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A review of ammonia emission mitigation techniques for concentrated animal feeding operations

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Several approaches have been suggested and evaluated for reducing ammonia emissions from excreted animal manure: reducing nitrogen excretion through dietary manipulation, reducing volatile ammonia in the manure to stop ammonia loss, and segregating urine from faeces to reduce contact between urease and urine. When urine–faeces segregation is not an option, urease inhibitors can also be used to reduce or eliminate the hydrolysis of urea into ammonia. Methods for reducing the more volatile ammonia in manure include the reduction of pH, which shifts the equilibrium in favour of ammonium over ammonia; use of other chemical additives that bind ammonium-N; and the use of biological nitrification–denitrification to convert ammonium into non-volatile N-species such as nitrite, nitrate, or gaseous nitrogen. Other methods for mitigating ammonia emissions target emitting surfaces, and include capturing air (using physical covers) and treating the captured air to remove ammonia (using bio-filters or bio-covers, and scrubbers), and direct manure injection or incorporation into the soil. Manure collection facility designs and appropriate facility management are also essential for abating ammonia emissions. This paper provides a review of these approaches in the context of concentrated animal feeding operations (CAFOs).

1. Introduction

Ammonia emitted from concentrated animal feeding operations (CAFOs) in the USA may soon be subjected to state and federal regulations to protect air resources. Data for estimating emissions to the atmosphere from such facilities are being collected from an ongoing National Air Emission Monitoring Study (NAEMS) funded by the Agricultural Air Research Council, a non-profit organisation that receives its funds from livestock industry groups, and overseen by the US Environmental Protection Agency (EPA) Office of Air Quality Planning and Standards. There is a need to identify and develop practices and technologies that will assist producers in mitigating NH_3 emissions, not only to enable CAFOs to meet regulatory requirements but also for livestock producers to act as good environmental stewards.

Ammonia volatilisation is one of the pathways for N loss from animal feeding operations. Ammonia volatilisation is a critical issue because not only does it represent a loss of fertiliser value and but it can adversely impact the environment. Ammonia can also be deposited from the atmosphere and may be beneficial to plants as a nutrient source for

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Table 1 – Summary of ammonia abatement strategies in concentrated animal feeding operations (Arogo et al., 2006)

	Source or location			
	Excreted manure and urine	Confinement facilities	Treatment and storage	Land application
Control practice	• Reduce N excreted by reduced protein diets or improved balance of amino acids • Dietary electrolyte balance, affecting urinary pH	• Minimise emitting surface area • Remove manure frequently (belt transport, scrape, or flush) • Filter exhaust air (bio-scrubbers, biofilters, or chemical scrubbers) • Manure amendments (acidifying compounds, organic materials, enzymes, and biological additives)	• Cover to reduce emissions or collect gas • NH_3 stripping, absorption, and recovery • Chemical precipitation e.g. struvite • Biological nitrification (aerobic treatment) • Acidifying manure	• Injection or incorporation into soil soon after application • Application method to reduce exposure to air (e.g. low-pressure irrigation near surface, drag, or trail hoses) • Acidifying manure

growth but when excess N is deposited in N-sensitive ecosystems, this may impact the ecosystem negatively. Potential consequences associated with exceeding threshold concentrations of both oxidised and reduced forms of N in the environment include: (1) respiratory diseases caused by exposure to high concentrations of fine particulate aerosols ($PM_{2.5}$); (2) nitrate contamination of drinking water; (3) eutrophication of surface water bodies resulting in harmful algal blooms and decreased water quality; (4) vegetation or ecosystem changes due to higher concentrations of N; (5) climatic changes associated with increases in nitrous oxide (N_2O); (6) N saturation of forest soils; and (7) soil acidification through nitrification and leaching.

The objective of this paper is to review the state of the science for mitigating NH_3 emissions from animal feeding operations and to summarise the effectiveness of current mitigation strategies. Strategies for reducing NH_3 losses from CAFOs (Table 1) are directed towards: (1) reducing NH_3 or NH_4^+ formation or production, (2) physical containment of NH_3 or NH_4^+ after their formation, and (3) reducing volatile N species (Arogo et al., 2006). Some specific potential control strategies for NH_3 emission from animal production facilities include changing animal diet, redesigning or renovating barns, cleaning the exhaust air from buildings, treating manure, and improving the application of manure to land. In practice, to achieve adequate NH_3 volatilisation abatement in animal production operations, combinations of these control strategies are used.

2. Reduction of nitrogen excretion

Minimising nitrogen excretion, which can be achieved through dietary modifications, is naturally the first line of defence in curbing NH_3 emissions from livestock operations (Satter et al., 2002). Available research data indicate that diets fed to animals have profound effects on NH_3 emissions from excreted manure. Feeding ruminants with excess dietary protein, diets with imbalanced amino acids or diets without adequate energy needed for ruminal fermentation result in increased urinary and faecal N losses, which consequently increases NH_3 emissions from manure.

In non-ruminants (e.g. pigs), NH_3 losses have been reduced by either shifting N excretion from urine to faeces by increasing fibre in the feed or reducing the N content in the diet (Canh et al., 1997, 1998b). Several reports indicate that reducing crude protein (CP) in pig diets and supplementing with amino acids can reduce N excretion by 28–79% from the manure. This is based on an average of 8% reduction in N excretion per unit of CP reduction (Kerr, 1995; Turner et al., 1996; Hobbs et al., 1996; Canh et al., 1998a). Panetta et al. (2006) reported decreased NH_3 emission rates from 2.46 to 1.05 mg min^{-1} with decreasing dietary CP levels from 17.0% to 14.5%. Similarly, O'Connell et al. (2006) observed increased NH_3 emissions from slurry from pigs fed a 22% CP diet compared with a 16% diet. For broiler and layer chickens, reduced protein diets have resulted in reduced N excretion (Jacob et al., 2000). Thus, with some few notable exceptions (McGinn et al., 2002; Clark et al., 2005), reducing dietary CP results in significant reductions in NH_3 loss from pig facilities (Turner et al., 1997; Otto et al., 2003; Hayes et al., 2004; Velthof et al., 2005) and poultry operations (Ferguson et al., 1998; Nahm, 2003). Other strategies such as supplementing the diet with zeolite (Kim et al., 2005), antibiotics and probiotics (Han and Shin, 2005), vegetable oil (Leek et al., 2004), plant extracts (rich in tannins and saponins; Colina et al., 2001), and exogenous enzymes (Smith et al., 2004; O'Connell et al., 2006) have been used with varying success to reduce NH_3 losses from pig and cattle manure. In practice efforts to reduce NH_3 emissions must be balanced with animal performance to determine optimum protein concentrations and forms in the diet (Cole et al., 2005; Panetta et al., 2006).

In ruminants (e.g. cattle), diet composition can also have significant effects on urinary excretion of urea and consequently the losses of NH_3 from manure and the overall efficiency of utilisation dietary N (Klopfenstein et al., 2002; Satter et al., 2002). Generally, ruminants are relatively inefficient at utilising of dietary N. The efficiency of transfer of feed N into milk protein N (MNE) is on average $25 \pm 0.1\%$, with a minimum and a maximum of 14% and 40%, respectively (Hristov et al., 2004a), the bulk of the remaining N being lost to the environment via urine and faeces. Within limits, urinary N losses from dairy cows linearly decrease with decreasing dietary CP levels without affecting milk and milk protein yields and composition; a MNE of 36% was achieved with the lowest CP (13.5%) in the study of Olmos Colmenero and Broderick (2006). Cows fed 15.0–18.5% CP diets produced similar milk yields (32–39 kg day^{-1}) while simultaneously increasing N excretion and urinary N proportion (Groff and Wu, 2005). Reduction in the excretion of urinary N from dairy cows can mainly be achieved by reducing N intake in form of ruminally degradable protein (RDP); Kebreab et al., 2002). Using a combination of predictive equations (urine volume) and chemical analyses (urine composition), de Boer et al. (2002) demonstrated the importance of the ruminal N balance (referred to as the OEB value in the Dutch System) in reducing N losses from dairy cows. Increasing OEB from 0 to 1000 g cow^{-1} day^{-1} resulted in a linear increase in urinary N excretions. Feeding excess RDP resulted in greater ruminal N and milk urea N concentrations and increased urinary N losses (by 27%; Hristov et al., 2004b). Decreasing CP in the diets fed to cows (17–15% CP, ruminally undegradable protein (RUP) of 5.5–7.3) in mid or late lactation (14–12.5% CP) can reduce the cost of the diet and waste N excreted from cows. However, early lactating dairy cows need sufficient dietary RUP. After peak milk and DMI, CP and especially RUP requirements decline with declining milk production (Kalscheur et al., 1999). Using ruminally protected amino acids enables an efficient use of low-CP diets for production purposes. With ruminally protected methionine (up to 25 g day^{-1}), milk yield was maintained and MNE increased from 26% to 34% as dietary CP decreased from 18.6% to 14.8% (Broderick, 2005). Methionine supply to low (13%)-CP diets decreased the proportion of urinary N in the total excreta N (Krober et al., 2000). Carbohydrate level and availability in the diet can also have a significant effect on ruminal N utilisation and consequently urinary urea output. Increasing the dietary net energy of lactation concentration from 6.48 to 6.77 MJ decreased urinary urea N excretion and increased MNE (from 25% to 30%, respectively), while increasing the dietary CP level from 15.1% to 18.4% had an opposite effect by increasing urinary urea N excretion and decreasing MNE (Broderick, 2003).

