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Original Research

Ammonia Stripping with Plant Ash Enhanced Removal and Recovery Rate of Ammonia Nitrogen From Biogas Slurry

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Abstract

This study was conducted to evaluate the effects of plant ash based ammonia stripping process on removal and recovery of ammonia-nitrogen (NH_3-N) in biogas slurry (BS), in order to provide theoretical reference for the feasibility of plant ash, as replacement of sodium hydroxide. The best mixing ratio of plant Ash and biogas slurry, gas-liquid ratio, stripping time and stripping temperature was also determined to optimize the process. The results showed that the (NH_3-N) removal rate was 85.27% and the recovery rate was 76.45%, at 10:2 biogas slurry and plant ash mixing ratio, the gas-liquid ratio of 2000, the stripping temperature of 30ºC and the stripping time of 2 h. Compared with sodium hydroxide as stripping promoter the removal rate and recovery rate of ammonia nitrogen in biogas slurry were increased by 4.15% and 6.49% respectively, and the operation cost of ammonia nitrogen stripping process was reduced by plant ash replacing sodium hydroxide. The comprehensive analysis suggested that it is feasible to combine the plant ash with biogas slurry to remove ammonia nitrogen.

Keywords: biogas slurry, plant ash, ammonia nitrogen, removal, recovery

Introduction

The rapid urbanization and overburdened population intensify the food demand and production gap. The ever increasing food demand and economic race for fast track development imposed enormous pressure to continuously expand the scale of livestock and poultry breeding industries which ultimately produce a large amount of solid and liquid organic waste which also contained pathogenic microorganisms. If not handled properly or pretreated before dispose of it will cause severe environmental hazards and health related consequences [1-3]. To process the huge amount of organic waste, anaerobic digestion is proven to be an efficient strategy to treat the fecal sewage of large-scale farms [4-7]. Anaerobic digestion can effectively kill pathogenic bacteria and parasitic microorganisms, preserve nutrients in organic waste, generate biogas energy, and biogas slurry from

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livestock and poultry feces [8-10]. The biogas slurry as a useful byproduct of anaerobic digestion can be utilized as efficient organic fertilizer. However, its direct application is not environmentally safe due to higher concentration of ammonia nitrogen, which can cause water eutrophication and groundwater pollution [11, 12]. Pretreatment, transportation and application of biogas slurry towards the field in eco-friendly manner is considered as a challenging task due to its large volume as in liquid phase, higher concentration of ammonia nitrogen and lack of farmland near the biogas plant sites which can affect the sustainable operation of the biogas plants. Therefore, reducing the ammonia nitrogen content in biogas slurry and increasing the carrying capacity of biogas slurry per unit farmland is one of the effective ways to realize biogas slurry consumption.

To remove the ammonia nitrogen content in biogas slurry various approaches have been adopted such as denitrification, membrane extraction, catalytic liquid-phase oxidation, selective ion exchange, adsorption precipitation, new ultrasonic and microwave irradiation [13, 14]. However, these methods have some limitations such as higher cost, low ammonia nitrogen removal efficiency at low temperature, long treatment time, secondary pollution and high ammonia nitrogen concentration in effluent, therefore the acceptability and application of these methods in field condition is limited. Among different methods ammonia nitrogen stripping process is considered most suitable and widely used denitrification treatment method for sewage and biogas slurry due to low treatment cost, stable treatment effect and higher efficiency rate [15-19]. The traditional ammonia nitrogen stripping process takes air as the carrier and makes full contact between gas and water under alkaline conditions, resulting in that the ammonia concentration in the gas phase is always lower than the equilibrium concentration. To achieve the purpose of ammonia nitrogen removal and recycling dissolved ammonia in sewage continuously enters the gas phase through the gas-liquid interface and converts ammonium ions (NH_4^+) into dissolved ammonia (NH_3). The research shows that ammonia nitrogen in sewage exists as NH_3 and NH_4^+, and there is a balance relationship between them that is $NH_4^+ + OH^- = NH_3 + H_2O$. This equilibrium is highly dependent on pH such as at pH = 7 most ammonia nitrogen in sewage exists as NH_4^+, whereas, at when pH>7, the balance moves to the right and the proportion of free ammonia increases. Additionally, temperature also affects the concentration of free ammonia in sewage. The proportion of free ammonia increases with the increase in temperature. However, at higher pH level (pH = 11) 98% of ammonia nitrogen in sewage exists as free ammonia without rising the temperature [20]. Many studies indicated that pH value, gas-liquid ratio, temperature and stripping time directly affect the stripping efficiency of ammonia nitrogen with the following order such as pH>temperature>stripping time>gas-liquid ratio [21-25].

