Nitrogen removal from digested slurries using a simplified ammonia stripping technique

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Abbreviation footnote[1]

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[1] Abbreviations:

LFSD: Liquid fraction of separated digestate

USD: Unseparated digestate

Abstract

This study assessed a novel technique for removing nitrogen from digested organic waste based on a slow release of ammonia that was promoted by continuous mixing of the digestate and delivering a continuous air stream across the surface of the liquid. Three 10-day experiments were conducted using two 50-L reactors. In the first two, nitrogen removal efficiencies were evaluated from identical digestates maintained at different temperatures (30 °C and 40 °C). At the start of the first experiment, the digestates were adjusted to pH 9 using sodium hydroxide, while in the second experiment pH was not adjusted. The highest ammonia removal efficiency (87%) was obtained at 40 °C with pH adjustment. However at 40 °C without pH adjustment, removal efficiencies of 69% for ammonia and 47% for total nitrogen were obtained. In the third experiment two different digestates were tested at 50 °C without pH adjustment. Although the initial chemical characteristics of the digestates were different in this experiment, the ammonia removal efficiencies were very similar (approximately 85%). Despite ammonia removal, the pH increased in all experiments, most likely due to carbon dioxide stripping that was promoted by temperature and mixing. The technique proved to be suitable for removing nitrogen following anaerobic digestion of livestock manure because effective removal was obtained at natural pH (≈ 8) and 40 °C, common operating conditions at typical biogas plants that process manure. Furthermore, the electrical energy requirement to operate the process is limited (estimated to be 3.8 kWh m^{-3} digestate). Further improvements may increase the efficiency and reduce the processing time of this treatment technique. Even without these advances slow-rate air stripping of ammonia is a viable option for reducing the environmental impact associated with animal manure management.

Keywords

Ammonia removal; nitrogen reduction; biogas anaerobic digestion; manure management; CO_2 stripping

1. Introduction

Anaerobic digestion of animal manure for biogas production can improve both the characteristics of the manure and the sustainable recycling of nutrients, while simultaneously recovering energy. Frequently, biogas installations do not own the necessary area for the land application of the high-nitrogen digestate at acceptable rates, and this limitation is more severe in nitrate-sensitive regions and in regions where a nitrogen surplus already exists. Thus, digestate must be treated further to reduce the nitrogen content and comply with agro-environmental guidelines and rules for land application. Nitrogen can be removed from digestate biologically through processes such as nitrification and denitrification, but these processes do not facilitate recovery of the nitrogen. Furthermore, the high ammonia, phosphate and solids contents of digestates make biological processing difficult (Lei et al., 2007). Even in areas where there is no nitrogen surplus, the management of digestate may benefit a nitrogen recovery process to produce a mineral fertiliser that is easy to transport and utilize on crops. For this reason physico-chemical nitrogen removal processes such as struvite formation, membrane filtration or NH_3 stripping are more attractive than biological processes.

In particular, NH_3 stripping has been successfully used to remove nitrogen from different wastewaters, e.g. pig slurry, landfill leachate and wastewaters from the production of mineral fertilizers (Gustin and Marinsek-Logar, 2011; Laureni et al., 2012). The efficiency of air stripping depends on four main factors: pH, temperature, ratio of air to liquid volume, and liquid characteristics. Combined stripper/absorber plants operate by heating the influent (to