Dietary CP levels and the effects on urinary urea excretion are directly related to NH_3 emissions from cattle manure. Smits et al. (1995) fed dairy cows two diets differing in ruminally available protein (OEB; 40 vs. 1060 g day^{-1}) and reported a significant increase in urinary urea-N concentrations and NH_3 emissions from manure (by 39%) with the high-OEB diet. Kulling et al. (2001) demonstrated that at 17.5% CP in the diet, N losses from manure after 7 weeks of storage were from 21% (slurry) to 108% (urine-rich slurry: urine to faeces ratio of 9:1) greater than the N losses from manure from cows fed 12.5% CP, with respective NH_3 emissions rates of 163 and 42 $\mu g\, m^{-2}\, s^{-1}$. Low-protein diets (13.5–14% CP) fed to dairy cows resulted in significantly lower NH_3 release from manure compared with the high-CP (15–19%) diets (Frank and Swensson, 2002; Frank et al., 2002). Similar results were reported for feedlot cattle (Cole et al., 2005; Todd et al., 2006). For example, decreasing the CP content of the diets of finishing cattle from 13% to 11.5% reduced daily NH_3 flux by 28% (Todd et al., 2006). In summary, reducing CP in beef cattle diets is a practical and cost-effective way of reducing NH_3 emissions from feedlots.

Ammonia volatilisation is directly related to the proportion of aqueous NH_3 in the total ammoniacal-N (TAN). In general, at a constant temperature pH determines the equilibrium between NH_4^+ and NH_3 with a lower pH favouring the NH_4^+ form and hence lower potential of NH_3 volatilisation. Thus, low urinary pH may be a key factor for reducing NH_3 emissions from cattle manure. Various dietary treatments can decrease urinary pH (Stockdale, 2005). Anionic salts (Tucker et al., 1991; Bowman et al., 2003; Mellau et al., 2004) and high fermentable carbohydrate levels (Mellau et al., 2004; Andersen et al., 2004) can reduce urinary pH to below 6.0. In non-ruminants, diet acidification with organic (benzoic) acids (Martin, 1982) or Ca and P salts (Kim et al., 2004) reduced urinary pH and NH_3 emissions from pig manure (Canh et al., 1997, 1998a, b).

3. Reduction of volatile nitrogen

The volatilisation of ammonia from manure is predominantly influenced by the concentrations of unionised NH_3 and ionised NH_4^+ in solution if environmental factors are constant. Therefore, a rational way of reducing NH_3 volatilisation is to reduce the concentrations of these volatile N species. Five common approaches used to reduce volatile N include: urine–faeces segregation, inhibition of urea hydrolysis, pH reduction, binding ammonium, and bioconversion to non-volatile N species.

3.1. *Urine–faeces segregation*

In general, surplus and inefficient utilisation of crude protein or amino acids in livestock diets is the source of N in urine and faeces. The majority of N (as much as 97%) is excreted in the form of urea in the urine of cows or pigs and in the forms of organic N in the faeces (McCrory and Hobbs, 2001). In a matter of hours to a few days following excretion, urea is converted to NH_4^+ by the enzyme urease, which is found in the faeces but not in the urine (Beline et al., 1998). The NH_4^+ is subject to volatilisation from manure depending on the pH conditions. In contrast, the breakdown of complex organic N forms in faeces occurs more slowly, requiring months or even years to complete. In both cases, N is converted to either NH_4^+ at low pH or NH_3 at high pH. This is the basis of the segregation of faeces and urine immediately upon excretion of either so that urease enzymes in the faeces have reduced contact with the urea in urine. This concept has been tested in two ways. One method uses a conveyor belt to separate urine and faeces, with urine flowing into a pit, while the faeces left on the belt are conveyed into a separate collection

Table 2 – Summary of ammonia emission reduction from manure storages using urine–faeces segregation

Animal species	Segregation method	Emission reduction (%)	References
Pig	Laboratory studies	99	Panetta et al. (2004)
Pig	Conveyor belt	47–49	Lachance et al. (2005), Stewart et al. (2004)
Cattle	Pre-cast grooves in concrete floor	46	Swierstra et al. (2001)
Cattle	V-shaped pit floor with gutter at the V	50–65	Braam et al. (1997a)
Cattle	Sloped (3%) solid floor	21	Braam et al. (1997b)

pit (Lachance et al., 2005; Stewart et al., 2004). The other method drains urine away from faeces into a urine pit immediately after discharge using appropriate floor designs while the faeces are scraped or washed into a separate faeces pit (von Bernuth et al., 2005; Swierstra et al., 2001, 1995; Braam et al., 1997a, 1997b).

The efficacy of urine–faeces segregation in abating NH_3 emissions from animal manures is summarised in Table 2. Segregation of urine from faeces can achieve as much as a 99% reduction in NH_3 emissions in laboratory studies (Panetta et al., 2004). However, pilot- and full-scale urine–faeces segregation has proved to be less effective. Several researchers have evaluated a conveyor belt system (Lachance et al., 2005; Stewart et al., 2004). Lachance et al. (2005) compared the performance of three urine–faeces separation systems (belt, net, V-shaped scraper) in pig grower-finisher housing. Without the separation process, removing the manure every 2–3 days significantly reduced NH_3 emissions by 46%, compared to the 8-week removal in the control. Using the belt or the net and manure removal within a storage period of 2–3 days, the separation of the urine and faeces directly under slats resulted in a 49% reduction of NH_3 emissions; this practice was not significantly different from the former system (i.e. not separating urine and faeces but removing the manure every 2–3 days). Stewart et al. (2004) also evaluated an inclined conveyor belt used directly as a dunging area in a pig barn. The average NH_3 emission in this system was 47% lower than a conventional grower-finisher system with a pit plug design.

Faeces–urine separation has also been effective using various floor designs. Swierstra et al. (2001) investigated pre-cast concrete floors with grooves and a manure scraper in a cow barn. The urine drained along the grooves and through perforations in the grooves spaced about 1 m apart. The perforations were opened and closed to drain urine directly into a slurry pit below and to drain urine at one end of the alley. The faeces were then scraped to one end of the alley. The floor system was constructed in one compartment of a mechanically ventilated experimental building, while in another compartment, a traditional slatted floor served as a control treatment. Ammonia emissions in the test compartment with open and closed perforations were reduced by 46% and 35% compared with the control treatment.

A similar system utilising a V-shaped pit floor with an adapted scraper installed beneath the slatted floor of pig pens was evaluated by von Bernuth et al. (2005). Faeces on the pit floor slope were scraped to a collection point after the liquid, including urine, had drained to a holding tank via a central pipe. Ammonia concentration in ambient air did not exceed 7.5 ppm in the pens throughout the monitoring period. Braam et al. (1997b) evaluated mitigation of NH_3 emission from similar V-shaped solid floors with a gutter at the bottom of the V-groove to drain urine in cow houses, with and without water spraying. Ammonia emission from the system without spraying water was reduced by 50% on average compared with a control. In addition, NH_3 emission was further reduced by an average of 65% when water was sprayed at a rate of 6 l day^{-1} cow^{-1} following scraping with a frequency of 12 times per day. Swierstra et al. (1995) evaluated a slatted floor versus a solid sloping floor with a central gutter with or without a finish in cow barn. The emissions from inclined solid floors were about 50% of the emission of the conventional slatted floors, and floor surface finish did not significantly affect the emissions.