In industry, ammonia nitrogen stripping process mostly uses sodium hydroxide (NaOH), quicklime and calcium hydroxide as stripping promoters to rise the pH of sewage and maintain its alkalinity. This approach is not economical due to higher cost as well as it also produces secondary pollution hence not considered as ecofriendly [26-29]. Therefore, the selection of low-cost and pollution-free alkaline promoter is the key to reduce the cost and increase the efficiency of ammonia nitrogen stripping process as economically feasible and ecofriendly manner. Plant ash as an alternative stripping promoter can be used for this purpose which is the residue of herbaceous and woody plants after combustion. It is light weight, alkaline and has strong adsorption capacity; therefore, it has the potential to be used as ammonia nitrogen stripping promoter [30-32]. At present the information about the application of plant ash as ammonia nitrogen stripping promoter is scanty. Therefore, present study is designed to explore the potential of plant ash as striping promoter. This study starts with the stripping treatment of plant ash, Optimize the amount of plant ash, gas-liquid ratio, temperature and stripping time on the removal of ammonia-nitrogen, and then select the best process parameters, and constructs a process to provide a theoretical basis for the ammonia nitrogen removal. At last, it is to analyze the economy of ammonia nitrogen stripping process for full return of biogas slurry.

Materials and Methods

Test Materials

The experiment was conducted from October to December, 2021 in the biomass energy science and technology research center, Yantai Institute, China Agricultural University, Yantai City, Shandong Province, China. The biogas slurry was obtained from biogas plant of a dairy farm and the plant ash used in this experiment was obtained from a straw thermal power plant in Yantai City, Shandong Province. The characteristics of biogas slurry and plant ash are shown in Table 1.

Ammonia Nitrogen Stripping Experimental Device

The ammonia nitrogen stripping device used in the experiment was provided by Shanghai Dayou Instrument Company of China (model: DYG013) and optimized according to experimental design. The main configuration and parameters are shown in Table 2, and the schematic diagram of the device is shown in Fig. 1. The biogas slurry and plant ash were mixed in specified proportions, stirred and, regulated to the set temperature then transported to the stripping tower by the water pump. After aeration, the biogas slurry

Table 1. Properties of biogas slurry and plant ash.

Items	Test Materials	
	Biogas slurry	Plant ash
pH	8.43	11.04 (w/v = 1:2.5)
Ammonia nitrogen (mg/L)	225.14	0.00
Total nitrogen (mg/L)	3061.80	621.52
COD (mg/L)	2580.0	/
BOD (mg/L)	1474.5	/
SS (%)	0.36	/
Escherichia coli (MPN/mL)	12000	/
Ascaris eggs mortality (%)	100	/
Particle size (μm)	/	10-100
BET surface area (m^2/g)	/	6.15
Mean pore size (nm)	/	7.686
Element content (%)	/	C (3.17); H (0.29); O (3.82); S (0.70)

returns to the biogas slurry tank, and the gas is recovered by the sulfuric acid solution.

Experimental Design

The first step is to determine the optimum mixing ratio of biogas slurry and plant ash, followed by gas-liquid ratio, stripping time and temperature. Finally, the process parameters were finalized and applied synergistically at the same time, the economic evaluation was conducted for the feasibility of process extension.

Determination of Mixing Ratio of Biogas Slurry and Plant Ash

Biogas slurry (1000 kg) was mixed with 100, 200, 300 and 400 kg of plant ash to make 10:1, 10:2, 10:3 and 10:4 mixing ratios. The stripping experiment was carried out under the condition of gas-liquid ratio of 2000 (aeration capacity of 1000 m^3/h, liquid flow of 0.5 m^3/h), temperature of 30ºC and stripping time of 3 h. The removal rate and recovery rate of ammonia nitrogen were measured respectively.

