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A. Serna-Maza, S. Heaven, C.J. Banks. (2017) In situ biogas stripping of ammonia from a digester using a gas mixing system. Environmental Technology (in press) DOI: 10.1080/09593330.2017.1291761

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***In situ* biogas stripping of ammonia from a digester using a gas mixing system**

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**Abstract**

Previous studies have suggested the use of digester biogas mixing systems for *in situ* ammonia removal from anaerobic digestates. The feasibility of this was tested at moderate and complete gas mixing rates at mesophilic and thermophilic temperatures in a 75-L digester. Experimental results showed that at gas mixing rates typical of full-scale commercial digesters the reduction in TAN concentrations would be insufficient to allow stable acetoclastic methanogenesis in mesophilic conditions, or to prevent total inhibition of methanogenic activity in thermophilic food waste digestion. Simulation based on batch column stripping experiments at 55 ⁰C at gas violent flow rates of 0.032 m3 m-2 min-1 indicated that ammonia concentrations could be reduced below inhibitory values in thermophilic food waste digestion for organic loading rates of up to 6 kg VS m-3 day-1. These mixing rates are far in excess of those used in full-scale gas-mixed digesters and may not be operationally or commercially feasible.

**Keywords:** Ammonia removal; in situ stripping; mixing rate; anaerobic digestion; food waste.

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**1 Introduction**

 Anaerobic digestion (AD) of high nitrogen feedstocks can be subject to process instability as a result of ammonia inhibition, leading to volatile fatty acid (VFA) accumulation, a fall in biogas production and in the worst cases to failure of the digestion [1-3]. One possible solution is to reduce the total ammonia nitrogen (TAN) concentration in the digester by gas stripping, with the potential for recovery of ammonia as a valuable secondary product. To date, four main process options have been considered to achieve this. These are: removal from the feedstock prior to digestion [4-6];post-hydrolysis stripping, in which organic nitrogen is hydrolysed to release TAN for removal, leaving a lower nitrogen hydrolysed substrate to be fed to the main digester [7-9]; *in situ* gas stripping from the main digester alongside biogas production [10-12];and removal from a digester side-stream in an optimised stripping process, with low TAN digestate returned to the main digester [13, 14].In addition, ammonia can be recovered by post-digestion stripping, although this option will not reduce TAN concentrations in the main digester [12, 15, 16].

 In terms of simplicity the *in situ* process appears to have some advantages for implementation in gas-mixed digesters, since TAN is removed directly from the main digester as it is released during degradation, making use of the existing gas mixing system. Significant changes in operating temperature or pH in order to enhance stripping are not possible, however, as these may be detrimental to methane production. The concept therefore relies mainly on modifications to gas flow rates and gas transfer systems to improve the stripping performance.

 The potential feasibility of *in situ* gas stripping during digestion of food waste [12] and pig manure [11] has been indicated by batch studies and modelling of removal kinetics. Semi-batch culture experiments carried out with chicken manure [10] and continuous trials conducted with diluted (1:1) distillery residue have also successfully decreased digestate TAN concentrations [17]. All of these trials used small-scale reactors with high gas recirculation rates, which may not be practicable in full-scale systems. In addition, altering the mixing system and increasing gas flows by biogas recycle is likely to affect the digestion process in other ways which may or may not be beneficial [18]. Mixing promotes good contact between the microbial population and the substrate: inadequate mixing can result in stratiﬁcation, dead zones in the digester, and/or formation of a ﬂoating layer of solids [18, 19]. Proper mixing is therefore essential to achieve optimum performance. Intensive continuous mixing, however, has been reported as detrimental to digestion performance in some cases, resulting in instability in high solids systems [21, 21]. Perry and Green [22] recommended gas flows of 0.007 m3 m-2 min-1 to achieve moderate mixing; while Turovskiy and Mathai [23] suggested that complete mixing of sludges could be achieved at gas flow rates of 0.005–0.007 m3 m-3 min-1 in an anaerobic digester with a confined gas recirculation mixing system. The question is whether gas flow rates typical of those used for mixing can achieve sufficient TAN removal, or if not whether the required gas flows can be achieved economically and without harming the digester performance. The overall aim should be to provide the minimum flow rate needed to achieve a target TAN concentration, thereby minimising the investment and operating costs of the stripping process and reducing any risk of process disturbance or losses in gas production.

