

Impact of Separating Dairy Cattle Excretions on Ammonia Emissions

V. K. Vaddella, P. M. Ndegwa,* H. S. Joo, and J. L. Ullman Washington State University

About 80% of dairy cattle N intake is excreted in urine and feces. Urinary-N is about 75% urea, whereas fecal-N is mostly organic. Urinary-N (urea) can only be volatilized when it is hydrolyzed to ammonia (NH_3) in a process catalyzed by urease, which is predominantly found in feces. Minimizing contact between urine and feces may be an effective approach to reducing urea hydrolysis and subsequent NH_3 emissions. Previous studies have reported 5 to 99% NH_3 emissions mitigation within barns from separation of feces and urine. The objective of this study was to compare NH_3 emissions mitigation via separation of urine and feces in postcollection storage to a conventional scrape manure handling method where urine and feces are comingled. Laboratory scale studies were conducted to evaluate NH_3 emissions from simulated postcollection storage of three waste streams: (i) idealistically separated feces and urine (no contact between urine and feces), (ii) realistically separated urine and feces (limited contact of urine and feces), and (iii) conventionally scraped manure (control). From the results of these studies, NH_3 losses ranking in descending order was as follows: aggregate of realistically separated waste streams (3375.9 ± 54.8 mg), aggregate of idealistically separated urine and feces (3047.0 ± 738.0 mg), and scrape manure (2034.0 ± 106.5 mg), respectively. Therefore, on the basis of these results, the extra effort of separating the waste streams would not enhance mitigation of NH_3 losses from postcollection storage of the separated waste streams compared to the conventional scrape manure collection system.

EMISSION OF NH_3 from livestock operations is of particular concern because of its broader adverse environmental impacts. Negative impacts of NH_3 emissions include crop damage, odors, eutrophication, decreased animal and human health, and impairment of visibility due to the formation of aerosol haze (USEPA, 2009; Gay and Knowlton, 2005; Becker and Graves, 2004). Available data indicate that agricultural activities, in general, at regional and global levels contribute ~80% of total NH_3 emissions (USEPA 2002, Liang et al., 2002; Aneja et al., 2000; Sommer and Hutchings, 1995; Battye et al., 1994). For example, NH_3 emissions in Europe from agricultural activities are estimated to be responsible for ~90% of total anthropogenic NH_3 emissions (Buijsman et al., 1987). Similarly, NH_3 emissions in Asia from agricultural activities account for ~77% of total anthropogenic NH_3 emissions (Zhao and Wang, 1994). In the United States, NH_3 emission is currently regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and Emergency Planning and Community Right-to-Know Act. Under these statutes, a livestock operation emitting 45 kg d^{-1} of NH_3 or H_2S must report the release. Livestock operations, however, are exempt under CERCLA regulations during normal manure handling on farms. Exceptions to this exemption include breached lagoons or holding ponds, and manure spills. It is also likely that NH_3 (as a secondary source of $\text{PM}_{2.5}$) may soon be regulated under the Clean Air Act (Ndegwa et al., 2008). Consequently, it is crucial to evaluate and develop cost-effective methods that producers can choose from to mitigate NH_3 emissions from confined animal feeding operations (CAFOs) to comply with current and future legislation.

In ruminants, the conversion of feed-N into milk and meat are inefficient processes and approximately 75 to 80% of the feed-N intake is excreted in urine and feces (Moncrief, 1999). Urinary N is about 75% urea, whereas fecal N is mainly in the form of undigested organic N compounds (Tamminga et al., 1994; de Boer et al., 2002). Ammonia can be emitted at any point in animal feeding operations including: animal housing, solids-liquids separation units, manure storage facilities (under floor pits and anaerobic lagoons), and from manure application (for soil amendment) sites (Liang et al., 2002). Many approaches to mitigate NH_3 emissions have been proposed including: urine-feces separation, reducing

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*Corresponding author (ndegwa@wsu.edu).

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5585 Guilford Rd., Madison, WI 53711 USA

Biological Systems Engineering, Washington State Univ., P.O. Box 646120, Pullman, WA 99164. Assigned to Associate Editor Tim Clough.

Abbreviations: CAFO, confined animal feeding operation; CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act; CHPT, cyclohexylphosphoric triamide; ISF, idealistically separated feces; ISU, idealistically separated urine; PPDA, phenyl phosphorodiamidate; RSF, realistically separated feces; RSU, realistically separated urine; RSUF, realistically separated urine and feces; TAN, total ammonia nitrogen; TKN, total Kjeldahl nitrogen; TS, total solids; TVS, total volatile solids.

manure pH, NH₃ binding, biological treatments, appropriate building designs and manure management, emissions capture and treatment with filters and biofilters, and land application strategies (Ndegwa et al., 2008).