Determination of Gas-Liquid Ratio

Setting the gas-liquid ratio at 1000, 2000 and 3000 (aeration capacity of 500 m^3/h, 1000 m^3/h and 2000 m^3/h, liquid flow rate of 0.5 m^3/h), and then measured the ammonia nitrogen removal and recovery rate under the condition of optimum mixing ratio, temperature of 30ºC and stripping time of 3 h.

Determination of Temperature

Setting stripping temperature at 10, 20, 30 and 40ºC, and then measured the ammonia nitrogen removal and recovery rate under the condition of optimum mixing ratio, optimum gas-liquid ratio and stripping time of 3 h.

Determination of Stripping Time

Setting stripping time at 1 h, 1.5 h, 2 h, 2.5 h, 3 h, 3.5 h and 4 h, and then measured the ammonia nitrogen removal and recovery rate under the condition of optimum mixing ratio, optimum gas-liquid ratio and optimum stripping temperature.

Stripping Process Assembling and Economic Analysis

The process was assembled and optimized on the basis of optimum stripping parameters and carried out the economic analysis of the process in comparison with the stripping process using NaOH as promoter (control).

Methods for Sample Collection and Determination

According to the experimental design, 50 mL of the mixed liquid of biogas slurry and plant ash and 50 mL of sulfuric acid solution were taken for the determination of ammonia nitrogen concentration and

Table 2. Configuration and parameters of biogas slurry ammonia nitrogen stripping device.

Equipped device	Parameter
Power control system	Leakage protector; Voltmeter; Variable frequency control unit: 2.2 KW
Fan control system	One fan: air volume 2100 m^3/h, power 0.85 KW; Gas flowmeter
Temperature control system	Electric heating tube: temperature 0-60ºC, power 0.6 KW; Refrigerated circulator: 1.5 KW
Biogas slurry conveying system	One mixing motor: power 25W, rotational speed 90 rpm; One water pump: power 1.5 KW, flow 3 m^3/h; Liquid flowmeter; Biogas slurry tank: About 1.7 m long, 1.2 m wide and 0.8 m high
Stripping tower	1.5 m high, 0.25 m inside diameter, containing a hollow polyhedral ball with a diameter of 25 mm
Ammonia nitrogen recovery system	One liquid tank: 40 cm long, 40 cm wide and 70 cm high, containing 100 L of 1 mol/L sulfuric acid solution

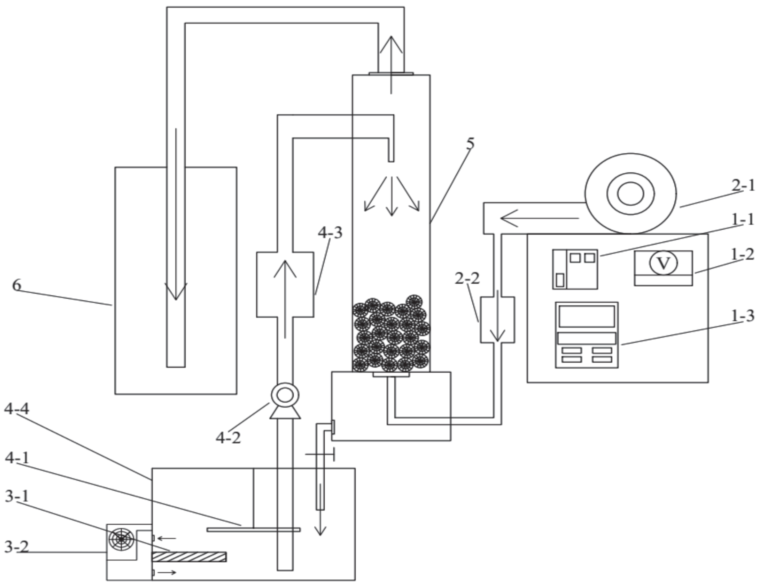

Fig. 1. Schematic diagram of ammonia nitrogen stripping device.
Reference signs: power control system 1, leakage protector 1-1, voltmeter 1-2, control unit 1-3; Fan control system 2, fan 2-1, gas flowmeter 2-2; Temperature control system 3, electric heating tube 3-1, refrigerated circulator 3-2; Biogas slurry conveying system 4, mixing motor 4-1, water pump 4-2, liquid flowmeter 4-3, biogas slurry tank 4-4; Stripping tower 5, ammonia nitrogen recovery system 6.