 The aim of the current work was to assess TAN removal at typical biogas mixing rates in a pilot-scale continuously-stirred tank reactor (CSTR) digester operating at mesophilic and thermophilic temperatures. Additionally, ammonia removal kinetics obtained in batch experiments were used to estimate whether *in situ* stripping of a fed digester could prevent ammonia inhibition. For this novel study, a surrogate digestate based on diluted source segregated domestic food waste (SS-DFW) digestate with a controlled TAN concentration was selected for the trial, since high nitrogen feedstocks of this type are known to cause ammonia inhibition to acetoclastic methanogenesis at mesophilic temperatures [24, 25], and to all methanogenic *Archaea* in thermophilic conditions [3, 26, 27-29]. Food waste digestate from the same source has also been used previously in stripping trials [12, 16], thus allowing useful comparisons to be made between this and earlier work.

**2 Materials and methods**

2.1 Digestate

The digestate used was taken from a digester treating SS-DFW [31]. It was sieved and diluted with tap water, and urea (CO(NH2)2) was added to allow adjustment of the starting TAN concentration to a target value of ~5 g N kg-1 wet weight (WW). The resulting digestate had a total alkalinity (TA) of 14 g CaCO3 kg-1 WW, a partial alkalinity (PA) of 12 g CaCO3 kg-1 WW, and an intermediate alkalinity (IA) of 2 g CaCO3 kg-1 WW. The results obtained with this digestate were compared with those from previously reported tests carried out using the same methodology, on undiluted fresh sieved food waste digestate with the following characteristics: TAN 4.7 - 5.2 g N kg-1 WW, total solids (TS) 6.60 %, TA 25 g CaCO3 kg-1 WW, PA 18 g CaCO3 kg-1 WW, IA 5 g CaCO3 kg-1 WW [31].

2.2 75-L CSTR digester

A CSTR digester of the type described by Zhang et al. [30] with a working volume of 75 L and working depth of 60 cm, was modified by the addition of 8 gas spargers mounted in the reactor base. These were open-ended stainless steel tubes of 4 mm internal diameter, spaced at intervals of 8.5 cm in a circular configuration. Biogas, used for both mixing and stripping, was pumped through the digester by a diaphragm gas pump (KNF, N828-KNE) in a closed circulation loop with a bypass to facilitate accurate flow control. Ammonia in the gas stream was trapped as a condensate, in water and finally in a 0.25 N H2SO4 solution; these three traps were sufficient for complete removal from the gas stream. Two rotameters (Key Instruments, air range 4-50 L min-1 and 0.4-5 L min-1) were calibrated to biogas as described in Serna-Maza et al. [13] and installed in the gas mixing and bypass lines to control the flow to each of these from the diaphragm pump. The digester was maintained at mesophilic (35 ± 1 ⁰C) or thermophilic (55 ± 1 ⁰C) temperature depending on the required experimental conditions, using a thermostatically-controlled thermocirculator connected to a spiral heat exchanger located inside the digester close to the wall. The system configuration is shown in Figure 1.

2.3 Small-scale batch stripping column

The stripping column was a 56 cm high water jacketed glass tube with an internal diameter of 10 cm and a sintered glass sparger 3 cm in diameter in the base. Temperature was controlled to 55 ºC using a thermocirculator (Techne, C-85A). The stripping gas was circulated from the headspace through three ammonia traps as above, then back to the sparger using a peristaltic pump (Watson Marlow, Sci-Q 323), with an impermeable gas bag in the loop which acted as an expansion vessel.

2.4 Stripping tests

 TAN removal in the 75-L digester was evaluated using biogas recirculation rates between 0.005-0.035 L L-1 min-1 (0.003-0.021 m3 m-2 min-1) (Table 1). These were chosen to represent moderate and complete mixing, based on the recommendations of Perry and Green [22].

 At the beginning of each test the digester headspace was flushed with a 65:35 % (v/v) CH4:CO2 mix (BOC, UK) to remove the air from the system. At the end of the flushing process a valve (V5, Figure 1) was opened to a gas bag, which acted as an expansion vessel to allow for volume changes in the system over time.