A similar study by Braam et al. (1997a) also evaluated a traditional slatted floor and two solid floor systems; one of the latter was sloped (3%) and drained urine into a urine-gutter while the other was not inclined at all. Both the solid floors were either highly scraped (96 times a day) or normally scraped (12 times a day). The non-sloped solid floor scraped normally had the same NH_3 emission as the slatted floor, while the sloped solid floor, also normally scraped, further reduced NH_3 emission by 21% over the other two systems. Increasing scraping to 96 from 12 times day^{-1} decreased the emission of NH_3 by only 5%, a level which may not economically justify the extra scraping efforts.

All the urine–faeces segregation methods evaluated and reviewed in this paper have been shown to reduce NH_3 emissions from livestock barns by about 50% compared to the conventional manure handling systems (mixed urine–faeces systems). In addition, some limited flushing following faeces scraping from the sloped floors further significantly reduces NH_3 emissions. In conclusion, the critical factors that need to be considered in the choice of the method for separating urine from faeces are the cost of installation, the level of maintenance, and the ease of use versus cost of operation.

3.2. *Urease inhibitors*

The enzyme urease found in the faeces rapidly hydrolyses urea and uric acid into NH_4^+-N when urine is mixed with the faeces (Beline et al., 1998). However, urease inhibitors can block this hydrolysis and reduce NH_3 emissions from the manure.

In laboratory experiments, two urease inhibitors, cyclohexylphosphoric triamide (CHPT) and phenyl phosphorodiamidate (PPDA), have been shown to successfully control urea hydrolysis in typical cattle and pig slurries (Varel, 1997). At dosages of $10\,mg\,l^{-1}$, both inhibitors stopped the hydrolysis of urea in cattle and pig waste for 4–11 days. In contrast, hydrolysis of urea in untreated cattle or pig waste (i.e. control) was complete within 1 day. A weekly addition of the inhibitors was the most effective method of preventing urea hydrolysis. Weekly additions of 10, 40, and 100 mg of PPDA per litre of cattle waste (5–6 g urea l^{-1}) prevented 38%, 48%, and 70% of the urea, respectively, from being hydrolysed during a period of 28 days. For the pig waste (2×5 g [urea] l^{-1}), the same PPDA concentrations prevented 72%, 92%, and 92%, respectively, of the urea from being hydrolysed during the same study period. The results of these experiments provide technical strategies for significant control of NH_3 emissions from livestock facilities while increasing the fertiliser value by improving the N:P ratio.

Another laboratory study was conducted to evaluate the effect of the rate and frequency of urease inhibitor application on NH_3 emissions from simulated beef cattle feed-yard manure surfaces (Parker et al., 2005). The urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide (NBPT) was applied at rates of 0, 1, and $2\,kg\,ha^{-1}$, at 8-, 16-, and 32-day frequencies, and with or without simulated rainfall. Synthetic urine was added every 2 days to the manure surface. This urease inhibitor, applied every 8 days was most effective, with the 1 and $2\,kg\,NBPT\,ha^{-1}$ treatments resulting in 49–69% reduction in NH_3 emission rates, respectively. According to the authors, the 8-day, $1\,kg\,NBPT\,ha^{-1}$ treatments had the most promising benefit/cost ratios, ranging between 0.48 and 0.60. Although the technical and economic potentials of use of NBPT for reducing NH_3 emissions in beef cattle feed yard were demonstrated, the authors cautioned that because of possible build-up of urea in the pen surfaces, higher NBPT application rates may be necessary with time. In an earlier study, Varel et al. (1999) reported accumulation of urea, less concentration of TAN, and more concentrations of total-N in cattle feedlot manure when $20\,mg\,[NBPT]\,kg^{-1}$ of manure was applied weekly for 6 weeks compared with control. However, Panetta et al. (2004) reported contradictory results when NBPT was applied to pig slurry in laboratory studies. In these laboratory studies, additions of single ($76\,\mu l\,l^{-1}$) and double ($152\,\mu l\,l^{-1}$) dosages of NBPT increased NH_3 emissions by 50% and 140% compared with the control.

Although use of urease inhibitors has appeared promising in laboratory studies, no case studies were found in the literature for the use of these additives in the control of NH_3 emissions in full-scale CAFOs. The lack of adoption of urease inhibitors may be attributed to the unknown effects of these chemicals on the crops or pastures where the manure is eventually applied as fertiliser.

3.3. *Reduction of manure pH*

Ammonia volatilisation is directly proportional to the proportion of non-ionised aqueous NH_3 in the TAN. When the temperature is held constant, pH determines the equilibrium between NH_4^+ and NH_3 in aqueous systems. A lower pH leads to a lower proportion of aqueous NH_3 and, therefore, to a lower potential of NH_3 volatilisation. Acidification of animal manure to mitigate losses of NH_3 relies on this basic principle. The greatest increase in NH_3 release takes place between a pH of 7 and 10: NH_3 volatilisation decreases below pH 7, but around a pH of 4.5, there is almost no measurable free ammonia (Hartung and Phillips, 1994).

Past studies have clearly demonstrated the efficacy of pH reduction in the mitigation of NH3 volatilisation from livestock manure. The results of these studies are summarised in Table 3. Acidification of pig and cattle slurries from a pH of 8 to a pH of 1.6 using H_2SO_4 reduced NH_3 emissions progressively and completely stopped NH_3 volatilisation at a pH of 5 in pig slurries and at a pH of 4 in cattle slurries (Molloy and Tunney, 1983). Jensen (2002) maintained a pH of 5.5 using H_2SO_4 in pig manure in full-scale sow-confinement buildings with slatted floors and under-the-floor manure pits. These researchers reported reduction of ambient concentrations of the NH_3 by about 75–90%, while the weight of the pigs increased by $1074\,g\,day^{-1}$ during the study period compared to the pigs in the control buildings.

In a similar study, Stevens et al. (1989) used H_2SO_4 to acidify cow and pig slurries to pHs of 5.5 and 6.0, respectively. Under these pH conditions, NH_3 volatilisation was effectively reduced by 95% in the lab and by 82% in the field. Similar studies (Frost et al., 1990), using sulphuric acid to acidify whole cattle slurry to a pH of 5.5, reduced NH_3 volatilisation by 85%. Al-Kanani et al. (1992) in laboratory experiments similarly reported NH_3 loss reduction of 75% when sulphuric acid was applied to pig manure. Somewhat lower NH_3 loss reductions (14–57%) were reported by Pain et al. (1990) when sulphuric acid was used to lower the pH of cattle slurry to about 5.5. Husted et al. (1991) investigated the use of hydrochloric acid (HCl) in the acidification of stored cattle slurry, and noted that the addition of $240\,mEq\,[HCl]\,l^{-1}$ resulted in a reduction of the potential NH_3 loss by as much as 90% compared to the control. Safley et al. (1983) reported a reduction of about 50% in NH_3 loss using 85.2% Certified grade phosphoric acid at the estimated stoichiometric ratio, within 28 days of dairy cattle manure storage. Al-Kanani et al. (1992) reported a significantly greater (about 90%) reduction in NH_3 loss using the same phosphoric acid concentration on pig manure. Phosphoric acid, however, adds P concentration in the manure, which is undesirable. Some of the weaker acids such as propionic and lactic acids are just as effective as the strong acids, and have been observed to reduce NH_3 emissions by as much as 90% when the pH of the manure is maintained at 4.5 (Parkhust et al., 1974).

Other researchers have investigated the use of other acidifying additives (e.g. aluminium potassium sulphate or alum, ferric chloride, sodium hydrogen sulphate, and calcium chloride) to reduce NH_3 emissions from livestock manure (Li et al., 2006; Armstrong et al., 2003; Shi et al., 2001; Kithome et al., 1999; Al-Kanani et al., 1992; Husted et al., 1991; Witter and Kirchmann, 1989a; Mackenzie and Tomar, 1987; Molloy and Tunney, 1983). Although most of these additives effectively reduce pH, they are generally not as effective in reducing NH_3 losses as the strong acids because, unlike their counterparts, they cannot maintain stable pH conditions.