pH after stripping. Ammonia nitrogen concentration was determined by automatic distillation acid titration, and pH is determined by pH meter [17]. The calculation of ammonia nitrogen removal rate is shown in Formula (1), and the calculation of ammonia nitrogen recovery rate is shown in formula (2).

$$\omega_1 = \frac{V_1 \times 14 \times c \times 1000}{V \times c_0} \times 100\% \quad (1)$$

$$\omega_2 = \frac{V_2 \times 14 \times c \times 1000 \times V_b + mV}{V_a \times V \times c_0} \times 100\% \quad (2)$$

In the formula:
V_1 – volume of sulfuric acid standard solution consumed in stock solution titration (mL);
c – concentration of sulfuric acid standard solution (mol/L);
V – volume of liquid to be measured for each sampling (mL);
c_0 – ammonia nitrogen concentration of original biogas slurry (mg/L);
V_2 – volume of sulfuric acid standard solution consumed in titration of recovery solution (mL);
m – cumulative ammonia nitrogen content in the sample recovery solution (mg);
V_a – total volume of reaction recovery solution (L);
V_b – total volume of biogas slurry to be treated (L).

Statistical Analysis of Data

Three replicates were set in each group. Data were statistically analyzed by using Excel 2016 and SPSS 24.0. The least significant difference (LSD) test was used to determine the significant difference among treatment means.

Results

Effect of Different Mixing Ratio of Biogas Slurry and Plant Ash on Ammonia Nitrogen Removal and Recovery Rate

Table 3 showed that with increasing plant ash content in biogas slurry with the mixing ratio of 10:1 to 10:4 significantly increased the pH. In terms of stripping time, the ammonia nitrogen removal and recovery rate of biogas slurry also increased with the increase in stripping time from 0.5 h to 3 h. As compared to 10:1 ratio with increasing treatments (10:2, 10:3 and 10:4), Ammonia nitrogen removal rate was increased 5.96, 7.4 and 7.02% respectively and recovery rate was increased 6.19, 7.25 and -13.56% respectively, after stripping for 3 hours. The statistical analysis showed that 10:2 and 10:3 treatments give similar results and showed maximum ammonia nitrogen removal and recovery rate therefore, the 10:2 treatment for 3 h is the most suitable and costs effective treatment.

Effect of Different Gas-Liquid Ratio on Ammonia Nitrogen Removal and Recovery Rate

The data presented in Table 4 indicated that with increasing gas-liquid ratio from 1000 to 3000 as well as the stripping time (0.5 to 3 h) significantly enhanced

Table 3. Effect of different mixing ratios on ammonia nitrogen removal and recovery rate.

Items	Mixing ratio	pH	Stripping time (h)					
			0.5	1.0	1.5	2.0	2.5	3.0
Removal rate (%)	10 : 1	9.56	37.02b	58.02d	66.95d	74.94b	80.61c	84.78b
	10 : 2	9.93	43.26a	61.20c	72.37c	84.24a	87.67b	90.74a
	10 : 3	10.17	45.59a	64.44b	76.70b	85.44a	89.58ab	92.18a
	10 : 4	10.26	42.96a	73.43a	82.07a	87.25a	90.39a	91.80a
Recovery rate (%)	10 : 1	9.56	28.31b	50.86bc	63.60b	68.71b	72.42b	75.47c
	10 : 2	9.93	30.95ab	52.82ab	66.69a	76.02a	80.10a	81.66a
	10 : 3	10.17	32.42a	54.33a	68.21a	76.66a	81.22a	82.72ab
	10 : 4	10.26	30.40ab	48.09c	55.37c	59.29c	61.18c	61.91d

Explanation: Each value represents the mean of 3 replicates; The different lower-case letters stand for significant differences at 0.05 level between treatments.

