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PRELIMINARY TRIALS OF *IN SITU* AMMONIA STRIPPING FROM SOURCE SEGREGATED DOMESTIC FOOD WASTE DIGESTATE USING BIOGAS: EFFECT OF TEMPERATURE AND FLOW RATE

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ABSTRACT

Batch experiments to remove ammonia from food waste digestate were set up, and preliminary runs undertaken. These experiments were based on gas stripping in a heated column reactor; the effects of different temperatures (35 ºC, 55 ºC and 70 ºC) and gas flow rates (0.125, 0.250 and 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}) were considered using biogas as the stripping gas. At 35ºC, an increase in the ammonia removal rate by approximately 4.5 times was observed when the flow rate increased from 0.125 to 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}. At 55 ºC, and flow rates of 0.250 and 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}, ammonia removal of 3.46 and 9.38 % d^{-1}, respectively, were achieved. The highest values of removal of ammonia were reached at 70 ºC: 18.4 and 10.4 % d^{-1}, for 0.250 and 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1} flow rates respectively.

Keywords: ammonia removal, anaerobic digestion, food waste, stripping

1. INTRODUCTION

The potential energy in food processing wastes is high because of the rich content of organic components (Digman and Kim, 2008). Although anaerobic digestion is a suitable and proven technology for stabilizing the organic fraction of municipal solid waste (OFMSW) (Hartman and Ahring, 2005; Benabdallah El Hadj et al., 2009), there are reports related to digesters operating entirely on source segregated food waste (SSFW) which suffer from process instability due to the composition of the feedstock with a high protein and fat content and possible nutrient deficiencies (Banks et al., 2008).

Anaerobic digestion effluents from organic wastes typically contain high concentrations of ammonium, phosphate, suspended solids, and persistent organic substrate. Therefore, there is a growing interest in this treatment due to its advantages in terms of energy and the fact that it produces fertilizer for recycling the nutrients to agricultural land (Salminen et al., 2001; Fricke et al., 2007). However, some issues remain regarding the use of digestates as fertilizer.

During anaerobic digestion of SSFW one of the operational problems is that nitrogen compounds enter the process mostly in the form of proteins. High concentrations of both ammonia and ammonium are produced due to the degradation of proteins and aminoacids and although anaerobic digestion can remain stable at high total ammoniacal nitrogen concentrations (i.e. 2-10 g L^{-1} for poultry litter (Gangani Rao et al., 2008)), the result can be a significant reduction of biogas and methane production. Ammonium is an essential nutrient for microorganisms and it contributes to the stabilisation of the pH value in the reactor. This, in the form of ammonium bicarbonate buffers the system allowing it to operate even with high volatile fatty acid (VFA) concentrations. Free ammonia is known to be highly toxic, especially to acetoclastic methanogens. However, it has recently been found that the ammonium ion also inhibits biogas production during the anaerobic digestion of OFMSW by as much as 50% at high ammonium concentrations (3800 and 5600 mg L^{-1} under mesophilic and thermophilic conditions, respectively (Benabdallah El Hadj et al., 2009)). Furthermore, excess ammonia can inhibit not only the methanogenesis in anaerobic reactors (Nielsen and Angelidaki, 2008), but also the hydrolysis (Poggi-Varaldo et al., 1997). In fact, hydrolysis of organic matter is the bottleneck for the degradation of complex organic matter found in SSFW. Therefore, to improve the hydrolytic and methanogenic steps, to optimize the biogas and methane yields and to obtain a properly digested effluent from domestic food waste that can be used as fertilizer, while avoiding nitrogen pollution in farming areas where high ammonia digestate has been used (Woli et al., 2004), a simple and effective process for removing ammonia is required.

Although there are many recent research works focusing on nitrogen removal from manure and wastewater, including biological denitrification (Wett and Rauch, 2003), ammonia-stripping (Lei et al., 2007), precipitation with phosphorus and magnesium as struvite (Uludag-Demirer et al., 2008), electrochemical conversion (Lei and Maekawa, 2007), microwave radiation (Lin et al., 2009) and ultrasound (Wang et al., 2008), there are no reports in the literature regarding *in situ* ammonia removal from SSFW digestate.

Ammonia stripping is a controlled process for the removal of ammonia from a solution which, combined with absorption, can remove and recover ammonia from wastes (Bonmatí and Flotats, 2003). The stripping process is relatively simple and stable if the pH and temperature remain constant. The procedure is unaffected by toxic compounds, that could disrupt the performance of a biological system (US EPA, 2000). Air stripping has been reported as an economical and efficient physical method for removing ammonia from poultry litter leachate (Gangagni Rao et al., 2008), and it can be carried out with or without chemicals to control the pH (Bonmatí and Flotats, 2003). Large additions of lime to increase the pH would increase the formation of calcium carbonate possibly resulting in severe maintenance problems (Liao et al., 1995).