Batch stripping tests to determine the kinetics of TAN removal of dilute and undiluted digestate at thermophilic temperature, and violent mixing were carried out in the small-scale stripping column. The results were used to model a 75-L digester with undiluted digestate, fed at different OLRs and with violent biogas mixing in order to control TAN concentration. In operation the batch column was filled with 1 or 2 kg of the digestate under test and the system was flushed of air by pumping 65:35 % (v/v) CH4:CO2 mixture while venting the gas from the top of the stripping column for 15 minutes. The gas loop was then closed to the ambient air and the gas flow rate was set at the experimental rate (0.125 L min-1 L-1 or 0.250 L min-1 L-1). Ammonia in the gas stream was completely removed in a series of traps (condensate, water, and 0.25 N H2SO4 solution).

2.5 Analytical methods and data analysis

pH, alkalinity, total solids (TS), and TAN concentration were determined following the analysis protocols used in Serna-Maza et al. [13].

 In order to evaluate the effectiveness of the stripping technique and to allow comparison with previous studies, the concept of the time constant (τ) was used. This represents the time required to reduce the TAN concentration by (1 - e-1), or approximately 63% of the initial value, and thus allows quantitative comparison between experimental runs with different initial and final concentrations [31].

2.6 Modelling of the in situ stripped SS-DFW anaerobic digester

The steady-state TAN concentration for an *in situ* ammonia stripped anaerobic digester fed at different OLR was modelled using a nitrogen mass balance for six scenarios, in which the digester temperature (mesophilic and thermophilic), digester contents (dilute and undiluted digestate) and the mixing rate (complete and violent) were varied. The following values were used in modelling: VS content of SS-DFW = 210 g VS kg-1 WW (VSfood waste); constant TAN concentration in the unstripped digester (TANunstripped) of 5.2 g N kg-1 WW [13]; and *in situ* stripping system works 24 hours per day (as in the current experiment). It was assumed that the TAN concentration follows an exponential decay curve during stripping (equation 1) [12, 13]; and the experimentally derived time constants are realistic and applicable. TAN concentration in the *in situ* stripped reactor (TANreactor;g N kg-1 WW) was determined using equation 2

$F\_{stripping}=e^{\frac{-t}{τ}}$ (1)

Where: Fstripping is the TAN fraction of the initial TAN concentration left in the reactor after stripping; *t* is stripping time (hours) and τ is the ammonia removal time constant (hours).

$TAN\_{reactor}=\frac{\frac{OLR\_{reactor}}{VS\_{food waste}}}{\frac{OLR\_{reactor}}{VS\_{food waste}}+\left(1-F\_{stripping}\right)}∙TAN\_{unstripped}$ (2)

Where: OLRreactor is the organic loading rate applied to the reactor (kgVS m-3 day-1).

**3 Results and discussion**

3.1 Experimental results for in situ stripping at moderate and complete mixing rates

Figure 2a shows the biogas flow rates applied to the reactor and the digestate TAN concentration, and Table 2 summarises the results of the mesophilic stripping experiment. TAN removal after 16 days of operation was minimal at the tested gas flow rates and mesophilic temperature, as can be seen in Figure 2a. The very small change in TAN concentration, coupled with the use of biogas as a stripping agent which reduces carbonate removal, meant that the pH value (8.21 - 8.31) and the alkalinity profile remained almost constant during the course of the experiment. The calculated time constants at biogas flow rates of 0.015 and 0.035 L L-1 min-1 (0.008-0.021 m3 m-2 min-1) were 10000 and 50000 respectively (Table 2): these high values are as expected, since low ammonia removal implies a high time constant.

 Table 3 shows the nitrogen balance at the end of the experimental run at 35 ⁰C. The balance was calculated based on the changes in mass and TAN concentration produced in the dilute digestate in the reactor and in the ammonia traps. These traps were only removed at the end of the experimental run; solutions were not regenerated each time the flow was increased, since little or no decrease in TAN concentration was observed in the reactor. The amount of unaccounted-for nitrogen in the system was as low as 0.3 % of the initial TAN, or 1.6 g N.

Figure 2b shows the TAN concentration profile during the thermophilic experiment at different biogas flow rates, while Table 2 summarises the results. It should be noted that after 190 hours of operation the reactor working volume was adjusted to its initial value by the addition of water, giving a discontinuity in TAN concentration at this point. TAN removal in the thermophilic trial increased when the biogas flow rate was increased to 0.015 L L-1 min-1 (0.008 m3 m-2 min-1), at the upper end of the moderate mixing range [22]. No further improvement was found at higher gas flow rates within the flow range tested.