Table 4. Effect of different gas-liquid ratio on ammonia nitrogen recovery and removal rate.

Items	The gas-liquid ratio	Stripping time (h)					
		0.5	1.0	1.5	2.0	2.5	3.0
Removal rate (%)	1000	24.31b	37.85b	49.29b	63.00b	69.03c	76.06b
	2000	41.26a	61.20a	72.37a	84.24a	87.67a	90.74a
	3000	43.23a	59.88a	71.47a	80.44a	83.96a	88.06a
Recovery rate (%)	1000	17.53c	31.73c	44.41c	53.64c	63.15c	70.14c
	2000	27.40b	52.82a	66.69a	76.02a	80.10a	81.66a
	3000	30.74a	48.06b	59.83b	68.99b	74.82b	77.16b

Explanation: Each value represents the mean of 3 replicates; The different lower-case letters stand for significant differences at 0.05 level between treatments.

the ammonia nitrogen removal and recovery rate. However maximum increase was observed at 2000 gas liquid ratio at 3 h of stripping time. With the continuation of stripping time, the ammonia nitrogen removal and recovery rate in the treatment with gas-liquid ratio of 2000 were always higher and reached 119.30%, 103.04% and 116.42%, 105.83% at stripping time of 3.0 hours, than those of the other two treatments with gas-liquid ratio of 1000 and 3000, respectively. The data showed that gas-liquid ratio of 2000 was the best for the ammonia nitrogen stripping from biogas slurry and plant ash.

Effect of Temperature on Ammonia Nitrogen Recovery and Removal Rate

The data presented in Table 5 indicated that removal and recovery rate of ammonia nitrogen in biogas slurry increased with the increase in the stripping temperature and time (Table 5). After stripping for 1 hour, compared to the treatment with stripping temperature of 30ºC, the ammonia nitrogen removal rate in the treatments with stripping temperature of 10ºC and 20ºC decreased by 35.01% and 11.42%, while it increased by 2.85% in the treatment with stripping temperature of 40ºC. As stripping time ranged from 1.0 h to 3.0 h, there were no significant differences in ammonia nitrogen removal rate between stripping temperature of 30ºC and 40ºC. Therefore, it could be included that 30ºC for 3 h can be used as the best temperature for ammonia nitrogen stripping.

Effect of Stripping Time on Ammonia Nitrogen Removal and Recovery Rate

Under the conditions of the best mixing ratio (10:2), the best gas-liquid ratio (2000) and the best stripping temperature (30ºC), the influence of stripping time on the ammonia nitrogen removal and recovery rate of biogas slurry was shown in Fig. 2. At initial striping time time (0.25 h to 0.75 h) the ammonia nitrogen removal rate showed straight down trend and recovery rate showed gradual increase. After 1.0 h, ammonia nitrogen removal and recovery rate were increased gradually,

Table 5. Effects of different temperatures on ammonia nitrogen removal rate and recovery rate.

Items	Temperature (ºC)	Stripping time (h)					
		0.5	1.0	1.5	2.0	2.5	3
Removal rate (%)	10	16.24c	28.15d	39.72c	45.62c	52.21c	56.90c
	20	25.36b	33.99c	46.41b	55.30b	64.54b	70.79b
	30	40.70a	63.16b	72.32a	85.69a	88.00a	91.16a
	40	42.05a	66.78a	74.25a	87.50a	89.94a	92.78a
Recovery rate (%)	10	12.78d	22.56d	33.58c	38.58d	45.72c	49.56c
	20	17.79c	28.42c	39.20b	48.64c	55.95b	63.42b
	30	27.72b	49.84b	63.82a	74.64b	79.33a	82.69a
	40	29.50a	52.69a	65.52a	78.05a	81.48a	83.84a

Explanation: Each value represents the mean of 3 replicates; The different lower-case letters stand for significant differences at 0.05 level between treatments.

and reached the peak at 1.5 to 1.75 h, followed by a significant drop. Different from the ammonia nitrogen removal rate, ammonia nitrogen recovery rate of biogas slurry showed a gradual upward trend in the period of 0.25 h to 2.0 h and reached the maximum value at 2.0 h, and then decreased significantly. The ammonia nitrogen recovery rate in the period of 3.5 to 4 h was only 0.07% of that in the period of 1.75 h to 2.0 h that showed the optimum time limit for stripping process that was 2 h for ammonia nitrogen stripping from biogas slurry.