The removal of NH_3-N from different wastes by stripping is currently practised on supernatants after stabilization by anaerobic digestion (Bonmatí and Flotats, 2003; Lei et al., 2007). Chemical precipitation requires the addition of a reagent, which may introduce new pollutants to the process (Lin et al., 2009). Furthermore, the post-treatment of high strength leachate can be difficult and costly. Thus, the development of an *in situ* removal technique would be an attractive alternative, potentially offering both economic and environmental advantages. An ammonium removal process in the same system as anaerobic digestion, biogas stripping for instance, would be advantageous, as a notable level of nitrogen removal may be achieved resulting in relief of the inhibition problems known to the process. Furthermore, the biogas produced in the process could be used for stripping and purified during ammonia absorption using water and /or sulphuric acid.

The aim of this research was to study ammonia removal from SSFW digestate. The experiments are based on gas stripping in a heated column reactor; the effects of temperature and gas flow rate have been considered using biogas as the stripping gas. The removal of a small amount of ammonia could be sufficient to allow the biological process to operate more effectively. The results from these preliminary trials carried out in batch mode will be used for the selection of ammonia stripping conditions to be tested in continuous operation experiments.

2. METHODS

Substrate

Food waste digestate was collected from a commercial digester which treats SSFW from a mixture of commercial and municipal sources. The digestate, which contained a total ammonium concentration in the range of 6700-7700 mg L^{-1}, was homogenized with a commercial garbage grinder to an average size of below 4 mm. Further characterization of digested food waste is outlined in Table 1.

A stripping process is usually applied to supernatant residues, different dosages of calcium hydroxide are added and after stirring and precipitation, the supernatants are stripped. In our case, since the addition of chemicals could disturb the anaerobic digestion process, none were used. Therefore, the digestate was directly treated by biogas stripping, with no pre-treatment before the stripping experiments.

Although the initial VFA concentration was different for each experiment (17960 ± 4640 mg Acetic acid L^{-1}); pH (8.2 ± 0.2) total ammonium concentration (7270 ± 346 mg L^{-1}) and TKN (9000±550 mg L^{-1}) were very similar in all cases. The differences for other parameters determined, such as total (57.8±7 g Kg^{-1}) and volatile (41.2±6 g Kg^{-1}) solids, can be explained because of the high heterogeneity of the raw material and also because steady-state conditions are not often reached in full-scale anaerobic digestion processes since plants are subjected to disturbances due to the variations of influent flow.

Experimental set up

The experimental set up of the reactor is outlined in Figure 1. A glass column (47.5 cm high x 10 cm internal diameter) with a thermally controlled water jacket, heated by a water circulator (Techne Circulator C-85 A) **(4),** was used for stripping in batch conditions. For each experiment 2 kg of source segregated food waste digestate (with a density of 1006 ± 13 mg L^{-1}) was placed inside the column which was then sealed. The digestate was then subjected to a gas flow which was bubbled into the bottom of the column through a diffuser. The gas used for stripping was synthetic biogas (CH_4:CO_2, 65:35, BOC, Guildford, UK).

After passing through the digestate, the biogas charged with ammonia was bubbled through a trap of 70 mL of deionised water **(1)** and then through two serial traps (250 mL volume) of 40 % sulphuric acid solution **(2)** to capture the ammonia, after which the biogas was pumped back into the bottom of the digester in a closed loop, using a peristaltic pump

(Watson Marlow 601 S) **(3)**. A flowmeter **(7)** was placed between the peristaltic pump and the stripper column to control the biogas flow rate.

Between the deionised water trap **(1)** and the first sulphuric acid trap **(2)**, a tedlar bag **(8)** with biogas (50% of its 5 L of volume) was placed. This tedlar bag allowed for thermal expansion of the gas within the system as well as a store for the biogas produced during the assay or, as a reserve if more biogas was required for the system.

Experimental Procedure

Ammonia removal was performed by bubbling biogas through the digestate. Although the adsorption process was performed at room temperature, the stripping process was performed at temperatures of 35 ºC, 55 ºC and 70 ºC at gas flow rates of 0.125, 0.250 and 0.375 $L_{biogas}\ L_{digestate}^{-1}\ min^{-1}$. The flow rates were chosen taking into account the common flow rates used in full scale anaerobic digesters for mixing. The stripping experiments were continued until no further ammonia removal occurred, and this happened when pH was lower than 7.5. The operational conditions of the different experiments carried out, including their duration, are summarized in Table 2.

The temperatures of 35 ºC and 55 ºC were chosen as they are the optimal mesophilic and thermophilic temperatures, respectively, at which anaerobic digesters commonly operate. 70 ºC is the temperature used for pasteurisation. The main limiting factor for ammonia air stripping at 70 ºC is the availability of a cheap thermal energy source. Most food waste treatment plants have a pasteurizer for deactivating the pathogens present in the waste. Consequently, ammonia biogas stripping could take place at this point of the treatment plant, meaning no investment would be necessary.