80 °C) fed to the plant and adding lime or NaOH to increase pH to 10.5–11 and promote NH_3 volatilization. When lime is used, a precipitation tank is normally provided prior to stripping in which phosphates, salts and carbonates can precipitate. Generally in industrial plants, the recommended volumetric gas-to-liquid flow ratio is 600–700:1 (Zarebska et al., 2014) and 95% efficiency of ammonia removal is expected. Unfortunately, temperature and pH modification both require extra effort and often entail added cost. In addition, pH control can require the use of dangerous chemicals that introduce health and safety concerns. Thus, although the design of NH_3 stripping technology is well advanced, there exist limitations in its practical application at farm facilities. In this context digested animal manure slurries (i.e., digestates) present important advantages over untreated slurries for NH_3 stripping; the necessary heat to stimulate the stripping process is readily available from the biogas that is generated during digestion, and higher pH resulting from digestion favours un-ionized NH_3 (Gustin and Marinsek-Logar, 2011; Jiang et al., 2014; Serna-Maza et al., 2014). In fact, in the anaerobic conditions of a biogas reactor, the mineral fraction of total nitrogen (as total Kjeldahl nitrogen, TKN) increases owing to conversion of organic nitrogen (Jiang et al., 2014), but remains in the liquid as ammoniacal nitrogen (i.e., NH_4^+ and NH_3). Furthermore, many biogas plants treat the digestate using solid-liquid separation to obtain a solid fraction rich in phosphorus and organic nitrogen, and a low-solids liquid fraction where most of the ammoniacal nitrogen remains. The separated liquid, from a stripping prospective, has even better characteristics than the raw digestate due to the lower solids content. Studies have demonstrated that slurry and digestate characterised by higher solids content exhibit a lower nitrogen removal efficiency than those with low-solids content, probably due to binding of ammonium ions by organic matter in high-solids inputs (Bonmatí and Flotats, 2003; Zarebska et al., 2014).

The potential applicability of the stripping process to digestate has been widely reported (Bonmatí and Flotats, 2003; Gustin and Marinsek-Logar, 2011; Jiang et al., 2010; Jiang et al., 2014; Laureni et al., 2012; Lei et al., 2007; Limoli et al., 2016; Morales et al., 2013; Quan et al., 2010; Zeng et al., 2006). However, most of these studies achieved good removal efficiencies in a short time by combining a high air-to-liquid feed ratio (from 5:1 to 850:1) with pH corrections and/or high temperature (up to 80 °C). Bonmatí and Flotats (2003) obtained complete NH_3 removal from digested pig slurry at 80 °C without pH modifications; however, the difficulty and expense of operating at this temperature was recognized as an obstacle to the practical application of this approach. Gustin and Marinsek-Logar (2011) investigated the effect of pH, temperature and airflow on the continuous stripping of NH_3 from the effluent of an anaerobic wastewater treatment plant (treating pig slurry and other organic materials) and showed that pH had the most relevant effect on NH_3 stripping. At the beginning of the stripping process pH may increase. García-González et al. (2015) and Zhu et al. (2001) showed that when manure was mixed and aerated, pH would increase due to CO_2 stripping, and good nitrogen removal efficiencies could be obtained without using chemicals. Particularly interesting was the study of Lei et al. (2007), which showed that the pH of an anaerobic digestate can be increased from 7.5 to 9.1 by CO_2 stripping in only one day at 15 °C.

These studies suggest the possibility of developing a slow-release stripping process that is easy to implement and manage at farm facilities and overcomes the limitations typical of this technology, which are mainly related to the large demand for thermal energy and the need for additives. In fact, although the principle of the stripping process is well known, its application to digested slurry has not yet been fully successful due mainly to (a) the need to remove solids prior to the stripping columns, (b) the large energy (thermal and electrical) demand and

(c) the requirement for chemicals. Therefore, there is the need to develop new solutions based on simplified technologies that are able to achieve adequate nitrogen removal and have only limited pre-treatment and energy requirements. Recent studies (Garcia-González and Vanotti, 2015; Garcia-González et al., 2015; Starmans and Timmerman, 2013; Vanotti et al., 2017) have examined some alternative systems that might meet these design criteria; however, none of the techniques evaluated were able to satisfy all constraints, especially the one related to the high solids content of the slurry processed.

The study here presented investigated the performance of a stripping process based on a new concept of installation in which slow-rate NH_3 volatilization was promoted in a closed reactor containing continuously mixed digestate. The volatilised ammonia was removed by an air stream through the headspace of the reactor. The objectives of the study were to assess the effect on nitrogen removal efficiency of temperature, pH correction and type of digestate.