Table 3 – Summary of ammonia emission reduction from manure storages by lowering pH

Animal species	Agent or substance	Emission reduction (%)	References
Cattle and pig	Sulphuric acid	14–100	Molloy and Tunney, (1983), Jensen (2002), Stevens et al. (1989), Frost et al. (1990), Al-Kanani et al. (1992), Pain et al. (1990)
Cattle	Hydrochloric acid	90	Husted et al. (1991)
Cattle and pig	Phosphoric acid	50	Safley et al. (1983)
Pig	Phosphoric acid	90	Al-Kanani et al. (1992)
Broiler	Alum	89	Li et al. (2006)
Cattle	Alum	91–98	Shi et al. (2001)
Cattle	Calcium chloride	71–78	Shi et al. (2001), Witter (1991)
Poultry and cattle	Calcium chloride	10–15	Kithome et al. (1999); Husted et al. (1991)
Cattle	Monocalcium phosphate monohydrate	87	Al-Kanani et al. (1992)

Li et al. (2006) reported an 89% reduction in NH_3 volatilisation when alum was applied at the rate of 2 kg [liquid aluminium sulphate] m^{-2}[surface area]. Armstrong et al. (2003) observed that application of liquid alum equivalent to 0.5, 1.0, and 1.5 kg [aluminium sulphate] m^{-2} of broiler litter surface was effective at maintaining in-house NH_3 concentrations at below 25 ppm for 2, 3, and 3 weeks of the grow-out, respectively. Shi et al. (2001) investigated the efficacy of alum on beef cattle manure. Compared to the control, NH_3 emission reduction during 21 days of monitoring was 91.5% at 0.45 kg ha^{-1} alum and 98.3% at 0.9 kg ha^{-1} alum. The advantage of using alum to reduce NH_3 emissions is the reduction in soluble phosphorus and the reduced potential for phosphorus run-off or leaching.

Investigations by Witter and Kirchmann (1989a) on the efficacy of calcium and magnesium salts on NH_3 loss during aerobic treatment revealed that the efficiencies of most of these salts ranged between 85% and 100% within 2–3 weeks and between 23% and 52% by the seventh week of incubation. Shi et al. (2001) evaluated the efficacy of $CaCl_2$ in reducing NH_3 emissions from beef cattle manure in the laboratory. Compared to the control, 21 days after application NH_3 emissions were reduced by 71.2% and 77.5% at 4500 and 900 kg ha^{-1} [$CaCl_2$] application. Calcium chloride was less effective than alum at the same application rates. Witter (1991) examined NH_3 volatilisation following the addition of $CaCl_2$ to fresh and anaerobically stored manure before land application of the respective slurries. Within 48 h after application, $CaCl_2$ reduced NH_3 loss by 73% in the fresh manure and by 8% in the anaerobically digested manure. Kithome et al. (1999) reported a 10% decrease in NH_3 volatilisation with the addition of 20% $CaCl_2$ to poultry manure. This is similar to the maximum 15% NH_3 emission reduction reported by Husted et al. (1991) achieved by addition of 300–400 mEq [$CaCl_2$] l^{-1} to cattle slurry. Calcium chloride is thus only suitable for reducing NH_3 loss in poultry housing, and may not be suitable for reducing NH_3 loss from land-applied slurries that have previously been stored under anaerobic conditions. Al-Kanani et al. (1992) reported a significant reduction in pH and NH_3 emission (87%) when monocalcium phosphate monohydrate (MCPM) was applied to cattle manure. Mackenzie and Tomar (1987) also investigated addition of MCPM to liquid pig manure with and without aeration. A decrease in pH was observed with addition of MCPM, but the pH increased when addition of salt ceased. During subsequent aeration, total nitrogen (TN) decreased significantly in the control manure, while no significant change was observed in the TN in the manure with MCPM.

Overall, strong acids tested for reducing slurry pH are more cost-effective than the weaker acids and acidifying salts, but are more hazardous for use on the farm than the latter. Thus, although the acidifying salts and other weaker acids may be less effective than strong acids, they are non-hazardous and relatively low cost, which increases their suitability for on-farm use.

3.4. *Ammonium binding*

This category of substances has a high affinity for binding onto NH_4^+ ions thus reducing NH_3 volatilisation through decreased concentration of free NH_4^+ ions. The methods of ammonia binding in some cases are not well understood. A summary of the performance of these substances is provided in Table 4.

Zeolite is a cation-exchange material, which, due to its crystalline-hydrated properties resulting from its infinite 3-dimensional structure, has a high affinity and selectivity for NH_4^+ ions (Mumpton and Fishman, 1977). A layer of 38% zeolite placed on the surface of composting poultry manure reduced NH_3 losses by 44% (Kithome et al., 1999). An earlier

Table 4 – Summary of ammonia emission reduction from manure storages using ammonium binders

Animal species	Binding agent	Emission reduction (%)	References
Poultry	Zeolite	1.5–96	Kithome et al. (1999), Witter and Kirchmann (1989b), Nakaue et al. (1981), Li et al. (2006)
Pig	Zeolite	71	Portejoie et al. (2003)
Pig	Sphagnum peat moss	80–99	Al-Kanani et al. (1992), Barrington and Moreno (1995)
Poultry	Sphagnum peat moss	24	Witter and Kirchmann (1989b)
Pig	Saponins (yucca extract)	23	Kemme et al. (1993)
Pig	Alliance®	24	Heber et al. (2000)
Poultry	De-Odorase®	50	Amon et al. (1997)

study by Witter and Kirchmann (1989b) investigating the efficacy of zeolite on the reduction of NH_3 loss from poultry manure during aerobic incubation reported an insignificant 1.5% reduction in NH_3 loss when mixed with manure in the ratio of 1:4. Nakaue et al. (1981) observed a reduction of up to 35% NH_3 loss by addition of 5 kg m^{-2} of zeolite to broiler litter. Portejoie et al. (2003) investigated reduction of NH_3 loss in pig manure during storage and land application using zeolite, and reported a 71% reduction in NH_3 emissions. Li et al. (2006) evaluated the efficacy of zeolite in reducing NH_3 emissions from fresh poultry manure in laboratory experiments. Application of typical medium rates of 5% (w/w) zeolite reduced NH_3 emission by 81%. Zeolite appears to be more effective for reduction of NH_3 emission in animal slurries and liquid manures than in the solid poultry manures.

Two other additives in this category evaluated for abatement of NH_3 emissions in livestock manures are sphagnum moss (*Sphagnum fuscum* peat) and yucca plant extracts (saponins). Al-Kanani et al. (1992) compared the efficacy of several amendments on liquid hog manure and concluded that sphagnum moss was just as effective as the strong acids (reducing NH_3 volatilisation by as much as 99%), although it did not lower the pH to the same levels as the acids. Barrington and Moreno (1995) observed that a 20 mm depth cover of floating sphagnum reduced NH_3 loss by as much as 80%. Similar results were reported by other researchers (Al-Kanani et al., 1992), but Witter and Kirchmann (1989b) reported a somewhat lower (24%) reduction in NH_3 emissions when sphagnum moss, mixed in the ratio of 1:4, was used in poultry manure during aerobic incubation. This product also seems to be more effective on the animal slurries than on the solid poultry manure in the same way as zeolite. Kemme et al. (1993) reported an NH_3 loss reduction of 23% when saponins were applied to pig slurries. Panetta et al. (2004) reported similar results when these extracts were applied to pig slurry in laboratory studies. In this category, saponins do not seem to be as effective in mitigating NH_3 emissions as either zeolite or peat moss.