Samples were drawn from a port **(5)** near the bottom of the column, over the experimental period (at least once a day) and analyzed for ammonia, partial and total alkalinity and pH to determine their evolution.

Water and sulphuric acid solutions from the three ammonia traps were measured, sampled and analysed at the end of the experiment to determine the ammonia mass balance. Additionally, VFA, total Kjeldahl nitrogen (TKN), total solids (TS) and volatile solids (VS) were analysed on the digested food waste at the beginning and end of every experiment.

Analytical Methods

TS and VS were measured gravimetrically according to standard methods (APHA, 2005). Sieved samples were used for the determination of several parameters according to standard methods (APHA, 2005): pH was determined using a Jenway 3010 pH-meter (Jenway, London, UK), ammonia using the steam distillation method (APHA, 2005) and TKN using the digestion-steam distillation method (APHA, 2005). Partial (at pH 5.75) and total alkalinity (at pH 4.3) were measured by pH titration according to Jenkins *et al*. (1983). VFA were analyzed using a Shimadzu GC-2010 (Shimadzu, Tokyo, Japan). A capillary column SG EBP 21 was used with helium as the carrier gas at a flow rate of 191 mL min^{-1}. The GC oven temperature was programmed to rise from 60 ºC to 210 ºC over 15 minutes, with a final hold time of 3 minutes. The temperatures of the injector and detector were 200 ºC and 250 ºC, respectively. The sieved samples were first centrifuged at 14000 rpm for 20 minutes, and the supernatant liquor was then acidified with formic acid (10%). The samples were compared to standard solutions (50, 250 and 500 mg L^{-1}) of acetic, propionic, iso-butyric, n-butyric, iso-valeric, valeric, hexanoic and heptanoic acids.

The ammonia removal efficiency (expressed in percentage) can be calculated by using the following expression:

$$Ammonia\,removal\,efficiency\ (\%) = \frac{[Ammonia]_i - [Ammonia]_f}{[Ammonia]_i} * 100 \qquad (1)$$

where $[Ammonia]_i$ is the initial ammonia concentration, and $[Ammonia]_f$ is the concentration of ammonia at the end of the experiment. Therefore, the ammonia removal rate is determined as follow:

$$Ammonia\,removal\,rate\,(\%\,d^{-1}) = \frac{Ammonia\,removal\,efficiency\ (\%)}{Operation\,time\,(d)} \qquad (2)$$

3. RESULTS AND DISCUSSION

In order to achieve the maximum removal of ammoniacal nitrogen from digestate by biogas stripping, temperature and flow rate were considered. In all cases ammonia was removed from the digestate and captured in the water and acid traps, the results being summarized in Table 3.

The results were presented comparing assays developed at the same temperatures but different flow-rates. The variations of the ammonia concentrations with the operation time in the experiments performed are shown in Figures 2a, 3a and 4a at 35 ºC, 55 ºC and 70 ºC, respectively.

Temperature: 35 ºC

Free ammonia concentration depends mainly on three parameters: the total ammonia concentration, temperature and pH (Hansen et al., 1998). It increases as the temperature and/or pH rise. At a high pH, inhibition by VFA decreases because the acids become dissociated, whereas inhibition by ammonia increases as the free form becomes prevalent (Fricke et al., 2007).

As can be seen in Figure 2, at 35 ºC the pH was relatively constant and, for the three flow rates studied, higher than 8, although an initial increase was observed. In acidic and neutral media ammonia nitrogen occurs as NH_4^+. In basic solution, non-volatile NH_4^+ is converted to volatile NH_3. Therefore, at pH 8 the volatilization of ammonia is slower than at a higher pH (Malpei et al., 2008). However a continuous, albeit low, ammonia removal rate was achieved.

At 35 ºC the ammonia removal rate was lower than in the experiments at higher temperatures. The rates of removal at both 0.125 and 0.250 $L_{biogas}\ L_{digestate}^{-1}\ min^{-1}$ were similar and the concentrations of ammonia at the end of the experiments (~ 200 hours) were 6370 and 5950 mg $N\text{-}NH_3\ L^{-1}$, respectively. However, at the increased flow rate, 0.375 $L_{biogas}\ L_{digestate}^{-1}\ min^{-1}$, the ammonia removal rate was approximately 4 times greater, meaning that after 54 hours the ammonia concentration was 6090 mg $N\text{-}NH_3\ L^{-1}$. This demonstrates the importance of the flow rate in the removal process, as was reported previously (Liao et al., 1995). The final ammonia concentration at the flow rate of 0.375 $L_{biogas}\ L_{digestate}^{-1}\ min^{-1}$ (~ 78 hours) was 5670 mg $N\text{-}NH_3\ L^{-1}$.