Ammonia volatilization occurs after urinary urea is hydrolyzed in biochemical processes catalyzed by urease, which is predominantly found in feces (Bussink and Oenema, 1998; Beline et al., 1998; Elzing and Monteny, 1997). Laboratory studies have shown that adding urease inhibitors such as cyclohexylphosphoric triamide (CHPT) and phenyl phosphorodiamidate (PPDA), which block urease hydrolysis, can be used to reduce NH₃ emissions by 38 to 70% (Varel, 1997). However, this method of controlling NH₃ emissions requires the addition of urease inhibitors to manure slurries at regular intervals. Because urea is only found in urine, and the urease enzyme that catalyzes urea hydrolysis is predominantly found in feces, it may be hypothesized that avoiding contact between feces and urine after excretion of these two compounds would mitigate NH₃ emissions from such excretions. Past studies have reported that reduction of NH₃ emissions ranging from 5 to 99% can be achieved by the separation of urine and feces in barns (Lachance et al., 2005; Stewart et al., 2004; Panetta et al., 2004; Braam et al., 1997a). No studies, however, have evaluated the impact of urine–feces separation on NH₃ emissions during postseparation storage of the separated urine or feces.

It is noteworthy that, even if absolute isolation between urine and feces is achieved, it is still possible that the urea in urine could still undergo hydrolysis since urease is ubiquitous in the environment. In real life, it is very difficult, if not impossible, to completely eliminate contact between urine and feces. In practice, urine–feces separation has been achieved using one of two methods. The first method uses a sloped conveyor belt that delivers feces to a manure pit. Urine flows down the slope into a separate pit (Lachance et al., 2005; Stewart et al., 2004). The second method uses a floor design that drains urine immediately into a pit after urination. Feces is scraped or washed into a separate storage area (von Bernuth et al., 2005; Swierstra et al., 2001; Braam et al., 1997a,b).

In realistic separation of urine and feces, the animal will usually urinate on the floor or the belt, which are commonly covered with previously excreted piles of feces. The urine then drains away from the feces onto the barn floor. In this scenario, a bit of the feces will be carried away by the urine and some of the urine remains on the feces. Hypothetically, therefore, the drained urine may have already picked up urease from feces, which will then accelerate urea hydrolysis during post-separation storage. On the other hand, the urea in the urine entrapped (or held) in the feces will also inevitably hydrolyze rapidly. In the idealistic separation of urine and feces, urine and feces are collected directly from the back of animals after excretion ensuring no contact between the urine and feces.

This study addressed two important questions: (i) the achievable NH₃ emission mitigation from realistic separation of feces and urine vis-à-vis the mitigation from idealistic urine–feces separation, and (ii) whether preventing any contact between urine and feces would delay or stop urea hydrolysis, given the fact that urine-urea hydrolysis may also be catalyzed by urease ubiquitous in the environment. This research further compared urine–feces separation techniques with scrape

manure system (the control) in regard to mitigation of NH₃ emissions from postcollection storage of dairy manure.

Materials and Methods

Fecal and urine samples used in this study were collected from randomly selected lactating cows at the University of Idaho research dairy farm. The Holstein cows were maintained under identical management and dietary regimes. Sampling procedures were approved by the University of Idaho Institutional Animal Care and Use Committee. Fecal material was either collected directly from the rectum or from the ground immediately after being voided and still fresh. The respective fecal samples were subsequently combined to form a single composite sample. Urine samples were collected by massaging the vulva and capturing the expelled urine in sanitized containers. Similar to the fecal samples, all urine samples were combined into one composite sample. Both fecal and urine samples were collected in the morning when cows were held for managerial purposes. The composite fecal and urine samples were immediately transported in a refrigerated container to the laboratory where they were kept frozen to minimize microbial degradation.

Simulated scraped manure, realistically separated urine (RSU), realistically separated feces (RSF), idealistically separated urine (ISU), and idealistically separated feces (ISF) components were prepared in the following manner. Frozen feces and urine were thawed under ambient conditions overnight before the preparation of the components and commencement of the experiments. Simulated scraped manure was constituted by mixing feces and urine in a ratio of 1.68:1 (1680 g feces and 1000 g of urine) on a weight basis. The feces to urine excretion ratio was previously determined as a daily average for lactating cows (Vander Pol et al., 2007, 2008; Morse et al., 1994). To simulate realistic separation of urine and feces, about 2.0 kg of urine was discharged over 3.36 kg of feces (1.0:1.68 ratio) and placed on a pan inclined at a 14% slope. Urine was poured from an approximate height of 1.25 m, the height of an average cow (Kertz et al., 1997), to simulate conditions encountered when a cow excretes urine on previously deposited feces. A clean container was used to collect 500 g of the urine that drained from the pan (RSU), while 840 g of the fecal material remaining on the pan (RSF) was collected in a separate container. ISU and ISF were represented by 500 g and 840 g of the urine and manure samples, respectively, that were never brought into contact with each other.

