manure using gas-permeable membranes: effect of waste strength and pH. Waste Manage. 38, 455–461.
Garcia-Gonzalez, M.C., Vanotti, M.B., Szogi, A.A., 2015. Recovery of ammonia from swine manure using gas-permeable membranes: effect of aeration. J. Environ. Manage. 152, 19–26.
IFA, 2009. Energy Efficiency and CO_2 Emissions in Ammonia Production. Retrieved from <www.fertilizer.org/HomePage/library/Publication-database.html/Energy-Efficiency-and-CO2-Emissions-in-Ammonia-Production.html>.
Liao, P.H., Chen, A., Lo, K.V., 1995. Removal of nitrogen from swine manure wastewaters by ammonia stripping. Bioresour. Technol. 54, 17–20.
Lin, H., Wu, X., Miller, C., Zhu, J., Hadlocon, L.J., Manuzon, R., Zhao, L., 2014. Pilot-scale field study for ammonia removal from lagoon biogas using an acid wet scrubber. J. Environ. Sci. Health, Part B 49 (6), 439–448.
Magrí, A., Vanotti, M.B., Szogi, A.A., Cantrell, K.B., 2012. Partial nitrification of swine wastewater in view of its coupling with the anammox process. J. Environ. Qual. 41 (6), 1989–2000.
Masse, L., Massé, D.I., Pellerin, Y., Dubreuil, J., 2010. Osmotic pressure and substrate resistance during the concentration of manure nutrients by reverse osmosis membranes. J. Membr. Sci. 348, 28–33.
Milan, Z., Sanchez, E., Weiland, P., de Las Pozas, C., Borja, R., Mayari, R., Rovirosa, N., 1997. Ammonia removal from anaerobically treated piggery manure by ion exchange in columns packed with homoionic zeolite. Chem. Eng. J. 66 (1), 65–71.
Ndegwa, P.M., Hristov, A.N., Arogo, J., Sheffield, R.E., 2008. A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosyst. Eng. 100, 453–469.
Nelson, N.O., Mikkelsen, R.L., Hesterberg, D.L., 2000. Struvite formation to remove phosphorus from anaerobic swine lagoon effluent. In: Moore, J.A. (Ed.), Proc. 8th International Symposium Animal, Agricultural, and Food Processing Wastes. ASAE, St. Joseph, Michigan, pp. 18–26.
Paerl, H.W., 2006. Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: interactive effects of human and climatic perturbations. Ecol. Eng. 26 (1), 40–54.
Ribaudo, M., Johansson, R., Jones, C., 2007. Environmental credit trading: can farming benefit? Amber Waves 4, 46–51.
Rothrock Jr., M.J., Szögi, A.A., Vanotti, M.B., 2013. Recovery of ammonia from poultry litter using flat gas permeable membranes. Waste Manage. 2013 (33), 1531–1538.
Stevens, R.J., Cornforth, I.S., 1974. The effect of aeration on the gases produced by slurry during storage. J. Sci. Food Agric. 25, 1249–1261.
Technicon Instruments Corp., 1977. Individual/Simultaneous Determination of Nitrogen and/or Phosphorus in BD Acid Digests (Dialyzer). Industrial Method 337-74W/B. Technicon Instruments Corp., Tarrytown, NY.
USDA Economic Research Service, 2013. Average U.S. Farm Prices of Selected Fertilizers, 1960–2013. Retrieved from <http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx>.
U.S. Energy Information Administration, 2015. Electric Power Monthly with Data for June 2015. Retrieved from <http://www.eia.gov/electricity/monthly/pdf/epm.pdf>.
Vanotti, M.B., Hunt, P.G., 2000. Nitrification treatment of swine wastewater with acclimated nitrifying sludge immobilized in polymer pellets. Trans. ASAE 43 (2), 405–413.
Vanotti, M.B., Szogi, A.A., Hunt, P.G., 2005. Wastewater Treatment System. U.S. Patent No. 6893567.
Vanotti, M.B., Szogi, A.A., Vives, C.A., 2008. Greenhouse gas emission reduction and environmental quality improvement from implementation of aerobic treatment systems in swine farms. Waste Manage. 28, 759–766.
Vanotti, M.B., Szogi, A.A., Millner, P.D., Loughrin, J.H., 2009. Development of a second-generation environmentally superior technology for treatment of swine manure in the USA. Bioresour. Technol. 100, 5406–5416.
Vanotti, M.B., Szogi, A.A., 2011. Use of gas-permeable membranes for the removal and recovery of ammonia from high strength livestock wastewater. Proc. Water Environ. Fed., Nutr. Recov. Manage., 659–669
Vanotti, M.B., Szogi, A.A., 2015. Systems and Methods for Reducing Ammonia Emissions from Liquid Effluents and for Recovering the Ammonia. U.S. Patent No. 9005333.
Wing, S., Wolf, S., 2000. Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ. Health Perspect. 108 (3), 223–238.
Zarebska, A., Romero Nieto, D., Christensen, K.V., Fjerbaek Sotoft, L., Norddahl, B., 2015. Ammonium fertilizers production from manure: a critical review. Crit. Rev. Environ. Sci. Technol. 45, 1469–1521.
Zhu, J., Luo, A., Ndegwa, P.M., 2001. The effect of limited aeration on swine manure phosphorus removal. J. Environ. Sci. Health, Part B 36 (2), 209–218.