2. Material and methods

2.1. Experimental apparatus

The pilot plant used in the study (Fig. 1) consisted of two Poly(methyl methacrylate) containers (reactors), each with a volume of 50 L (40-cm diameter and 40-cm height) and a tight-fitting polyvinylchloride lid with ports for sampling and inserting probes. Each container had an (ambient) air inlet regulated by a flow meter (2–30 L min^{-1}, Key Instruments, Trevose, PA, USA) and an outlet for the NH_3-charged air. The air flow was generated by a membrane pump (EVO30 series, ELECTRO A.D., Barcelona, Spain) and was set at 10 L min^{-1} to ensure one air exchange of the headspace every minute and enhance the slow release of NH_3. This flowrate correspond to an air velocity over the liquid surface of 0.1 m s^{-1} in agreement with the results of Ye et al. (2008).

The reactors were equipped with a mechanical stirrer that consisted of two horizontal blades mounted on a vertical shaft and oriented to mix the liquid in a downward direction. The mixer was driven by an electrical motor with a gearbox and a shaft rotation of 50 rpm. The temperature of reactors was regulated using a 13 W m^{-1} self-regulating heating tape (part no. 665-7485, RS Components, Corby, UK) installed externally around the circumference of the reactors and controlled by a thermostat (Ecotron T, Jumo, Fulda, Germany) connected to a temperature probe (Pt1000, Italcoppie, Cremona, Italy) immersed in the reactor liquid. Probes to measure pH (PHE-1335, Omega Engineering, www.omega.com) and Redox potential (ORE-1311, Omega Engineering, www.omega.com) were continuously monitored using a computer and LabView Software (National Instruments, Austin, USA). The probes were positioned approximately 10 cm beneath the surface of the reactor contents and connected to pH and redox circuits (EXP-R35-062 and EXP-R35-058, respectively, Atlas Scientific LLC, New York, USA).

2.2. Experimental methodology and nitrogen loss assessment

Three experiments (A, B and C) were conducted using the equipment described in Section 2.1. Experiment A was designed to evaluate the nitrogen removal efficiency at a defined pH and two different temperatures (30 °C and 40°C). Therefore, the digestate pH was increased to pH 9 by adding an appropriate amount of sodium hydroxide (NaOH). Experiment B was similar to A but the pH was not modified; this facilitated assessing the possibility of using this process without additives. Experiments A and B were performed in duplicate to obtain a repetition of results.

The third experiment (C) was conducted to evaluate the process using different types of digestate (experiments C1 and C2). As in experiment B the pH of the digestates was not modified. The temperature was set at 50°C.

The experimental conditions are summarised in Table 1. All experiments had 10-d durations, a time chosen because it is a reasonable hydraulic residence time for a full-scale installation. At the start of each experiment, each reactor was filled with approximately 40 L of digestate from a batch of 100 L that had been thoroughly mixed manually.

Experiments A and B used the liquid fraction of separated digestate (LFSD) that was collected following mechanical (screw press) separation from a 1-MW biogas plant processing animal manure (pig and cattle slurry, cattle farmyard manure and poultry manure) and a limited amount (5%) of maize silage. Experiment C examined unseparated digestates (USD), one (USD-C1) from the same source as for experiments A and B, and another (USD-C2) from a 360-kW biogas plant that processed cattle slurries and a small amount of maize silage (2%).

Digestate samples were analysed at the beginning and the end of each experiment for TKN, total ammoniacal nitrogen (TAN), pH, dry matter content (total solids, TS) and volatile solids content (VS), which were determined using standard procedures (APHA, 2012). Daily, a sample of digestate from each reactor was collected and analysed for TAN and pH to identify the transformation of digestate over time. Additionally, during experiment B the concentrations of NH_3, CO_2, N_2O and CH_4 were measured using a trace gas analyser (P-TGA 1302 Photoacoustic gas-monitor, Innova AirTech Instruments, Ballerup, Denmark).