 TAN removal was higher in thermophilic conditions than in mesophilic: this was as expected since the strippable free ammonia fraction in the digestate increases with increasing temperature [31, 32]. The pH value (8.47 - 8.65) was slightly higher than in the mesophilic trial, but still sub-optimal for ammonia removal [31, 32]. The alkalinity profile once again remained almost constant during this stripping experiment.

 Table 3 shows the TAN balance at the end of the thermophilic experiment. Under these conditions the uncounted-for N was slightly higher than in the *in situ* mesophilic trial. At the beginning of the mesophilic trial the volume of liquid in the reactor was measured accurately; in the thermophilic trial which followed on immediately, however, the liquid volume was estimated by mass balance, and this may be a reason for the small increase in unaccounted-for N.

It is clear that significant TAN removal was not achieved in either mesophilic or thermophilic conditions at the gas flow rates tested, which correspond to realistic values for moderate and complete mixing. Although higher recirculation rates could be achieved, these were not used, as violent mixing is known to require an excessive energy input; and may also carry the risk of destabilising the digestion process, although long-term studies are needed to verify this.The very high time constants obtained at these mixing rates indicate that the process is unlikely to be effective in full-scale digesters in cases where it is desired to reduce an existing high concentration of ammonia within a relatively short period. Although successful ammonia removal has previously been reported in experimental studies on distillery residues [17] and chicken manure [10], the quoted volumetric gas flow rates of 0.25 and 1 L L-1 min-1 give estimated superficial rates of 0.074 and 0.294 m3 m2 min-1 respectively, corresponding to very violent mixing. In the next part of this work the digestate was therefore tested in the batch stripping column under violent mixing conditions to establish the time constants for removal, and to allow comparison with the performance of fresh undiluted digestate from a SS-DFW digester.

3.2 Stripping performance and time constants for undiluted and dilute food waste digestates at violent mixing rates

The results of the batch column stripping tests are presented in Figure 3, and show that ammonia was more easily removed from the dilute digestate than from the undiluted food waste digestate. The average time constants calculated at the two gas flow rates of 0.125 and 0.250 L L-1 min-1 (Figure 3a and b), both corresponding to violent mixing of 0.032 m3 m-2 min-1, were 625 and 278 for the dilute material compared to 1110 and 935 for undiluted digestate at the same gas flow rates. These time constants, which are 1.8 to 3.4 times smaller for the dilute digestate, indicate the stripping process is more effective than for digestate with a higher TS content from the same source. It is well documented that ammonia stripping efficiency is dependent on a number of factors. Of these, temperature and pH affect the equilibrium between the ionic and gaseous state to the greatest degree, and can thus significantly affect the stripping rate [32]. The influence of other digestate characteristics such as TS, VFA concentrations and alkalinity is less well understood, but these factors have also been shown to be important for ammonia stripping rates, possibly due to the specific binding capacity of digestate solids for ammonia [33]. The literature thus contains a range of ammonia removal rates and time constants for digestates from similar sources, even when the TAN concentration at the start of the stripping process is roughly equal. The time constant for the dilute digestate used here, however, is similar to the value of 699.6 reported by Walker et al.[12] for a digestate with 5.5% TS collected from a commercial AD plant fed mainly on SS-DFW and stripped at a gas flow rate of 0.125 L L-1 min-1 (equivalent to a superficial flow rate of 0.032 m3 m-2 min-1), the same conditions as used in the current study.

 Further analysis and simulation conducted by Walker et al. [12] suggested that *in situ* ammonia stripping was a promising technique but would require thermophilic conditions and a volumetric biogas flow of 0.375 L L-1digestate min-1, equivalent to 0.048 m3 m-2tank cross-section min-1 in the stripping column and 0.224 m3 m-2 min-1 in the 75-L CSTR digester. This would represent very violent mixing based on the definition by Perry and Green [22], and is more than 17 times the superficial gas flow rate suggested by Turovskiy and Mathai [23] for complete mixing.