In all cases both partial and total alkalinity decreased during the experiments owing to the removal of ammonia and the precipitation of carbonates which contribute to this measurement (Cheung et al., 1997).

Although the removal rates were so low as to remove just 15 % of the ammonia present in the residue over almost 200 hours, it should not be forgotten that the residue was not treated with lime to increase the pH, and modest gas flow rates were used when compared with other researches; Liao et al. (1995) used between 15-30 L_{air} $L_{swine\ manure\ supernatant}^{-1}$ min^{-1}, while Lei et al. (2007) utilized from 3 to 10 L_{air} L^{-1} min^{-1} to strip the ammonia from the kitchen garbage supernatant. Furthermore, in a continuous anaerobic digester treating food waste, retention times of 50-100 days are typical, meaning that the maintenance of an ammonia concentration at 50% of the natural steady-state concentration only requires an ammonia removal rate of 0.5%-1% of the total per day. Therefore, with respect to an *in situ* process, the rates obtained here may be suitable.

Working with liquid swine manure, Liao et al. (1995) obtained ammonia removal efficiencies of 80% approx. after around 250 h of treatment operating at a pH of 9.3 and a flow rate of 15 L_{air} $L_{digestate}^{-1}$ min^{-1}, a considerably higher flow rate than those used in the present work. Furthermore, other conditions were very different from the present work in that the pH (~ 8) was also much lower and the initial TS much higher (> 50 %).

Temperature: 55 ºC

At 55 ºC free ammonia will always be higher than at 35 ºC, as was reported elsewhere (Lin et al., 2009).

For the three experiments performed at this temperature, the pH trend was similar; an initial increase, probably caused by equilibrating carbonates between the biogas and digestate, followed by a decrease, showing the effect of ammonia removal (Bonmatí and Flotats, 2003).

The results from ammonia removal at 55 ºC and 0.125 L_{biogas} $L_{digestate}^{-1}$ min^{-1}, shown in Figure 3a, did not follow the trends of the other experimental results; the ammonia initially decreased and then increased to a higher concentration. This could be explained by the low ammonia removal rate due to the decrease in pH (Figure 3b) which reduced ammonium volatility by shifting its dissociation reaction towards the ionic form, as was also observed by Bonmatí and Flotats (2003). It was thought that although there was a greater concentration of free ammonia at the higher temperature of 55 ºC (when compared to 35 ºC), it is possible that the flow rate was too low to remove an appreciable amount of ammonia. An increased gas flow rate increases the gas-liquid surface area, which in turn controls the amount of NH_3 diffused from water (Lei et al., 2007). After this anomalous result the flow rate was increased to 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1} for 30 minutes, and the final concentration of ammonia was approximately 5700 mg N-NH_3 L^{-1} (data not shown in the Figure). This suggests that there could be potential for an ammonia stripping process under continuous pH control to change the flow rate.

The two experiments at higher flow rates showed similar trends to those at 35 ºC. The ammonia removal rate increases with gas flow rate, stabilising at similar end concentrations (5740 mg L^{-1} at 0.250 L_{biogas} $L_{digestate}^{-1}$ min^{-1} and 6160 mg L^{-1} at 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}). The pH trend showed, as before, an initial increase followed by a decrease. However, in these cases the final pH was lower, dropping to around 7.5 in both experiments. Observation of the data shown in Figure 3 suggests that the decrease in pH to around 7.5-8 prevents further ammonia removal, which is in line with the findings of Lin et al. (2009).

Alkalinity decreased with time which led to a decreased pH. The high VFA concentrations influenced this drop.

Temperature: 70 ºC

Operation of the stripping process at 70 ºC resulted in the greatest ammonia removal rates as shown in Figure 4. Indeed the higher the temperature and pH, the higher the free ammonia fraction. However, a difference relative to the previous results should be pointed out - the increased flow rate (0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}), although resulting in the fastest initial ammonia removal, apparently removed less ammonia over the experimental period than the lower flow rate studied in this case (0.250 L_{biogas} $L_{digestate}^{-1}$ min^{-1}).