During the experiments some water evaporation occurred; therefore, the volume in each reactor was noted daily and used to obtain a mass balance of the nitrogen losses. To compare the nitrogen losses that occurred in the different experiments, the TAN contents were indexed relative to the initial TAN content of each digestate that was measured at the beginning of the experiment. Thus an NH_3 removal index from 0 (no removal) to 1 (complete removal) was developed as an indicator of the efficiency of the process. Because a moderate mineralization of organic nitrogen might have occurred during an experiment, the calculated TAN removal efficiencies were conservative and might underestimate the actual efficiencies achieved in some cases.

3. Results and discussion

3.1. Digestate transformation during the process

Table 2 presents the initial and final chemical characteristics of the digestates. Although the digestates used in experiments A and B were drawn from the same source, their characteristics were slightly different because the samples were retrieved at different times. In particular, digestate in experiment B had a higher concentration of TKN than that in experiment A, but both had very similar TAN contents (1.84–2.14 g kg^{-1}). Because digestate USD-C1 had not been subjected to mechanical separation, it was characterised by higher solids (3.14%) and nitrogen contents (TKN 4.5 g kg^{-1}) than digestates used in experiments A and B, although all were sourced from the same biogas plant. Digestate USD-C2 had the highest TS content (3.82%) and the lowest TAN content (1.58 g kg^{-1}) because this digestate was mainly derived from cattle slurry and had not been subjected to liquid-solid separation. The pH of digestate in experiment A was adjusted to 9 using NaOH; the pH of digestates at the start of experiments B, C1 and C2 were 8.35, 8.13 and 7.81, respectively.

At the end of the experiments the main treatment effect was a reduction of TAN concentration, and consequently of TKN concentration. During the NH_3 stripping process in experiments A and B, reactors did not experience conversion of organic nitrogen. García-

González and Vanotti (2015) also found that organic nitrogen remained stable in swine slurries for which pH had been in the range 8.5–9. In contrast, during experiment C at 50 °C, digestates USD-C1 and USD-C2 had 66% and 73%, respectively, of their initial organic nitrogen converted to inorganic forms.

These results highlight that after anaerobic digestion, further organic matter degradation can occur under several conditions. In this study, the degradation was probably stimulated by mixing of the digestates, by reactor temperatures higher than 40 °C and by pH lower than 9 (Sommer et al., 2013).

3.2. Nitrogen removal efficiencies

Nitrogen removal from the reactors was reflected by trends of the NH_3 removal index as shown in Fig. 2. As expected, NH_3 emission from digestates adjusted to pH 9 (experiment A) was different than from digestates having lower, natural pH because the artificially elevated pH moved the chemical equilibrium towards ammonia gas. At both temperatures, the NH_3 volatilization rate was very high initially but decreased noticeably after the first 3–4 days. Probably, the reduced concentration of NH_3 in the liquid after the first few days of emissions reduced the driving force, and thus the rate, of further emissions. At the end of experiment A, NH_3 reductions of 64% and 87% were obtained at 30 °C and 40 °C, respectively.

Nitrogen removal in experiments on digestates without pH corrections (experiment B) showed similar patterns as in experiment A, but lower efficiencies. At 30 °C, the NH_3 stripping process was slower than at the higher temperatures; after 10 days only 41% of the initial ammoniacal N was lost from digestate B at 30 °C. At this temperature, ammoniacal N in the reactor occasionally increased, albeit slightly, probably due to the mineralization of organic N together with the restricted NH_3 emissions. At higher temperatures, nitrogen removal was more apparent than at lower temperatures. Without pH correction at 40 °C the initial TAN of digestate B was reduced by 69%. In comparison to the nitrogen removal efficiency achieved in experiment A (using pH-adjusted digestate), the removal efficiency achieved with digestate B (same as digestate A, but without pH correction) was lower by 35% at 30 °C and by 21% at 40 °C. These results were comparable with those of García-González and Vanotti (2015) who observed that 81% and 57% of TAN was removed from swine manure with and without pH adjustment, respectively.