Ammonia Nitrogen Removal and Recovery Rate in Combined Process

The experimental results showed that the best combination process was that the mixing ratio (10:2), the gas-liquid ratio (2000), the temperature (30ºC) and the stripping time (2 h).

Under the optimum conditions, the ammonia nitrogen removal rate was 85.27% (Table 6). It could be seen from table 7 that the best theoretical combination was the mixing ratio of 10:2, the gas-liquid ratio of 2000, the temperature of 40ºC, the stripping time of 2h, the theoretical ammonia nitrogen removal rate could reach 86.59%, and the temperature was the main factor affecting the ammonia nitrogen stripping efficiency. Compared with the experimental results, the theoretical value only increased by 1.55%.

Economic Analysis of Combined Process

Most of the ammonia nitrogen removed by stripping can be collected by the recovery system and recycled in the form of ammonium sulfate fertilizer. Compared to NaOH as a promoter, the cost of plant ash was increased by 0.42 dollars, but the value of recovered ammonia

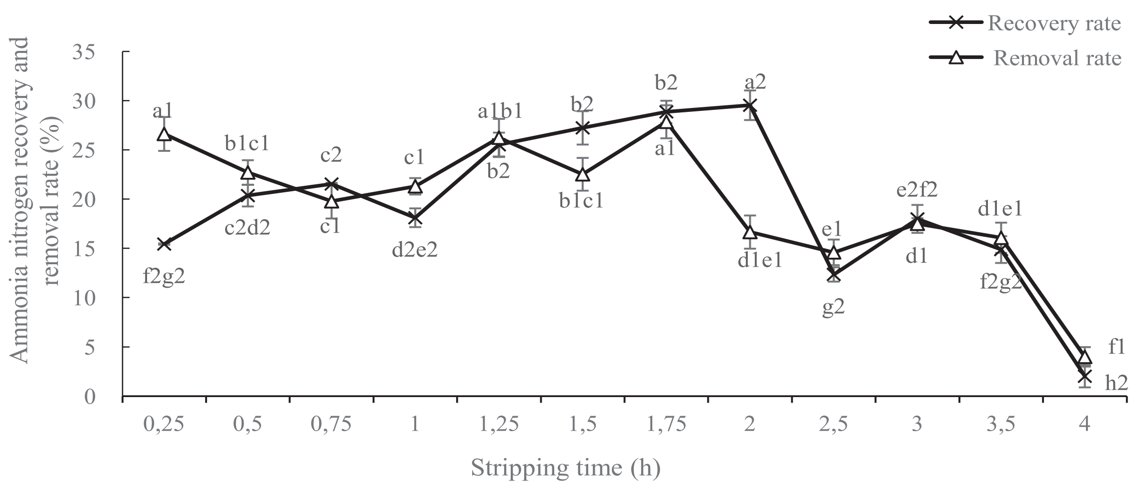

Fig. 2. Ammonia nitrogen recovery and removal rate in different time periods.
Explanation: The numbers 1 and 2 in the marked letters of significant difference in the figure represent the ammonia nitrogen removal rate and recovery rate respectively; Each value represents the mean of 3 replicates; The different lower-case letters stand for significant differences at 0.05 level between treatments.

Table 6. Effect of combined process on ammonia nitrogen removal and recovery rate.

Combined process	Parameter	Removal rate (%)	Recovery rate (%)
Mixing ratio of biogas slurry and plant ash (L/kg)	10:2	85.27	76.45
The gas-liquid ratio	2000		
Temperature (ºC)	30		
Stripping time (h)	2		

nitrogen increased by 0.11 dollars. After stripping, the plant ash will be collected and restriction indicators of returning to the field will be determined (Table 9). The values of all items meet the executive standards of China organic fertilizer (NY-525). Therefore, at similar power cost, stripping process with plant ash is considered to return the plant ash to the field without treatment. The combined process of plant ash and biogas slurry could achieve positive benefits in terms of economic performance, while the process of NaOH and biogas slurry showed negative result.