At 70 ºC and a flow rate of 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1} the pH did not show the trend of an initial increase followed by a gradual decrease. Temperature affects the chemical equilibrium between substances leading to a new chemical equilibrium that modifies the pH (Bonmatí and Flotats, 2003) and in this case the pH decreased from the start of the experiment because of the high ammonia removal rate. To be specific, the pH decreased to around 6.5 in less than 20 hours. This then prevented further ammonia removal since at this pH the ammonium ion prevails in solution, even at a high temperature, as has been stated by Fricke et al. (2007) and as was seen in the experiments at 35 ºC and 55 ºC (see Figure 4). Another effect which comes into play at a high temperature is the evaporation of the liquid in the digestate. Over the experimental period at the highest temperature and flow rate approximately 25% of the digestate content (0.5 litres) was lost as evaporated moisture. This meant that although ammonia was removed, the concentration in the digestate remained the same or even increased as can be seen in Figure 4. Mass balance is very useful to justify the real ammonia evolution in case (70 ºC and a flow rate of 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}), where a lot of water was evaporated. Taking into account the initial and final ammonia concentrations as well as the initial and final mass of SSFW, the initial mass of ammonia in this experiment was 14640 g N-NH_3 and the final 9020 g N-NH_3 with a mass unaccounted of 5.5 %. Therefore, an important ammonia removal was reached.

This defeats the purpose of removing ammonia in order to reduce 'in reactor' concentrations. Consequently, temperature is a crucial factor in the stripping process as was also reported elsewhere (Poulopoulos et al., 2005).

Alkalinity also decreased in all treatments (Figure 4d). The formation and precipitation of salts (Cheung et al., 1997) and/or CO_2 stripping (Collivignarelli et al., 1998) may explain this reduction. This loss of the buffering capacity during the stripping process together with the high VFA concentrations resulted in a decrease in pH. Moreover, the low VFA volatility at these pHs together with water evaporation, led to a slight increase in their concentration.

The conditions at 70 ºC and 0.250 L_{biogas} $L_{digestate}^{-1}$ min^{-1} showed a greater removal of ammonia over the experimental period and a greater overall removal rate compared to the higher biogas flow rate. This could be due to the fact that the removal of ammonia is initially slower and therefore did not lead to a rapid destabilisation in pH which in turn allows greater ammonia removal. However, this experiment had an initial VFA concentration of ~10,000 mg L^{-1} as compared with ~17,000 mg L^{-1} (see Table 1) in the other experiments which could explain the stable pH despite a large proportion of ammonia removal. This in itself is an interesting result since, if the ammonia stripping process was being used as a preventive measure for the build-up of VFA in a food waste digestate, the VFA concentration would in general be lower than 10,000 mg L^{-1}. If this result holds for all flow/temperature combinations then ammonia removal would be more effective on a time basis in a ‘healthy’ digester.

The variation in temperature and flow rate researched here leads to a change in the ammonia removal rate of one order of magnitude between ~1.8%-18.9 % day^{-1} under these conditions of high VFA concentrations (~17,000 mg L^{-1}) and ammonia (~7000 mg L^{-1}).

Ammonia mass balance

The ammonia mass balance showed that an average of 5% of the ammonia was not accounted for. Bonmatí and Flotats (2003) reported imbalances of between 6% and 16% when performing pig slurry air stripping assays. They attributed this to experimental error because ammonia was not detected in the second ammonia trap in any of the experiments. In the current work ammonia was detected in the water trap and also in the first sulphuric acid trap, but not in the second sulphuric acid trap.

The 5% of unaccounted for ammonia could be attributed to a number of causes including loss during sampling, leaks, vaporised ammonia at the end of the experiment and other experimental errors.

The concentration of TKN was also determined in all experiments and there were no differences in the relationship between TKN and total ammonium nitrogen during the experimental period meaning that no other forms of nitrogen were removed, as was also reported by Lin et al. (2009).

From the results of these batch experiments it is thought that biogas stripping is an interesting option for the effective removal of ammonia in an anaerobic digestion process, although further work is necessary. Future experiments will look into the possibility of stripping ammonia in a side stream process in a semi-continuous anaerobic digester. Digesters will be analysed for ammonia, alkalinity, biogas production and composition, pH and VFA in order to assess the effectiveness of ammonia stripping with regard to maintaining a healthy anaerobic process (e.g. no excessive build-up of VFA).

4. CONCLUSIONS

Ammonia removal from food waste digestate was possible using biogas stripping. Increased temperatures and gas flow rates both increased the rate of removal. A rapid ammonia removal caused a rapid drop in pH, which could hinder further ammonia removal.

At 35 ºC there was slow steady removal of ammonia (1.8-8.3 % d^{-1}) and little variation in pH. At 55 ºC, a low flow rate is not enough to remove the free ammonia fraction, causing an increase in the concentration of ammonia. Finally, at 70 ºC the apparent ammonia removal rate decreased with time (from 18.9 to 10.4 % d^{-1} at 0.250 and 0.375 L_{biogas} $L_{digestate}^{-1}$ min^{-1}, respectively) due to a higher rate of water evaporation in relation to the rate of ammonia stripping.