Results shown in Fig. 2 from experiment C illustrate that at 50 °C, NH_4-N removal efficiencies up to 84 % can be achieved from raw (i.e., unseparated) digestate. This efficiency was very close to that achieved at 40°C during experiment A in which only the liquid fraction of separated digestate was used, proving that good nitrogen removal efficiencies can be obtained even from digestates with high solids contents. Although the chemical characteristics of digestates USD-C1 and USD-C2 were different, the nitrogen removal efficiencies were very similar at 50 °C. Garcia-Gonzalez and Vanotti (2015) found similar removal efficiencies (> 89%) from three manures characterised by a low (1.07 g kg^{-1}), medium (1.68 g kg^{-1}) and high TAN content (2.3 g kg^{-1}). These results suggest that probably nitrogen removal efficiencies can be relatively stable from digestates of different origin if processed under the same conditions (temperature, airflow, mixing, pH).

The trends in NH_3 removal rates during the experiments can be explained also by the effect of pH modifications (Fig. 3). In experiment A, the initial digestate pH was artificially adjusted to 9, but thereafter only slightly increased during the experiment and fluctuated little (between pH 9 and 9.2). The pH patterns of experiment A were comparable to those observed by García-

González et al. (2015), who found that pH increases in swine manure following initial pH adjustment were slight (to 9.4 from 9 initially). In experiment B (using digestate without pH correction), digestate pH steadily increased until the end of the experiment. The highest pH (8.99) was observed at 30 °C, but at both 30 °C and 40 °C, the pH trends were similar. Because NH_3 volatilization should decrease pH, the observed pH trends might be unexpected; as discussed previously, NH_3 volatilization decreased over time. However, it is well known that digested slurry contains considerable CO_2 that can be easily released in conditions such as those of the experiment (i.e., heating and mixing). Thus, the changes in pH can be interpreted as the net result of two opposing phenomena: CO_2 stripping that increases pH and NH_3 stripping that reduces pH. A single unit of pH increment after just an hour of mixing was observed by García-González et al. (2015) and by Lei et al. (2007) who showed that the pH of anaerobic digestion effluent could increase from 7.4 to 9.3 because of CO_2 stripping. Thus, the lower pH measured in the reactors kept at 50 °C during experiment C was more expected considering that NH_3 removal was more substantial at this temperature than at the lower reactor temperatures in experiments A and B.

These results confirmed that temperature is one of the most influential parameters, together with pH, on the efficiency of NH_3 removal from digestate (Jiang et al., 2014). Besides moving the equilibrium of ammoniacal nitrogen toward the gaseous form, increasing temperature enhances the molecular diffusion in both liquid and gas films, thus increasing the rate of mass transfer. Değemenci et al. (2012) found that the mass transfer coefficient for a synthetic ammonia solution increased 7.25-fold when temperature increased from 20 °C to 50 °C.

3.3. Gas concentration measurements

Figure 4 shows the gas concentrations measured in the reactor headspace during experiment B. After 3–4 days, when the maximum pH was recorded, the maximum NH_3 concentrations also were observed (545 ppm at 40 °C and 297 ppm at 30°C). The CO_2 concentrations decreased during the experiment from very high values of almost 7.5 g m^{-3} initially to values lower than 2 g m^{-3} at the end of the 10-d experiment. Thus, although the main cause of pH increases initially was clearly due to CO_2 stripping (Zhu et al., 2001), another process that might have contributed to the pH increase was NH_3 production caused by the mineralization of organic matter (Sommer et al., 2013). Methane concentrations in the headspace were high (261 ppm at 40 °C and 120 ppm and 30 °C) during the first day (Fig. 4) and thereafter decreased; this may have occurred because continuous mixing facilitated the gas bubble release of residual biogas. The very low N_2O concentrations that were measured confirm that the nitrification process was not established during the NH_3 stripping process.