A host of other additives disguised by brand names, presumably to protect commercial interests of their inventors, have also been evaluated. Heber et al. (2000) evaluated a commercial manure additive (Alliance®) developed by Monsato EnvironChem (St. Louis, MO.) to improve air quality in pig buildings. Alliance® was sprayed onto the manure stored in pits underneath slatted floors. Compared to the control, this additive reduced NH_3 emissions by 24%, but also further diluted the manure by 20%. The authors estimated the cost of this additive at \$1.38 pig-space^{-1} year^{-1} or \$0.50 per marketed pig based on 135-day growth cycles, and a product cost of \$3.43 l^{-1}, and noted that because of the modest reduction in NH_3 emission, this additive may not be cost-effective to most producers. Amon et al. (1997) compared the effectiveness of another commercial additive (De-Odorase®) to a control (no additive) in broiler production. This product (De-Odorase®) significantly reduced NH_3 emission by 50% over the control. It is important for producers to ensure that the effectiveness of the respective additives has been scientifically verified by independent and reputable institutions before they adopt them for use in their facilities.

In summary, amongst ammonia binders, zeolite seems to be more effective for reduction of NH_3 emissions from animal slurries and liquid manures than in solid poultry manures. Sphagnum moss, like zeolite, also seems to be more effective on the animal slurries than on the solid poultry manure. Saponins do not appear to be as effective in mitigating NH_3 emissions as either zeolite or peat moss. In general, large quantities of these additives are required, and in most cases (with additives such as the acid/acidic salts), precautions must be taken to safeguard the safety of livestock and farm workers. In addition, use of acids may result not only in an undesirable increase in the mineral content of the manure/litter but also in the corrosion of equipment and structures. It is important to determine appropriate application methods to ensure that these additives are most effective.

3.5. *Biological treatments*

Biological treatment processes are either based on the assimilation and immobilisation of volatile N or the transformation of volatile N into non-volatile inorganic N. The former approaches are geared towards recovering N products from liquid animal waste and include the production of single cell proteins, amino acids, and protein-rich aquaculture plants such as duckweed and algae. These alternative systems will not be reviewed here.

Transformation of volatile N species to non-volatile species is a major biological treatment process comprising of coupled nitrification and denitrification processes. However, most treatments employ some variation of physical, chemical or components of both physical and chemical unit processes to provide suitable conditions for these processes to occur efficiently and cost-effectively. During nitrification, nitrifying bacteria transform TAN to oxidised N (nitrite and nitrate). These compounds are then biologically reduced to environmentally benign N gas (N_2) by denitrifying bacteria. The reaction rate of nitrification is extremely low compared to that of denitrification; consequently, nitrification is the rate-limiting step. Nitrification is the more critical step, and usually receives more attention in the biological treatment of wastewaters for removal of NH_3. Common biological treatment systems consist of either single or two bioreactors. The single-reactor systems are either run alternately in aerobic and anaerobic modes or have both aerobic and anoxic zones in the same reactor to effect nitrification and denitrification, respectively. In contrast, these processes take place in separate reactors in the two-reactors-systems. To enhance the nitrification kinetics in particular, other features such as cell immobilisation on inert materials or other methods of biomass enrichment are incorporated.

Hu et al. (2003) studied a continuous-flow intermittent aeration (IA) process for N removal from anaerobically pre-treated pig wastewater at the laboratory scale. In this study, experiments were conducted at different: influent COD concentrations, aeration: no-aeration ratios, hydraulic retention time (HRT), and solids retention time (SRT). At the HRT of 3 days and SRT of 20 days in the IA tanks, nitrification and denitrification were successfully achieved in the IA process. Nitrogen removal rates surpassed 80%, and nitrite and nitrate were less than 20 mg l^{-1} in the effluents. A similar system was evaluated by Zhang et al. (2006) for treating pig manure rich in N. In this study, a bench-scale sequencing batch reactor (SBR) was operated in a cyclic anaerobic–anoxic mode using low-intensity aeration of 1.0 L[air] m^{-3} [wastewater] s^{-1}, coupled with two-step influent feeding. Approximately 97.5% of the TN in the treated manure was removed, with only 15 mg N l^{-1} of the oxidised N (NO_3^+-N) left in the effluent. Luostarinen et al. (2006) evaluated a single-moving bed bioreactor (MBBR) for the treatment of anaerobically pre-treated dairy parlour wastewater and a mixture of kitchen waste and black water. The effect of intermittent aeration and continuous versus sequencing batch operation was also studied. The MBBRs removed 50–60% of N irrespective of the operational mode. Complete nitrification was achieved, but denitrification was impeded by insufficient carbon. The range of N removal in this study was, however, much lower compared with the rates reported by Hu et al. (2003) and Zhang et al. (2006). It is possible that these discrepancies may be due to the differences in the influent wastewaters. Loustarinen used milking parlour wastewater, while the Hu et al. (2003) and the Zhang et al. (2006) systems used pig wastewater. Another likely explanation is the confusion in the reporting of N (either as TN, TKN, or TAN).

Pan and Drapcho (2001) reported on a continuous-flow two-reactor (anoxic and aerobic) system for treatment of pig wastewater. The aerobic reactor was maintained at 5 mg l^{-1} dissolved oxygen. This system was run at HRT of 35 h in the anoxic system and 36 h in the aerobic system, and a recirculation ratio of 1.0. At a steady state, TAN in the effluent was reduced by about 85%, of which 51% was retained as nitrate in the effluent. A similar bench-scale system was evaluated by Ten-Have et al. (1994) for treatment of supernatant from settled pig manure. This system consisted of separate reactors for nitrification and denitrification and a recycle of mixed liquor from the former to the latter. More than 99% of the TAN was converted to nitrate. Complete denitrification was not accomplished because of inadequate fermentable carbon in the manure supernatant. Molasses were added to provide the extra carbon needed. Shin et al. (2005) investigated a slightly different two-reactor system for biological removal of N from pig wastewater rich in organic matter and N. This system consisted of a submerged membrane bioreactor (MBR) for nitrification, followed by an anaerobic up-flow bed filter (AUBF) reactor for denitrification. A total N removal efficiency of 60% was achieved at an internal recycle ratio of three times the flow rate. Complete nitrification of the ammoniacal-N was achieved in the process.

Vanotti and Hunt (2000) evaluated an immobilised-cell (encapsulated in a polymeric resin) system for enhanced nitrification of TAN in pig wastewater. This system was evaluated for treatment of high-strength pig lagoon wastewaters containing about 230 mg [NH_4-N] l^{-1} and 195 mg [BOD_5] l^{-1}. A culture of acclimated lagoon nitrifying sludge immobilised in 3–5 mm polyvinyl alcohol polymer pellets was used for this experiment. Alkalinity was maintained with inorganic carbon to ensure a liquid pH within the optimum range (7.7–8.4). In batch treatment, only 14 h were needed for nitrification of NH_4^+-N. In contrast, it took 10 d for a control (no pellets) aerated reactor to start nitrification, while as much as 70% NH_3 was lost via air stripping. In the continuous-flow treatment, nitrification efficiencies of 95% were obtained with NH_4^+-N loading rates of 418 mg[N] l^{-1} [reactor] day^{-1} at 12 h HRT. In all cases, the NH_4^+-N removed was entirely recovered in oxidised N forms. The immobilised-cell technology thus further enhanced TAN removal from anaerobic pig lagoon wastewater.

An 8 m^3 day^{-1} pilot-scale two-reactor system was evaluated by Westerman et al. (2000) for treatment of the supernatant from settled flushed pig wastewater. The main system consisted of two up-flow aerated biofilters connected in series. The aerated biofilters ran at around 27 °C, and removed about 84% of the TKN, 94% of the TAN, and 61% of the TN. A significant portion of the NH_3 was converted to nitrite and nitrate nitrogen. The TKN, TAN, and TN removal averaged 49%, 52%, and 29%, respectively, when the reactors were run at around 10 °C. The unaccounted N of about 24% could have been lost through NH_3 volatilisation or through denitrification within the biofilm. Westerman and Bicudo (2002) later evaluated a full-scale nitrification/denitrification system for biological treatment of flushed pig manure in a 3000 finishing facility. The system consisted of a pond with a mixing zone for denitrification, and an aeration zone for nitrification, with recirculation from the aeration zone to the mixing zone, and a recycle from the aeration zone to the barns for flushing. Nitrogen reduction in the effluent was 65–90%, with more than 90% of the N being in the inorganic N form. In addition, a significant reduction in odour perception, irritation, and unpleasantness from liquid samples drawn from the treatment system was reported. The report also noted the high-energy cost for the operation. Another full-scale nitrification–denitrification system was reported by Townsend et al. (2003). This system was constructed to serve 52,800 finishing pigs. Nitrification and denitrification occurred in a single wastewater treatment plant centrally located on the farm reducing TN by an average of 87%. Townsend et al. (2003) also reported significant foam generation during aeration, necessitating the continuous use of a defoaming agent for the treatment to continue.