The time constant reported by Walker et al. [12] was lower than that found for fresh food waste digestate, possibly due to changes occurring during storage [31]. The results obtained here confirm once again that values of the time constant are variable depending on digestate properties; but the relatively high values obtained even in these conditions also strongly support the view that *in situ* ammonia removal at moderate or complete mixing rates is unlikely to be effective for digestates with properties similar to those from SS-DFW.

3.3 Modelling of an in situ stripped SS-DFW anaerobic digester

The scenarios modelled are shown in Table 4, with the selected parameter values based on the above experimental results. Figure 4a shows the modelled values for TAN removal, while Figures 4b and c show the modelled steady state TAN concentrations for an anaerobic reactor with biogas stripping in mesophilic and thermophilic conditions respectively under the mixing conditions given in Table 4. Changing the initial value for unstripped TAN concentration would lead to a change in the final modelled steady state values as shown in Figures 4b and c; but the percentage TAN removal shown in Figure 4a remains valid in each case.

 *Mesophilic.* In mesophilic conditions with complete mixing and using the undiluted digestate time constant (scenario 1), steady state TAN concentrations at OLR 1 and 2 kg VS m-3 day-1 decreased by 21 and 12 % respectively in comparison to those for a reactor with no stripping. The equivalent values for dilute digestate (scenario 2) were 33 and 20 %. At higher OLR the modelled reductions in TAN concentration were correspondingly smaller (Figure 4a).

 In mesophilic digestion acetoclastic methanogenesis has been reported as the main acetate degradation route at TAN concentrations up to 3.3 g N L-1; above 5.5 g N L-1, however, the mechanism has clearly shifted to syntrophic acetate oxidation [24]. Using the experimentally-derived time constants for mesophilic conditions, neither of the scenarios modelled was capable of reducing TAN concentrations below 3.3 g N kg-1 (Figure 3b), where stable digestion by the acetoclastic route is achievable. At the digestate TAN concentration of 5.2 g N L-1 used in modelling, digesters show signs of instability. This can be alleviated, however, by trace element addition to stimulate the hydrogenotrophic methanogenic pathway which can function at TAN concentrations of up to 8 g N L-1 in mesophilic conditions [34]. For SS-DFW trace element addition may therefore be a simpler and more economical solution to achieve stable mesophilic digestion, although this does not provide an opportunity for ammonia recovery. For other materials such as chicken manure and slaughterhouse wastes, however, the TAN concentration can exceed 8 g N L-1, and in these cases the process will fail unless the waste is diluted or ammonia is removed.

 *Thermophilic*. With complete mixing (scenarios 3 and 4), the maximum reductions in the steady state TAN concentration were 36 % and 50 % for the undiluted and dilute digestate time constants respectively (Figure 4c). In studies of thermophilic digestion of SS-DFW, Yirong et al. [29] found toxicity occurred at ~3.0 g N kg-1 WW. Similar values have been identified for digestates from other feedstocks such as manures or organic wastes [1, 3, 35]. In both of the complete mixing scenarios, the TAN concentration could only be maintained below this value by limiting the feed rate to an OLR of < 1 kg VS m-3 day-1, a prohibitively low loading for a commercial AD plant. At violent mixing rates (scenarios 5 and 6) the maximum TAN removals achieved were 82 and 89 % for undiluted and dilute digestate respectively, with steady state TAN concentrations below the threshold for toxicity even at OLR 6 kg VS m-3 day-1 for undiluted digestate, and at OLR > 9 kg VS m-3 day-1 for dilute digestate.

 Figure 4d shows the value of the time constant required to achieve a TAN concentration lower than an inhibitory 3.0 g N L-1 in thermophilic conditions with *in situ* ammonia stripping at different OLR. When the modelled time constants are compared to the experimental values for each scenario, it can be concluded that scenarios 3 and 4 could maintain the TAN concentration below 3.0 g N L-1 at OLR of < 1.0 and up to 1.5 kg VS m-3 day-1 respectively. When violent mixing is applied (scenarios 5 and 6), the OLR at which this TAN concentration could be maintained increases to 6.2 and > 9 kg VS m-3 day-1 respectively. The TAN concentration in dilute digestate can be maintained below 3.0 g N L-1 at all of the modelled OLR (1 - 9 kg VS m-3 day-1), as the time constant is smaller than the required value of 770 hours even at the highest OLR considered. Dilution coupled with *in situ* stripping may therefore be a potential strategy to reduce the volume of water addition required. For undiluted material, only violent mixing flow rates are able to decrease digester TAN concentration to a safe value; and alternative approaches, such as side-stream processes in which the stripping conditions can be altered to enhance removal efficiency, may therefore offer a more effective solution at large scale despite the increase in operational complexity and infrastructure costs compared to the *in situ* approach.