While NH_3 and CH_4 concentrations showed a strong dependency on temperature, the other gases were not so sensitive to temperature. For CO_2 and CH_4 the main factor determining the observed patterns seemed to be the mixing of the digestate, which provoked the release of remaining CH_4 and CO_2 still dissolved in the digestate and inside gas bubbles within the digestate. During anaerobic digestion a large amount of CO_2 is produced, so the anaerobic effluent (i.e., digestate) has a high concentration of dissolved inorganic carbon (Moller, 2015). During storage of digestate, gas bubbles of CO_2 and CH_4 form in the bulk liquid and are easily released by mixing, which leads to a high volatilization of these compounds (Blanes-Vidal et al., 2012). The initial peak in CO_2 release after starting the mixing is related to the low solubility of CO_2 (Henry constant at 25 °C = 0.034 mol l^{-1} atm^{-1}). In comparison to CO_2, NH_3 has a much higher solubility (Henry constant at 25 °C = 60.381 mol l^{-1} atm^{-1}) (Blanes-Vidal and Nadimi, 2011) and this is the reason why NH_3 concentration did not increase (and subsequently decrease) as rapidly as CO_2 and CH_4. Instead, NH_3 tended to stay in solution as NH_4^+ (Sommer et al., 2007) and did not become one of the major components of gas bubbles (Blanes-Vidal and Nadimi, 2012). The gradual increase in NH_3 release also can be attributed to the increase in the pH of the digestate surface layer, caused by the co-release of CO_2 (Ni et al., 2009).

Although not a part of this study, the rate of mixing probably can be partly optimised. Nevertheless, an important function of mixing is its effect on the digestate surface. Crust formation or development of any film acting as a barrier on the digestate surface should be avoided to enhance gas release, especially of those components characterised by a low solubility (Sommer et al., 2013). Although the mixing strategy used in this study successfully prevented crust formation, further evaluation could improve the efficiency with which this was accomplished.

3.4. Practical application of the process

These experiments demonstrated the potential of a slow-release NH_3 stripping technology, based on a relatively long retention time and on limited pH adjustment, for the treatment of anaerobically digested livestock slurry. As discussed in Section 3.2, ammonia reductions of 80–90% were achieved. As shown in experiments, the relatively high dry matter content of unseparated digestate at the beginning of treatment did not seem to adversely affect the NH_3 removal efficiency. Such high ammonia removal efficiencies are encouraging because this technique is rather simple and does not require dedicated pre-processing of the digested slurry. In fact, considering that solid-liquid separation is already a common treatment step in many biogas plants, this novel modification of a trusted nitrogen removal process can be implemented easily in existing biogas installations.

As expected, better NH_3 removal was achieved at increased pH. However, as pH is not the only determinant of NH_3 volatilization, choices can be made among the influential operating parameters to achieve a desired NH_3 removal efficiency. For example, in these experiments the NH_3 removal efficiencies achieved in 10 days of retention time at 30 °C with digestate pH adjusted to 9 were the same as those achieved at 40 °C without pH adjustment (Fig. 2). Moreover, the same NH_3 removal efficiencies can be obtained by modifying the retention time. For example, achieving a target NH_3 removal efficiency of 60% was possible under almost all the experimental conditions tested in this study (with the exception treating digestate at 30 °C without pH adjustment) simply by varying the retention time.

These experimental results can be put in the context of a full scale installation. For example, a full scale facility could consist of modules, each capable of treating 10 m^3 d^{-1} digestate after separation. This size of module is adequate to maintain the same conditions as those of the pilot scale reactors while maintaining a reasonable height of the installation. The characteristics of the module, reported in Table 3, have been determined keeping the same proportion between the height and the diameter of the tank. The calculated air flow rate will maintain an air exchange of one headspace per minute (as in the pilot scale reactors). The stripping process has to be followed by a scrubber to wash the ammonia-charged air with acid (generally sulphuric acid) and recover nitrogen in the form of ammonia sulphate.