Discussion

The experimental results showed that the addition of plant ash in biogas slurry positively correlated with the pH value of the slurry (r = 0.966, *P* = 0.034). This was mainly because Potassium carbonate (K_2CO_3) in plant ash was ionized after dissolving in water, resulting in the corresponding increase of pH value of biogas slurry with the increase of additional amount of plant ash [30, 31]. At the rising pH value of biogas slurry i.e. 9.56 and 10.26, the ammonia nitrogen removal rate were between 84.78% and 92.18% respectively, indicating that the enhancement of alkalinity was conducive to the removal of ammonia nitrogen, which was consistent with the research results of Fakkaew and Guštin [15, 20]. There were no significant differences in ammonia nitrogen removal rate of biogas slurry after stripping for 2 hours and the potential for pH elevation was diminishing, when the mixing ratio of biogas slurry and plant ash was 10:2, 10:3 and 10:4. It might be that the increase in the additional amount of plant ash increased the viscosity of biogas slurry, hindered the ionization of K_2CO_3 in plant ash, and then inhibited the removal effect of hydroxide (OH^-) on ammonia nitrogen. In terms of ammonia nitrogen recovery rate, when the mixing ratio of biogas slurry and plant ash was 10:4, the ammonia nitrogen recovery rate was always significantly lower than the mixing ratio of 10:2 and 10:3, which was contrary to the fact that the increase of pH in the traditional ammonia nitrogen stripping process can effectively increase

Table 7. Orthogonal experiment of ammonia nitrogen stripping process parameters.

Serial number	Mixing ratio	The gas-liquid ratio	Temperature (ºC)	Removal rate (%)
1	10:1	1000	20	37.75
2	10:1	2000	30	74.94
3	10:1	3000	40	75.18
4	10:2	1000	30	63.00
5	10:2	2000	40	86.59
6	10:2	3000	20	54.41
7	10:3	1000	40	65.10
8	10:3	2000	20	58.59
9	10:3	3000	30	84.83
K1	62.62	55.28	50.25	
K2	68.00	73.37	74.26	
K3	69.35	71.47	75.62	
R	6.73	16.19	25.37	

Explanation: Ki is the average value under different levels of a single factor, and R is the very poor level of a single factor; Each value represents the mean of 3 replicates.

Table 8. Economic comparison of different ammonia nitrogen stripping process (dollars/1000 L biogas slurry).

Stripping process	Stripping promoter cost	Electricity consumption	Nitrogen recovery value	Utilization value of returning farmland	Economic performance
Plant ash and biogas slurry	1.42a	0.89a	1.28a	1.42a	0.39a
NaOH and biogas slurry	1.00b	0.89a	1.17b	0b	-0.72b

Explanation: The different lower-case letters stand for significant differences at 0.05 level between treatments.

the recovery effect of ammonia nitrogen. The main reason was that the excessive plant ash made the biogas slurry too viscous, resulting in a significant reduction in the amount of biogas slurry delivered to the stripping tower and thus reducing the stripping effect.

The gas-liquid ratio has a significant impact on the ammonia nitrogen removal rate of biogas slurry [21, 22]. The results showed that under the condition of gas-liquid ratio of 1000, the ammonia nitrogen removal rate of biogas slurry after stripping for 3 hours was 76.06%, and the stripping efficiency was relatively low. It might be that the low gas-liquid ratio made the gas unevenly distributed in the stripping Tower, resulting in obvious rupture of the liquid layer [10]. When the gas-liquid ratio elevated to 2000 and 3000, the ammonia nitrogen removal rate of biogas slurry increased significantly, which was consistent with the research results of Fakkaew and Morikubo, mainly because the higher gas-liquid ratio ensured more aeration, reduced mass transfer resistance and promoted ammonia stripping [15, 18]. The data analysis showed that when the gas-liquid ratio increased up to 2000 and 3000, there was no significant difference in the ammonia nitrogen removal rate, which might be because when the aeration volume reached a certain degree, the ammonia nitrogen removal rate had been closed to the theoretical proportion of ammonia molecules in biogas slurry, and further aeration could not further improve the ammonia nitrogen removal [24].