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Table 1. Characterization of the source segregated digested food waste used in the stripping experiments

Parameter	Unit	Min	Max	Mean

TS	g Kg^{-1}	50.4	67.6	57.8
VS	g Kg^{-1}	33.9	51.3	41.2
NH_3-N	mg L^{-1}	6755	7735	7170
TKN	mg L^{-1}	8260	9540	8954
pH	-	8.0	8.5	8.2
Partial Alkalinity	mg $CaCO_3$ L^{-1}	6375	14250	9469
Total Alkalinity	mg $CaCO_3$ L^{-1}	20875	27000	24000
VFA	g Acetic acid L^{-1}	9.8	23.8	18.0

Table 2. Operational conditions of the different assays developed

Assay	**Temperature (ºC)**	**Flow rate (L_{biogas} $L_{digestate}^{-1}$ min^{-1})**	**Initial pH**	**Duration of experiment (h)**
B1	35	0.125	8.1	196
B2	35	0.250	8.1	194
B3	35	0.375	8.3	78
B4	55	0.125	8.2	72
B5	55	0.250	7.9	104
B6	55	0.375	8.1	46
B7	70	0.250	8.3	56
B8	70	0.375	8.6	29

Table 3 Summary of the ammonia removal rates

Temperature (ºC)	**Flow rate (L_{biogas} $L_{digestate}^{-1}$$min^{-1}$)**	**Ammonia removal (%)**	**Ammonia removal rate (% d^{-1})**
35	0.125	15	1.84
35	0.25	15	1.86
35	0.375	27	8.31
55	0.125	N/A	N/A
55	0.25	15	3.46
55	0.375	18	9.39
70	0.25	44	18.9
70	0.375	13	10.4

N/A: not applicable

- (1) Water trap
- (2) Sulphuric traps
- (3) Peristaltic pump
- (4) Thermostatic bath
- (5) Sample port
- (6) Reactor
- (7) Flowmeter
- (8) Tedlar bag