The total energy requirement of the low-rate volatilization system is related to the aeration, the pumps and the mixer. A centrifugal fan assuring the required air flowrate with a pressure drop of 500 Pa has a power rating of 0.84 kW. The mixing energy requirement (5.76 kWh 100 m^{-3} d^{-1}; Lemmer et al., 2013) has been assumed to be similar to that for full scale biogas plants. In addition, a power of 0.5 kW has been considered for ancillary equipment (control systems, pumps, and lights). The total energy requirement is thus 3.8 kWh m^{-3} of digestate treated (Table 3). For the NH_3 removal efficiencies demonstrated in this research, the energy demand would be 2.1 kWh kg^{-1} of N removed (based on 1.8 kg m^{-3} of N removed at 40 °C). The reactor temperature of 40 °C used in this study was consistent with that of a typical mesophilic anaerobic digester. Thus, because these installations produce more heat than is required for sustained operation, the surplus energy could be used (at no extra energy cost) to maintain digestate in an NH_3 stripping reactor at the required temperature. Consequently, the energy cost of this low-rate NH_3 stripping system would be considerably lower than that for industrial NH_3 stripping systems. In such plants energy consumption depends mainly on system design (use of packed columns or tray columns) and heat recovery (Zarebska et al., 2014). Electricity consumption in the range 0.2–94 kWh m^{-3} feed has been reported (Morales et al., 2013; Zarebska et al., 2014) with the lower consumption associated with lower process temperature (e.g., 35 °C). Other proposed nitrogen removal systems, such as that presented by Starmans and Timmerman (2013), have a higher calculated energy cost (5 kWh m^{-3}) than that of the low-rate stripping system investigated in the present study.

Thus, considering an average electricity price for industries in the European Union of 0.125 €kWh^{-1} (Eurostat, 2016), the operational costs for the novel slow-rate N removal process examined in this study are 0.5 € m^{-3} of digestate. Including maintenance and investment cost (i.e., interest charges) the overall cost of the slow-rate stripping technique is 3.5 € m^{-3} of digestate processed, which is lower than the cost of other stripping technologies or other nitrogen removal processes (Lyngsø et al., 2011).

Furthermore the low-rate stripping process here presented requires no pre-treatment for increasing pH and phosphorus removal, thus there are no costs related to the purchase of chemicals such as NaOH or lime. The only costs for chemicals are related to the purchase of acids used for the scrubber. Generally sulphuric acid is used and its cost is about 0.08–0.10 € L^{-1}. Consequently the average chemical cost per kilogram of nitrogen removed is estimated to be in the range 0.5–0.7 €. However, these costs can be offset by income from the sale of the ammonium sulphate that is produced (about 0.5 € m^{-3} of ammonia sulphate at 6–8% N) (Ledda et al., 2013). Thus, the cost of the sulphuric acid can be at least be partially compensated by income from the ammonia sulphate produced.

Therefore, from a practical perspective the results of this study confirm the feasibility of using slow-rate NH_3 stripping following anaerobic digestion of livestock slurry, which naturally produces a digestate that has higher TAN content and pH than the untreated slurry. Moreover, because anaerobic digestion stimulates the mineralization of organic nitrogen, the process provides nitrogen in ample quantities that can be volatilized, enhancing the possibility of obtaining good nitrogen removal efficiency without the need for additives to raise pH.

4. Conclusions

This study evaluated the effectiveness of a novel modification of the NH_3 stripping process for removing nitrogen from anaerobically digested livestock slurry. The results of the study justify a number of conclusions. (1) Slow rate air stripping of digested livestock slurry is an effective technique by which to remove nitrogen as ammonia from this substrate; nitrogen removal efficiencies of 80–90% with the pilot scale trials were achieved. (2) Air stripping with pH adjustment to 9 or high temperature (50 °C) promotes a greater reduction of NH_3 from digested animal slurry than does lower pH and lower temperature. (3) Different combinations of three important operating variables (digestate pH, temperature and retention time) can yield similar nitrogen removal efficiencies. (4) Effective NH_3 reduction can be achieved at pH 8 and 40 °C, which are common operating conditions at typical biogas plants. (5) When utilized at a biogas plant operated at mesophilic temperatures, the stripping process can avail of surplus heat from the biogas plant to maintain digestate at the required temperature for NH_3 removal; thus, the added energy requirements for the slow-release stripping process are limited. (6) The nitrogen removal efficiency of the novel slow-release NH_3 stripping system is close to that of faster treatments that require higher pH and temperature conditions and have much higher energy costs.