On the one hand, temperature can affect the molecular diffusion coefficient of Ammonia (NH_3) in gas phase and liquid phase and adjust the distribution proportion of NH_3 in gas-liquid phase. On the other hand, it also affects the desorption of NH_3 from liquid phase [14, 21, 23]. With the increase in stripping temperature from 10ºC to 40ºC, the ammonia nitrogen removal and recovery rate of biogas slurry increased simultaneously, which indicating that the increase in temperature reduced the solubility of ammonia and promoted the effective removal of ammonia in the form of volatilization. Compared with the treatment with stripping temperature of 30ºC, although the ammonia nitrogen removal rate and recovery rate increased slightly when the temperature raised to 40ºC and the K value only increased by 1.36 (Table 7), the statistical analysis showed that there were no significant differences between the treatments, which was consistent with the research results of Costamagna and Quan [17, 29] who reported that when the stripping temperature rose to a certain range, only the synchronous increase of pH could achieve better stripping effect. In this study, the alkalinity provided by plant ash was limited, which could not realize the synchronous increase with temperature, so it restricted the promotion effect of temperature increase on ammonia nitrogen stripping. At the same time, considering that it was difficult to provide higher stripping temperature in the traditional stripping process, based on the stripping cost, and so temperature from 25ºC to 40ºC could be selected as the actual stripping temperature [24].

Morikubo, Değermenci, Tao et al. [18, 22, 25] studied the dynamic change of ammonia nitrogen concentration with stripping time in biogas slurry stripping process, and found that stripping time was the key factor to reduce ammonia nitrogen concentration and optimum stripping time resulting the maximum stripping effect, When the stripping time was in the range from 1.75 to 2.0 hours, the ammonia nitrogen removal and recovery rate decreased significantly, indicating that after a certain period of stripping, most of the ammonia nitrogen in the biogas slurry had been effectively removed resulting in a significant decrease in the ammonia nitrogen removal and recovery effect with the extension of stripping time. In the whole experiment, the recovery rate was always lower than the removal rate of ammonia nitrogen, which might be due to the fact that the striped ammonia gas was not completely absorbed by the sulfuric acid solution, and there was a partial overflow.

Table 9. Restriction indicators of returning plant ash to field.

Items	As (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Escherichia coli (MPN/g)	Ascaris eggs mortality (%)
Plant ash	8.27	0.81	47.34	1.69	125.30	61	100

After the combined stripping process of plant ash and biogas slurry, the ammonia nitrogen removal and recovery effect were effectively improved under the best parameters. The analysis of orthogonal test results showed that the combined stripping process was actually effective in the removal of ammonia nitrogen from biogas slurry. Compared with the traditional stripping process of NaOH and biogas slurry, plant ash as a stripping promoter could not only reduce the cost of ammonia nitrogen stripping, but also create the alkaline environment derived from carbonate and bicarbonate for stripping process, and could slow down the reduction of pH value in biogas slurry in the stripping process to a certain extent [31]. Therefore, it was feasible in theory and engineering for plant ash to replace alkaline promoter.

Conclusions

The optimized parameters of ammonia nitrogen stripping process with plant ash are mixing ratio of biogas slurry with plant (10:2), the gas-liquid ratio (2000), the stripping temperature (30ºC) and the stripping time (2 h) that maximize the ammonia nitrogen removal and recovery rate. Under this condition, it could remove 85.27% and recover 76.45% of ammonia nitrogen in biogas slurry. This integrated approach could reduce the cost of ammonia nitrogen stripping process and make it economically feasible technique to remove or recover the ammonia nitrogen form biogas slurry in the meantime. It also promotes the utilization of agricultural waste into valuable resources in eco-friendly manner.

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Conflict of Interest

The authors declare no conflict of interest.

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