 In both mesophilic and thermophilic conditions, modelling combined with small-scale batch tests to establish the relevant time constants provides a powerful tool to estimate steady state TAN concentrations and to choose an approach or combination of approaches that will allow stable digestion without ammonia toxicity.

**4 Conclusions**

*In situ* ammonia stripping trials with dilute SS-DFW digestate in a CSTR digester confirmed that removal was minimal at mesophilic temperatures and low at thermophilic temperatures when moderate and complete gas mixing rates, typical of those applied in commercial AD plant, are used. Simulation of a thermophilic system using experimentally-derived ammonia removal time constants showed that *in situ* biogas stripping at complete mixing rates cannot maintain ammonia concentrations below a typical inhibitory threshold of ~3.0 g N kg-1 WW in SS-DFW digesters operating at commercially viable loading rates. To achieve the necessary reduction under thermophilic conditions, violent mixing rates would be required; but longer-term studies would be needed to assess the effect of these on biologically-mediated performance. Even under mesophilic conditions, where ammonia toxicity thresholds are higher, achieving significant ammonia removal from SS-DFW still requires violent mixing. These mixing rates will increase both capital and operating costs, and it is unlikely this could be fully offset by the value of the recovered ammonia. The results from these experiments thus cast doubt on earlier studies which suggested *in situ* gas mixing was a realistic option without fully taking into account the effect of scale-up on mixing rates. *In situ* ammonia stripping in mesophilic conditions is therefore unlikely to become a commercial reality for wastes with intermediate TAN concentrations, where successful digestion can be achieved by trace element addition to stimulate the more ammonia tolerant hydrogenotrophic methanogenic consortium. At very high TAN concentrations, stripping may allow reduction of TAN concentrations below the higher inhibition threshold of about 8 g N L-1 where trace elements have been added. Under thermophilic conditions, where trace element addition has not been shown to be effective at raising the ammonia inhibition threshold, stripping combined with dilution may offer the best means of controlling TAN concentrations. Although stripping behaviour varies to some degree with digestate properties, a combination of batch measurements of time constants and simulation can be a valuable tool for selection of the appropriate combination of strategies to achieve the required TAN concentration at commercially viable organic loading rates.

**5 Acknowledgements**

The authors would like to acknowledge the support of the EU FP7 VALORGAS project 'Valorisation of food waste to biogas' (241334) (www.valorgas.soton.ac.uk) for this work.

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**Figure Captions**

**Figure 1** Schematic of CSTR *in situ* stripping reactor. E-1 Heater; E-2 CSTR reactor; E-3 Condensate trap; E-4 Water trap; E-5 Acid trap; E-6 Gas diaphragm pump; FI Flow indicator.

**Figure 2** TAN concentration profiles in *in situ* ammonia stripping experiments at different gas mixing rates (a) mesophilic temperature, 35 ⁰C; (b) thermophilic temperature, 55 ⁰C.

**Figure 3** Stripping performance comparisons between dilute and real digestate in the small-scale batch stripping column at violent gas mixing rates. (a) TAN concentration profile at 55 ⁰C and biogas flow rate of 0.125 L min-1 L-1; (b) TAN concentration profile at 55 ⁰C and biogas flow rate of 0.250 L min-1 L-1.

**Figure 4** Modelled steady-state digester TAN concentrations and removals at different *in situ* stripping mixing rates, OLR, temperatures and digestate types. Scenario 1: mesophilic temperature, complete mixing, real digestate, time constant 18000 h; scenario 2: mesophilic temperature, complete mixing, dilute digestate, time constant 10000 h; scenario 3: thermophilic temperature, complete mixing, real digestate, time constant 9000 h; scenario 4: thermophilic temperature, complete mixing, dilute digestate, time constant 5000 h; 5: thermophilic temperature, violent mixing, real digestate, time constant 1110 h; scenario 6: thermophilic temperature, violent mixing, dilute digestate, time constant 625 h. (a) TAN removed (%) , (b) mesophilic scenarios, (b) thermophilic scenarios, (c) required time constant to achieve TAN toxic threshold (3.0 g N L-1) in a thermophilic *in situ* stripped digester.