To confirm the applicability of the air stripping technique for a wider range of conditions than those studied, further research is necessary. The process should be tested on different digested livestock slurries to define the system performance when the waste material has characteristics different from those in this study. A second investigation should optimize the process in terms of airflow and mixing requirements to minimise energy requirements. Lastly, because CO_2 stripping can be a very good method by which to increase pH without using additives, research should evaluate if it would be advantageous to raise the reactor pH rapidly by optimizing the aeration system to accelerate the volatilization of CO_2.

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Table 1 Experimental conditions of the study.

Experiment	**Initial pH**	**Reactor 1 Temperature (°C)**	**Reactor 1 Digestate**	**Reactor 2 Temperature (°C)**	**Reactor 2 Digestate**
A	Corrected to pH 9	30	LFSD	40	LFSD
B	Not corrected	30	LFSD	40	LFSD
C	Not corrected	50	USD (C1)	50	USD (C2)

LFSD: liquid fraction of separated digestate from the same biogas plant

USD: unseparated digestate from two different biogas plants (C1 and C2)

Table 2 Digestate characteristics at the beginning and end of the experiments.

Experiment	**A***				**B***				**C**			
T (°C)	30		40		30		40		50 - C1		50 - C2	
	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
TS (%)	2.81 (0.19)	2.61 (0.22)	2.81 (0.19)	2.69 (0.09)	2.96 (0.26)	2.71 (0.35)	2.96 (0.26)	2.90 (0.07)	3.14	2.92	3.82	3.81
VS (%)	1.78 (0.19)	1.5 (0.24)	1.78 (0.19)	1.49 (0.3)	1.84 (0.18)	1.61 (0.21)	1.84 (0.18)	1.66 (0.04)	2.1	1.9	2.45	2.54
TAN (g kg^{-1})	1.84 (0.13)	0.66 (0.06)	1.84 (0.13)	0.24 (0.06)	2.14 (0.29)	1.25 (0.13)	2.14 (0.29)	0.67 (0.16)	2.38	0.45	1.58	0.25
TKN (g kg^{-1})	2.49 (0.1)	1.61 (0.03)	2.49 (0.1)	1.06 (0.28)	3.15 (0.19)	2.22 (0.12)	3.15 (0.19)	1.67 (0.06)	4.5	1.16	2.3	0.45
pH	9.05 (0.02)	9.07 (0.02)	9.05 (0.02)	9.07 (0.05)	8.35 (0.23)	8.99 (0.01)	8.35 (0.23)	9.04 (0.25)	8.13	8.63	7.81	8.5
TAN/TKN (%)	63 (4)	41 (3)	63 (4)	24.5 (12)	68 (6)	56 (3)	68 (6)	40 (8)	53	39	69	56

*Experiments A and B were replicated, thus results are the average of two sets of measurements. The standard deviation is shown in brackets. Experiment C was not replicated.

Table 3 Estimated characteristics of a module to treat 10 m^3 d^{-1} of manure and the associated energy requirement of the slow-rate ammonia stripping process

Dimensions	Height	m	5
	Diameter	m	5.0
	Total volume	m^3	120
	Headspace	m^3	20
	HRT	days	10
	Air flowrate	m^3 h^{-1}	1,200.00
Energy requirement for 10 days			
	Blower	kWh m^{-3} treated	2.02
	Mixer	kWh m^{-3} treated	0.576
	Ancillary	kWh m^{-3} treated	1.2
	Total	kWh m^{-3} treated	3.80
	kg N removed		1.8
	kWh kg N^{-1} removed		2.11