When designed and run appropriately, these systems can effectively (up to 99%) mitigate NH_3 emissions in CAFOs. It appears that the major hindrance is the economics of installing and operating the systems. An important element of biological N removal is the carbon source to complete the denitrification process. Reporting of N (either as TN, TKN, or TAN) needs to be well defined to enable inter-comparisons.

4. Building designs and manure managements

Accumulated urine and faeces on the floor is the main source of NH_3 volatilisation within animal buildings. The longer their residence times on the floor, the more the NH_3 volatilisation. The manure can be also thinly spread out, which further exacerbates NH_3 volatilisation as this provides larger surface areas. Frequent removal of manure may be critical in mitigating NH_3 volatilisation within the building. Scraping, flushing, slatted floors, conveyor belts, or combinations of these systems are currently the most common methods of removing manures from the floors or buildings.

Flushing floors with water every 2–3 h led to a 14–70% reduction in NH_3 loss compared to use of slatted floors in dairy barns (Voorburg and Kroodsma, 1992; Kroodsma et al., 1993; Ogink and Kroodsma, 1996). Increasing the flushing frequency, increasing the amount of water, and use of fresh water (as opposed to recycled water) further reduce NH_3 volatilisation within the building (Voorburg and Kroodsma, 1992; Monteny, 1996). However, since these practices may increase the volume of the slurry to be handled and also increase the cost of slurry utilisation, a compromise between flushing frequency, amount of water, use of fresh water, and the respective additional reduction of NH_3 losses has to be established.

Kroodsma et al. (1993) investigated the effects of different manure managements on NH_3 emissions from freestall dairy houses. Manure scraping every 3.5 h did not significantly decrease NH_3 emissions, while flushing with water every 3.5 h decreased the emissions by up to 70%. Frequent flushing (every 1–2 h) over short periods (2 s) was more effective than prolonged (3–6 s), but less frequent flushing (every 3.5 h). Ogink and Kroodsma (1996) evaluated two cattle manure management systems for reduction of NH_3 emissions from cow houses with partially slatted floors. One method was based on scraping the slats and subsequent flushing with water every 2 h, using 20 L[water] day^{-1} cow^{-1}. The second method was similar, except that 4 g [formalin] l^{-1} of flushing water was added. Compared to a control (no scraping or flushing), the former method only lowered the emission by 14%, while adding formalin to the flushing water reduced emissions by 50%. Misselbrook et al. (2006) reported that pressure washing and the use of a urease inhibitor in addition to yard scraping were more effective means of reducing emissions compared with yard scraping alone, while reduction of yard area per animal was also an effective strategy to reduce total emissions.

For slatted floor systems, the frequency of manure removal from the pits under the slats is critical in the management of NH_3 emissions within the building (Hartung and Phillips, 1994). Hartung and Phillips (1994) compared four different manure removal strategies: a partially slatted floor (PSF) with a slurry pit emptied every 2 weeks, a PSF with a sloped slurry channel beneath that is flushed several times a day, a PSF floor with continuous recirculating and flushing, and a PSF floor with a continuous recirculating and combined with a basin and plug. The control was a PSF with a slurry pit underneath providing storage for 6 months. Respective NH_3 volatilisations were 20%, 60%, 40%, and 80% less than in the control. In a similar study, Lachance et al. (2005) reported a significant 46% reduction in NH_3 emissions when manure was removed every 2–3 days, compared to the 8-week removal frequency in the control. Lim et al. (2004) evaluated several manure management strategies for reducing NH_3 emissions in confined finishing pigs. The strategies included daily flushing, and static pits with 7, 14, and 42 d manure accumulation cycles, with and without pit recharge, with some secondary lagoon effluent after emptying. Flushing and static pit recharge with lagoon effluent resulted in significantly less NH_3. Mean NH_3 emission rates were 15, 27, and 25 g day^{-1} AU^{-1} for the 1-, 7-, and 14-day cycles without pit recharge, and 10, 12, and 11 g day^{-1} AU^{-1} for the 7-, 14-, and 42-day cycles with pit recharge, respectively. The mean daily NH_3 emissions from the rooms with static pits were 51–62% lower with recharge than without recharge. In summary, less NH_3 emissions occurred when pits were recharged after emptying, and when pits were emptied more frequently.

In poultry buildings (cage) removing manure twice a week using belts or weekly with drying manure on belts reduced NH_3 emission from battery cage houses by 60% or more compared to allowing manure to stay on the belt. However, daily removal has the potential of further reducing NH_3 emissions, since hardly any degradation then takes place inside the house (Monteny, 1996; Cowell and Apsimon, 1998).

Ammonia volatilisation within the buildings is also a function of the building ventilation system. Ventilation would increase NH_3 losses because of reduced resistance to NH_3 transfer into the air above the manure. For example, a common practice to reduce elevated NH_3 levels in poultry houses is to increase ventilation rates above the values needed for proper litter moisture control. The increased ventilation rates reduce the NH_3 concentration in the house, but this translates directly into higher NH_3 emissions as well into the increased costs of running the ventilation fans.

5. Emissions capture and treatment

Important mitigation strategies of NH_3 and other gaseous emissions involve capturing or trapping the fugitive gases and subsequent treatment of the respective captured emissions. These strategies can be placed into two broad categories: (i) filtration and biofiltration and (ii) use of permeable and impermeable covers.

5.1. *Filtration and biofiltration*

Filtration is more a physical-chemical process while biofiltration not only traps but also biologically degrades or converts trapped compounds into their benign forms. Removing NH_3 from vented air using filters or scrubbers (water and acid) is feasible where barns are mechanically ventilated (Sommer and Hutchings, 1995; Groot Koerkamp, 1994). In most cases, the practical applications of these cleaning devices are limited due to their relatively high cost and technical problems due to dust, especially in poultry and pig houses.

Sun et al. (2000) described a 200 mm deep biofilter consisting of a mixture of compost and wood chips tested for removal of NH_3 from pig housing ventilation air. On average, this system removed 83% of NH_3 in the carrier air at a biofilter moisture content of 50% at a retention time of 20 s. Tanaka et al. (2003) also reported a reduction of 94% in NH_3 from composting air in a biofilter consisting of finished compost (of cattle manure and sawdust) within the first 72 h of treatment. Hong and Park (2005) reported a 100% NH_3 removal efficiency from air from a composting pile (of dairy manure mixed with crop residues) in a 500 mm deep, 50:50 manure compost to a coconut peel biofilter. Sheridan et al. (2002) evaluated a pilot-scale wood chip biofilter for reducing NH_3 from exhaust air from a pig finishing building. A 500 mm deep biofilter made from 20 mm screen size wood chips efficiently removed between 54% and 93% NH_3 depending on the volumetric loading rate. A filter bed moisture level of 63% or greater was recommended to maintain the biofilter efficiency. A biofilter consisting of a mixture of pine and perlite removed 95.6% NH_3 from ventilation air from a pig rearing facility in a pilot-scale system (Chang et al., 2004). Kastner et al. (2004) reported that a biofilter made of pre-screened yard waste compost reduced NH_3 by 25–95% in ventilation air from a modern 2400-sow farrow-to-wean unit, depending on the residence time and inlet NH_3 concentration. Martinec et al. (2001) evaluated several biofilter materials (biochips, coconut peels, bark-wood, pellets+bark, and compost) for reduction of NH_3 from pig operations. Ammonia reduction with these materials ranged between 9% and 26%.

There is a broad range of biofilter efficiencies in the removal of NH_3 in carrier air. The wide range of performances (9–100%) reported in the literature may be attributed not only to the wide range of biofilter materials but also to other factors such as maintenance of optimum moisture in the filter bed, the residence time of the air in the biofilter (Sun et al., 2000; Hartung et al., 2001; Tanaka et al., 2003), the NH_3 load in the incoming air (Sheridan et al., 2002; Kastner et al., 2004), and how well the microbial community is established in the biofilter. Well-designed and operated systems can effectively mitigate NH_3 emissions from livestock operations.