╌╌ Gas circuit

── Water circuit

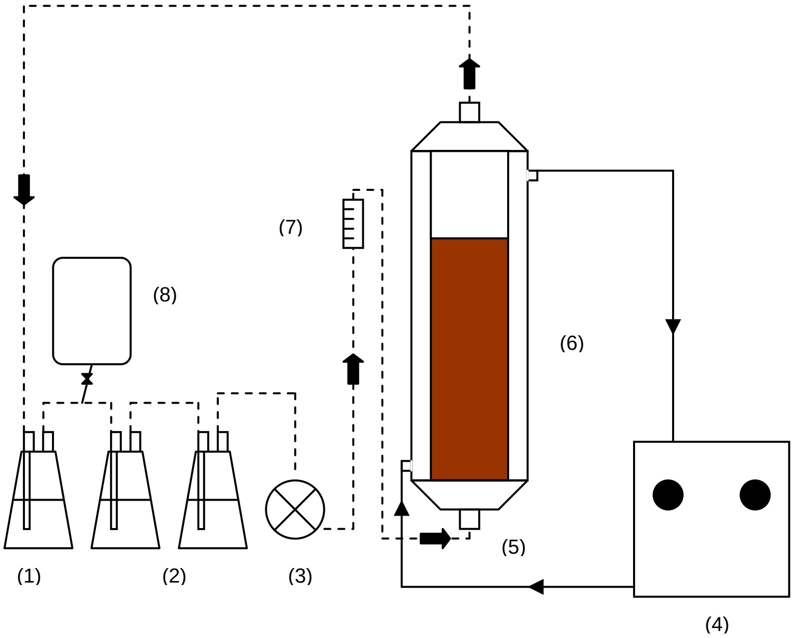

Figure 1. Schematic representation of the experimental system

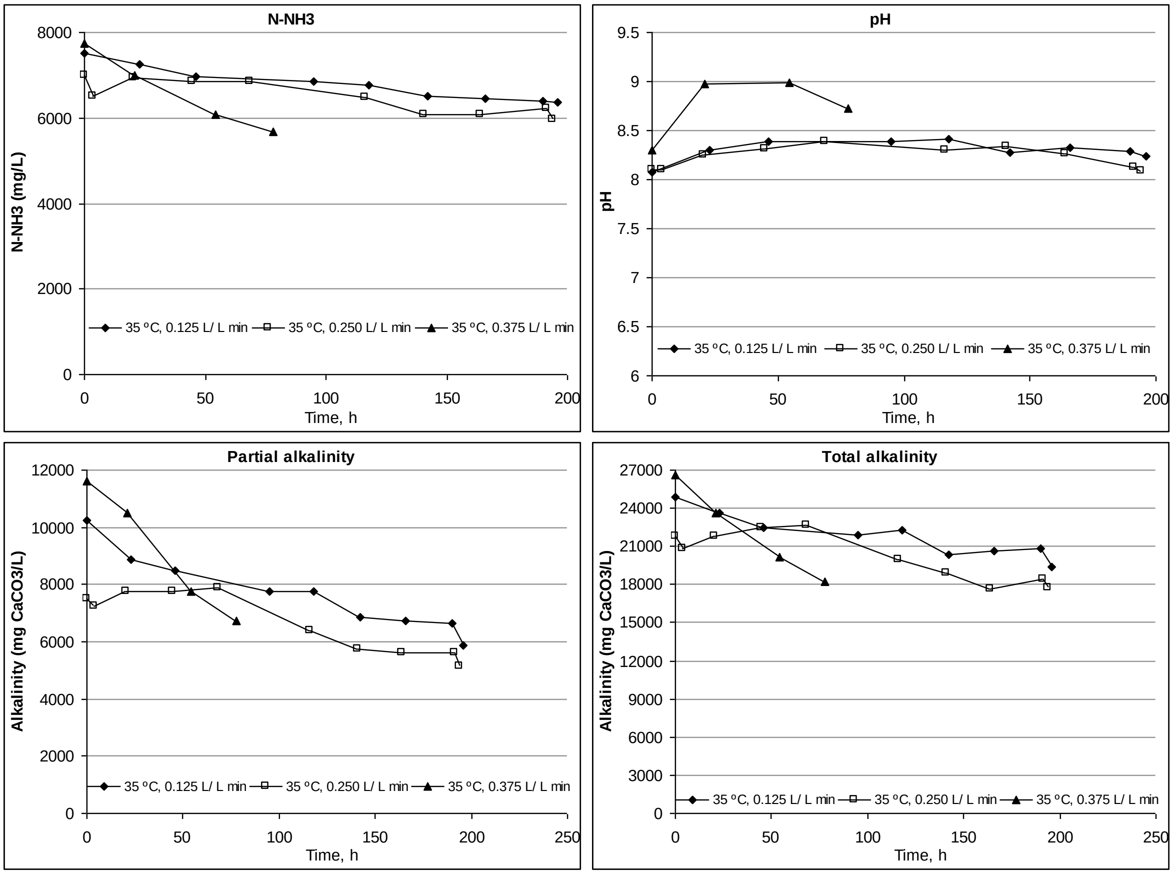

Figure 2. Ammonia stripping using biogas at 35ºC. Evolution of: (a) Ammonia nitrogen expressed as mg N-NH_3 L^{-1}, (b) pH, (c) Partial alkalinity expressed as mg $CaCO_3$ L^{-1}, and (d) Total alkalinity expressed as mg $CaCO_3$ L^{-1}