**Table 1** Experimental degrees of agitation

|  |  |  |
| --- | --- | --- |
| Volumetric biogas flow rate | Superficial biogas flow rate | Degree of agitation a |
| (L L min-1) | (m3 m-2 tank cross-section min-1) |  |
| *75-litre digester* |
| 0.005 | 0.003 | Moderate |
| 0.015 | 0.008 | Moderate |
| 0.032 | 0.019 | Complete |
| 0.035 | 0.021 | Complete |
| *Stripping column* |
| 0.125 | 0.032 | Violent |
| 0.250 | 0.032 | Violent |

a Based on Perry and Green (1999)22, with rates doubled as suggested for shallower tanks

Table 2 In situ ammonia stripping results summary at 35 ⁰C and 55 ⁰C

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Temperature | Biogas flow(L L-1 min-1) | Time (hours) | TAN start(g N kg-1 WW) | TAN removal (%) | Time constant (hours) |
| 35 ⁰C | 0.005 | 144 | 5.15 | - | - |
| 0.015 | 102 | 5.20 | 1.73 | 10000 |
| 0.035 | 138 | 5.10 | 0.48 | 50000 |
| 55 ⁰C | 0.005 | 215 | 4.40 | 0.8 | 25000 |
| 0.015 | 217 | 4.35 | 4 | 5000 |
| 0.032 | 191 | 5.00 | 5.4 | 5000 |
| 0.035 | 266 | 4.20 | 6.9 | 5000 |

**Table 3** Nitrogen mass balance in the reactor

|  |  |
| --- | --- |
|  | Mesophilic a |
| TAN in traps (g) | 5.2 |
| TAN start digestate (g)  | 385.2 |
| TAN end digestate (g) | 378.8 |
| TAN stripped (g) | 6.5 |
| N loss c (%) | 0.3 |
| N loss c (g) | 1.6 |
| Thermophilic b |
| Biogas flow (L L-1 min-1) | 0.005 | 0.015  | 0.032 | 0.035  |
| TAN in traps (g) | 6.8 | 9.1 | 24.0 | 29.8 |
| TAN start digestate (g)  | 330.8 | 324.6 | 375.4 | 307.3 |
| TAN end digestate (g) | 327.0 | 307.3 | 349.6 | 281.0 |
| TAN stripped (g) | 3.8 | 17.3 | 25.8 | 26.3 |
| N loss c (%) | 0.9 | 2.5 | 0.5 | 1.1 |
| N loss c (g) | -3.0 | 8.2 | 1.7 | -3.5 |

a Ammonia traps replenished at the end of the experiment (0.005, 0.015 and 0.035 L L-1 min-1)

b Ammonia traps regenerated every time the flow was increased

c N loss: Unaccounted-for ammonia nitrogen. Calculated by a mass balance (TAN start digestate - TAN end digestate -TAN in traps)

**Table 4** Mass balance modelling for an anaerobic digester treating SS-DFW with *in situ* ammonia stripping - conditions and time constants

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Scenario  | Temperature | Mixing rate | Digestate type | Time constant (h) |
| 1 | Mesophilic | Complete | Undiluted | 18000a |
| 2 | Mesophilic | Complete | Dilute | 10000b |
| 3 | Thermophilic | Complete | Undiluted | 9000a |
| 4 | Thermophilic | Complete | Dilute  | 5000b |
| 5 | Thermophilic | Violent | Undiluted | 1110c |
| 6 | Thermophilic | Violent | Dilute | 625c |

a Estimate based on experimental values obtained with dilute digestate (75-L digester with gas mixing system) and time constant ratio (1.8) between undiluted and dilute digestate determined at 0.125 L L-1 min-1

b Experimental value (75-L digester with gas mixing system and dilute digestate)

c Experimental value (stripping column with dilute and undiluted digestate at 0.125 L L-1 min-1)

**Figure 1.**



**Figure 2.**

|  |
| --- |
| aTemporary increase in gas flow rate due to pump malfunction |
| b |

**Figure 3.**

****

a



b

**Figure 4.**

|  |
| --- |
| a |
| b |
| c |
| d |