For the readers interested in more details on acid scrubbers and trickling filters, a comprehensive review of these technologies for treatment of exhaust air from pig and poultry houses in the Netherlands has recently been completed (Melse and Ogink, 2005). In that review article, NH_3 removal in acid scrubbers ranged from 40% to 100%, with an overall average of 96%, while NH_3 removal efficiency in bio-trickling filters ranged from −8% to +100% with an overall average of 70%. Process control with pH and automatic water discharge were sufficient to guarantee NH_3 removal efficiency in acid scrubbers. The review concluded that improvement of process control is required in bio-trickling filters to guarantee NH_3 removal efficiency. Recent results from Kosch et al. (2005) are similar to the values found by Melse and Ogink (2005).

5.2. *Impermeable and permeable covers*

The simplest control method to mitigate NH_3 emissions from storage and treatment systems open to the atmosphere is to use a physical cover to contain the emissions. Impermeable covers, which trap gases released from such systems, are regularly used in conjunction with scrubbers or biofilters. The effectiveness of these covers depends not only on their trapping efficiency but also on the effectiveness of the scrubber or the biofilter with which they are used in combination. Permeable covers trap and bio-transform NH_3 just like biofilters, and include materials such as straw, cornstalks, peat moss, foam, geotextile fabric, and Leca® rock. The performances of impermeable and permeable covers are summarised in Table 5.

In comparison to the uncovered control, two impermeable covers, a floating film (two 2-mm-thick polyethylene film layers glued together) and a tarpaulin, effectively reduced NH_3 emissions from pig manure lagoons by 99.7% and 99.5%, respectively (Funk et al., 2004). Scotford and Williams (2001) reported a nearly 100% reduction in NH_3 losses from a pig slurry lagoon covered with a floating 0.5-mm-thick reinforced ultraviolet light-stabilised opaque polyethylene cover. Funk et al. (2004) reported effective control of NH_3 emission using an air-supported 0.35-mm-thick vinyl-coated fabric cover installed on an earthen-embanked pig lagoon, but experienced major challenges in controlling the gas leakage. Ammoniacal-N is not soluble in oil; therefore, thin layers of oil (oil films) can also create impermeable covers over stored manure slurries. Heber et al. (2005) evaluated the efficacy of soybean oil sprinkling in NH_3 emission mitigation in tunnel-ventilated pig finishing barns. The oil-treated barn yielded 40% less NH_3 emission than the control barn. Better results were reported when a layer of vegetable oil was placed on the surface of manure liquid/slurry. Guarino et al. (2006) reported a reduction of NH_3 emissions between 79% and 100% when 3- and 9-mm-thick layers of vegetable oil were applied on stored pig and cattle slurries. Portejoie et al. (2003) reported similar NH_3 emission reductions (93%) with a 10 mm oil layer. Other laboratory and on-farm studies with a 6 mm rapeseed

Table 5 – Summary of the performances of permeable and impermeable covers in abating ammonia emissions from livestock manure storages

Cover type (s)	Emission reduction (%)	References
Polyethylene	80–100	Funk et al. (2004), Scotford and Williams (2001), Miner et al. (2003)
Tarpaulin	99.5	Funk et al. (2004)
Oil films	40–100	Heber et al. (2005), Guarino et al. (2006), Portejoie et al. (2003), Hornig et al. (1999)
Geotextile cover	44	Bicudo et al. (2004)
Straw covers	37–90	Clanton et al. (2001), Sommer et al. (1993), Hornig et al. (1999), Guarino et al. (2006), Xue et al. (1999), Miner and Pan (1995)
Surface crust, peat, & PVC foil	24–32	Sommer et al. (1993)
Leca rock	14–87	Sommer et al. (1993), Balsari et al. (2006)
Polymer composite	17–54	Zahn et al. (2001)
Pegulit	91	Hornig et al. (1999)
Wood chips	17–91	Guarino et al. (2006)
Corn stalks	37–60	Guarino et al. (2006)
Zeolite on permeable cover	90	Miner and Pan (1995)
Polystyrene foam	45–95	Miner and Suh (1997)

oil layer indicated control of NH_3 emissions by up to 85%, while a thinner 3 mm layer was ineffective (Hornig et al., 1999).

A permeable geotextile cover installed on pig manure storage facilities resulted in a 44% reduction in NH_3 emissions, but the cover performance deteriorated after 1 year (Bicudo et al., 2004). Clanton et al. (2001) reported 37%, 72%, and 86% reductions in NH_3 emissions from pig manure storage using 100-, 200-, and 300-mm-thick straw covers, respectively, supported on a geotextile fabric. The permeable geotextile fabric itself did not have a significant effect on NH_3 emissions without a straw layer. Compared to uncovered cattle and pig slurry, surface crust, peat, straw, PVC foil, and Leca® rock achieved 24%, 32%, 60%, 26%, and 14% maximum NH_3 emission reductions, respectively (Sommer et al., 1993). Zahn et al. (2001) reported a 54% reduction of NH_3 emissions from a lagoon covered with an acclimated proprietary polymer composite bio-cover. Compared to an uncovered control, Hornig et al. (1999) reported an NH_3 emission reduction of 80–91% with straw and Pegulit (a natural mineral buoyant material) covers. Development of a surface crust in stored cattle manure was as effective as a 150 mm layer of straw, and reduced NH_3 emissions by as much as 20% (Sommer et al., 1993). Guarino et al. (2006) reported effective NH_3 emission reduction from pig and cattle slurry with an adequate cover thickness of wheat straw, wood chip, and corn stalk. With 140-mm-thick straw, wood chip, and corn stalk covers, NH_3 emissions reductions were 100%, 91%, and 60%, respectively. However, by using 70-mm-thick covers, the respective NH_3 emission reductions were only 59%, 17%, and 37%. In laboratory studies, Xue et al. (1999) reported that 50–100 mm straw covers reduced NH_3 emissions by 90% from dairy manure storages. Miner and Pan (1995) reported permeable covers configured with straw, zeolite, or a combination of both, and effectively reduced NH_3 emissions by 90% from manure storage. A permeable polystyrene foam cover was reported to reduce NH_3 emissions by 45–95% in manure storages (Miner and Suh, 1997). In other laboratory and field studies, Miner et al. (2003) reported NH_3 emission reductions from pig slurries of about 80% using a 50-mm-thick permeable polyethylene foam lagoon cover. Balsari et al. (2006) evaluated a low-cost cover (Leca® balls layer) for NH_3 emission abatement from pig slurry storage and observed a significant NH_3 emission reduction (up to 87%) with a 100 mm layer of Leca® balls.

Impermeable covers are generally more effective (up to 100%) than permeable covers in NH_3 mitigation strategies from manure storage. However, costs for covers vary widely depending on the material used and the method of application. The length of time the covers will be in place is an important consideration. Removal and clean-up of the material left behind when the useful life of the covers is over are equally important. In addition, if no biofilters are used to clean up the trapped gases under impermeable covers, excessive NH_3 and other gaseous emissions may occur during land application. Massey et al. (2003) evaluated the economics of installing impermeable lagoon covers on pig farms, and showed that at a market price of \$55.88 to \$75.18 tonne^{-1}, the initial purchase price of the cover was the biggest hurdle. The second major hurdle was the availability of more land base to receive the conserved N, which could be about 3.5 times larger than open lagoons.

6. Land application strategies

Significant NH_3 volatilisation can occur when manure is surface-spread to fertilise crop and pasture fields. Minimising time of manure exposure on the surface of the ground is the most effective strategy for reducing NH_3 emissions during or after field application of manure. Direct injection, prompt ploughing-in, increased infiltration, and washing-in after applications are some of the methods available to limit this exposure time. Combining these improved field application techniques with other NH_4^+-holding techniques, such as use of additives, improves the NH_4^+ utilisation efficiency of crops and pastures, which further decreases NH_3 loss. A summary of the efficacy of various application strategies in reducing NH_3 emissions is given in Table 6.