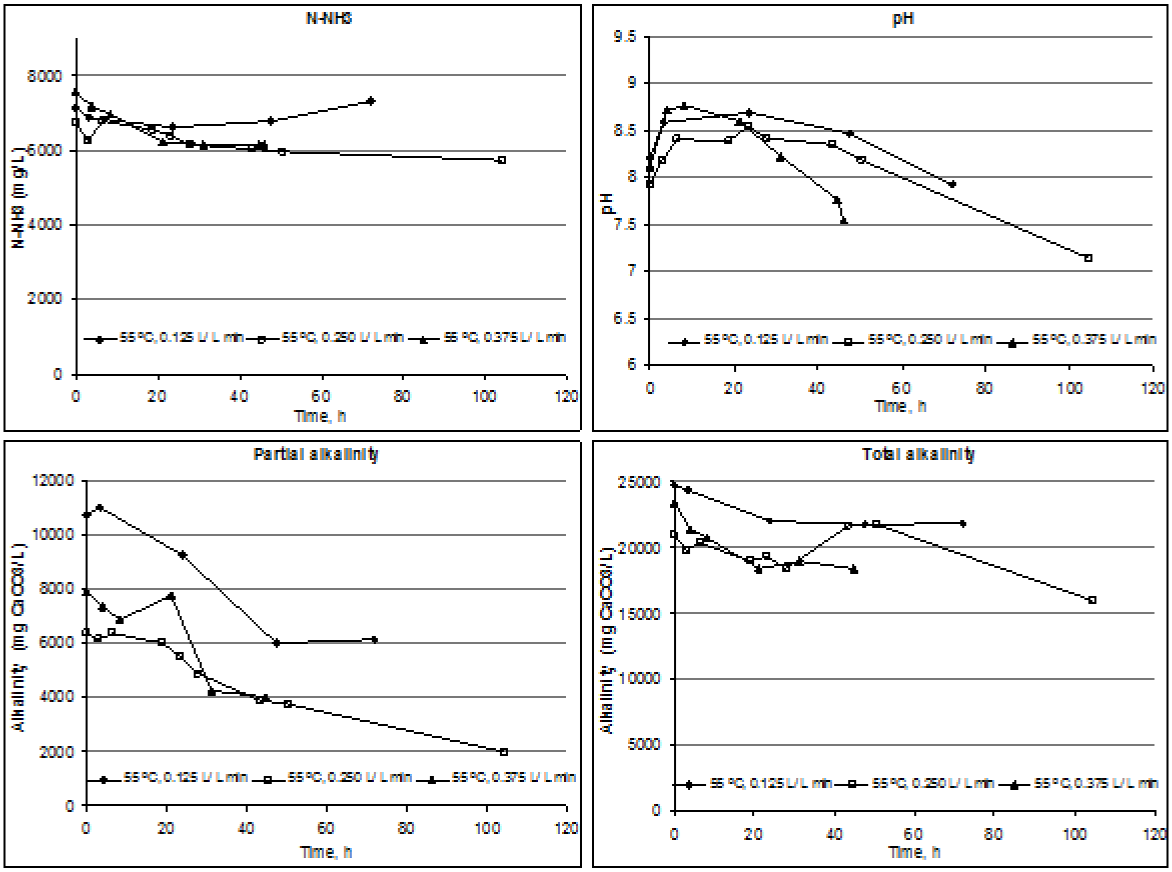

Figure 3. Ammonia stripping using biogas at 55ºC. Evolution of: (a) Ammonia nitrogen expressed as mg N-NH3 L-1, (b) pH, (c) Partial alkalinity expressed as mg CaCO3 L-1, and (d) Total alkalinity expressed as mg CaCO3 L-1.

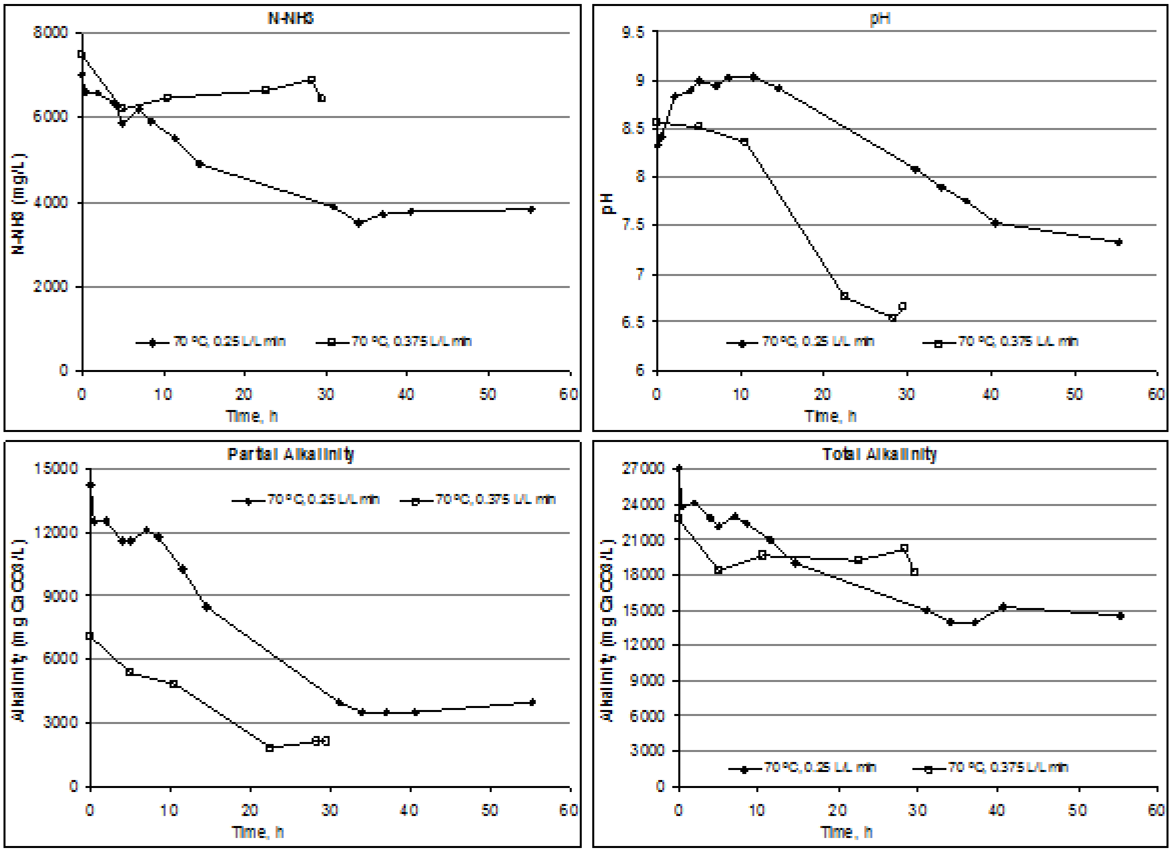

Figure 4. Ammonia stripping using biogas at 70ºC. Evolution of: (a) Ammonia nitrogen expressed as mg N-NH3 L-1, (b) pH, (c) Partial alkalinity expressed as mg CaCO3 L-1, and (d) Total alkalinity expressed as mg CaCO3 L-1.