In practice, direct injection or immediate incorporation of manure into the soil reduces NH_3 losses better than other application methods. Direct injections to within 30–300 mm depths reduced NH_3 volatilisation by 47–98% compared to surface applications (Hoff et al., 1981; Thompson et al., 1987; van der Molen et al., 1990; Svensson, 1994; Rubaek et al., 1996; Morken and Sakshaug, 1998; Smith et al., 2000; Sommer and Hutchings, 2001). Where direct injection or immediate incorporation is not an option, other surface placement methods such as band spreading, trailing shoe, and shallow slot injection are more effective than surface broadcasting. These practices have been reported to reduce NH_3 losses by between 39% and 83% compared with surface broadcasting (Thompson et al., 1990a; Svensson, 1994; Frost, 1994; Smith et al., 2000). Some of these researchers (Thompson et al., 1990a; Svensson, 1994), however, have pointed out that, with time, band spreading is not much more effective than surface broadcasting.

Research has also shown that NH_3 losses from surface-applied slurry are inversely related to infiltration. One method of increasing manure infiltration into the soil is manure dilution with water. Manure slurry diluted about 100% with water (from 10% to 4.5% dry matter) has been observed to reduce NH_3 losses by 44–91% (Sommer and Olesen, 1991; Stevens et al., 1992; Frost, 1994; Morken and Sakshaug, 1998). Another method of increasing infiltration is cultivating the soil surface or increasing the surface roughness. Cultivating the soil surface before surface application of slurry reduced NH_3 losses by between 40% and 90% compared to uncultivated soils (Sommer and Thomsen, 1993). A similar method of increasing infiltration is cultivating the top 60 mm of the soil to mix applied slurry with soil. This manure–soil mixing reduces NH_3 loss by as much as 60% compared to surface application (Van der Molen et al., 1990). An other research has shown infiltration is also higher at low soil moisture contents, and slurry application at lower soil moisture reduces NH_3 loss by as much as 70% (Sommer and Jacobsen, 1999). The inverse relationship between NH_3 loss and the rate (volume/time/area) of slurry application suggests that intermittent slurry application might also reduce NH_3 loss because of improved infiltration (Thompson et al., 1990b).

Ammonia losses from manure applied during crop growth periods may be reduced by using trail hoses, which apply the slurry onto the soil between rows of plants (Bless et al., 1991; Holtan-Hartwig and Bockman, 1994) or by using a trailing shoe (Smith et al., 2000). The reduced NH_3 loss is attributed to immediate absorption of NH_4^+ by plant leaves and roots, reduced slurry exposed surface, and canopy-modified microclimate not favourable for NH_3 volatilisation (Holtan-Hartwig and Bockman, 1994; Thompson et al., 1990a, b).

Atmospheric conditions play an important role in NH_3 loss reduction during slurry application. Sommer et al. (1991) reported a linear increase in NH_3 volatilisation between 0 and 19 °C during a 24-h period. In the same study, NH_3 loss increased significantly when the wind speed increased to 2.5 m s^{-1}, but no consistent increase in NH_3 loss was recorded between wind speeds of 2.5 and 4.0 m s^{-1}. In an earlier study, increasing the wind speed from 0.5 to 3.0 m s^{-1} increased NH_3 loss by about 29% in 5 days (Thompson et al., 1990b). These observations suggest that manure applications should be scheduled for calm conditions.

Table 6 – Summary of livestock manure application strategies for abatement of ammonia emissions

Application strategy	Emission reduction (%)	References
Direct injection	47–100	Hoff et al. (1981), Thompson et al. (1987), Rubaek et al. (1996), Morken and Sakshaug (1998), Smith et al. (2000), Thompson and Meisinger (2002), Svensson (1994), Van der Molen et al. (1990), Huijsmans et al. (2003), Hansen et al. (2003)
Slot injection	80–92	Morken and Sakshaug (1998), Frost (1994), Huijsmans et al. (2001)
Band application	0–65	Thompson et al. (1990a), Smith et al. (2000), Morken and Sakshaug (1998), Huijsmans et al. (2001)
Trailing shoe	43	Smith et al. (2000)
Slurry dilution	44–91	Morken and Sakshaug (1998), Frost (1994), Sommer and Olesen (1991)
Low soil water content	70	Sommer and Jacobsen (1999)
Soil surface cultivation	40–90	Sommer and Thomsen (1993), Van der Molen et al. (1990), Huijsmans et al. (2003)

In practice, direct manure injection or manure incorporation into the soil adds to the costs of manure application. However, the cost of injection or manure incorporation into the soil during land application to reduce NH_3 emissions may be recaptured in terms of better crop yields due to a more efficient utilisation of the applied manure. Considering other environmental benefits accruing from reduced NH_3 loss, as well as costs that may be incurred in legal conflicts due to NH_3 emissions, these practices can be economically justified.

7. Summary and conclusions

Reducing N excretion through dietary changes can effectively mitigate NH_3 emissions from livestock operations. In ruminants, reducing the CP intake by as little as 5% and supplementing diets with amino acids can reduce NH_3 emissions by as much as 74% from excreted manure. For non-ruminants, similar NH_3 emission reductions have been observed by replacing CP with amino acids, which shifts N excretion from urine to faeces.

All of the urine–faeces segregation methods evaluated and reviewed have reduced NH_3 emissions from livestock barns by about 50% compared to the conventional manure handling systems. Therefore, the critical factors that need to be considered in making the choice of method for separating urine from faeces from these method are the cost of installing the system, maintenance, and ease versus cost of operation. The closely related use of urease inhibitors for control of NH_3 emissions in CAFO has been somewhat successful at the laboratory level, but there is no pilot- or full-scale application reported in the literature. The lack of information of its efficacy at pilot- or full-scale facilities may partly explain why urease inhibitors have not been employed for on-farm control of NH_3 emissions. This lack of adoption may also be attributed to the unknown effects of these chemicals on the crops or pastures where the treated manures are ultimately utilised.

Acids and acidifying salts are effective at holding NH_3 in NH_4^+ form. However, strong acids reduce slurry pH more cost-effectively than the weaker acids and acidifying salts. In addition, because strong acids are more hazardous for use on the farm than acidifying salts and weaker acids, although the latter are less effective than the strong acids, they are more suitable for use on-farm. Among ammonia-binding amendments, zeolite and sphagnum moss are more effective for reducing NH_3 loss in manure slurries or liquid than in solid poultry manures. Saponins do not seem to as effective as either zeolite or peat moss in mitigating NH_3 emissions.

There are several other additives whose modes of operations are not known. It is important for producers to ensure that the effectiveness of these additives has been scientifically verified by independent and reputable institutions before they can adopt them for use in their facilities. Often, large amounts of the product are required and in most cases such as with the use of acid/acidic salts, precautions must be taken to safeguard the safety of livestock and farm workers. In addition, use of acids may result not only in an undesirable increase in the mineral content of the manure but also in the corrosion of equipment and structures. Selection of appropriate application methods for effective use of these additives is very important. Currently, there is a lack of standardised applications and evaluation protocols for these additives.

Impermeable covers are more effective than permeable covers in NH_3 mitigation strategies from manure storages. However, if no biofilters are used to clean up the trapped gases under impermeable covers, excessive NH_3 and other gaseous emissions may occur during land application. Although the biggest hurdle in the installation of impermeable lagoon covers on pig farms is the initial purchase price of the cover, another major consideration is availability of more land base required to receive the conserved N.

Biofilters exhibit a wide range of performances (9–100% effectiveness) in the removal of NH_3 in carrier air. This variability in effectiveness may be attributed not only to the wide range of biofilter materials but also to other factors such as maintenance of optimum moisture in the filter bed, the residence time of the air in the biofilter, the NH_3 load in the incoming air, and the status of the microbial community in the biofilter. However, these systems can effectively be used to mitigate NH_3 emissions from livestock operations. There is also a wide variation in the effectiveness of other NH_3 filters (scrubbers and trickling filters). Process control with pH and automatic water discharge were sufficient to guarantee NH_3 removal efficiency in acid scrubbers, while process control is required in biotrickling filters to guarantee NH_3 removal efficiency.

Although more costly, direct manure injection or manure incorporation into the soil are the most effective (up to 98%) methods for mitigating NH_3 emissions amongst methods of manure application to soil. However, the extra costs of injection or incorporating manure into the soil may be recaptured in terms of better crop yields because of more efficient utilisation of the applied manure. Direct injection or immediate incorporation into the soil may not only become attractive practices, but may also be economically viable considering other environmental benefits that will accrue from reduced NH_3 volatilisation, as well as costs that may be incurred in legally defending NH_3 releases.

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