To compare NH₃ emission rates over time between the post-collection storage of the respective waste streams, similar specially constructed apparatus consisting of a waste storage container, acid trap, flow meter to regulate air flow, and a vacuum pump to pull air through the system were used to collect emitted NH₃. Simulated scraped manure, RSU, RSF, ISU, and ISF were placed in separate waste storage containers in the quantities described above and sealed with tightly fitted lids. The vacuum pump drew air into the headspace of the waste storage containers through the respective acid traps at a controlled 1-L min⁻¹ air flow rate; an opening on the waste storage container open to the atmosphere allowed for replacement of the withdrawn air. Emitted NH₃ was collected in the acid trap that consisted of a 250-mL gas wash bottle containing 150 mL of 0.2 M sulfuric acid. This acid trap design was adopted from similar studies (Hristov et al., 2009;

Ndegwa et al., 2009; Misselbrook et al., 2005a; Shi et al., 2001). The study was conducted for 3 wk; acid traps were changed daily during the first week, every other day during the second week, and every third day during the third week. This disparate sampling scheme was used to account for higher NH₃ emissions at the onset that decreased over the course of the experiment. The samples collected from the acid traps were analyzed immediately for total ammonia nitrogen (TAN) concentration using standard methods (APHA 1992; APHA 1998). Ammonia emissions from each of the postcollection storages of ISU, ISF, RSF, RSU, and scrape manure were evaluated in triplicate. In addition, all studies were conducted simultaneously under temperature-controlled laboratory conditions (-17°C) to determine respective NH₃ emissions over the 3-wk duration.

Data Analysis

Data analysis of the NH₃ losses from the respective waste storage containers, which represented postcollection storage, was conducted on the basis of short-term (up to 14 d) and long-term (23 d) periods. Short periods (48 h, 7 d, and 14 d) were selected to evaluate urea hydrolysis (i.e., urease activities) and potential ammonia emission within the barn; whereas the long-term window allowed for a more thorough characterization of ammonia volatilization during actual postcollection storage. Linear regression was performed for each storage component using cumulative NH₃ emissions over time. NH₃ emission rates for the scraped manure, RSU, RSF, ISU, and ISF were compared. Cumulative average NH₃ losses for the different management types were calculated by summing the average daily NH₃ emissions determined for the study's duration (Table 1). The summary of NH₃ emissions from ISF, RSF, RSU, and scraped manure was on the basis of the mean of three replicates; whereas, the emissions from ISU were on the basis of the mean of two replicates. The third ISU replicate had very low urease activity resulting in very low NH₃ emissions during the 3-wk study period. Thus, this replicate was not included in the data analyses.

Results and Discussion

Details of the physical and chemical characteristics of RSF, RSU, ISU, ISF, and scrape manure total solids (TS); total

volatile solids (TVS); pH; TAN; and total Kjeldahl nitrogen (TKN) at the beginning and end of the studies are given in Table 2. At the beginning of the experiment, TAN in ISU and ISF were low. At the end of the study, both the test ISU and ISF had lower concentrations of TAN because of NH₃ loss via volatilization and probably also from limited conversion to other N species (NO₂⁻, NO₃⁻, or N₂) through nitrification-denitrification processes. Comparing the concentration of TAN at the beginning (4809 mg) and end (2029 mg) in the storage of scrape manure, a large fraction of potentially volatile TAN was still available at the end of the study. From the results presented, the loss of TAN from the ISF stream was the lowest at 76 mg (Table 1) during the 3 wk of postcollection storage, whereas about 67% (Table 2) of the initial TKN remained in feces at the end of the 3-wk study period. This is probably because the mineralization of organic N in the feces would take a longer time to convert into TAN.

Short-Term Studies

The results of cumulative NH₃ emissions from the respective storage of RSF and the scrape manure during the first 48 hr after excretion are shown in Fig. 1. Assuming that in a typical scrape where dairy manure scraping from the barn is done at least every 24 h, it is evident from these results that if the barn is designed to drain urine from the floor to the outside of the barn or animal housing, the feces (and any urine entrapped in the feces) remaining on the floor would release much less NH₃ than if the urine was not drained away (i.e., conventional scrape system). From the results of this study, draining urine away from feces within the barn can potentially reduce NH₃ emissions within the barn by approximately sixfold compared to the conventional scrape manure collection system. Therefore, on the basis of these results, it can be inferred that draining urine from the floors of barns immediately after excretion enhances mitigation of NH₃ emissions from the barn compared to the conventional scrape system. This concurs with previous studies that examined NH₃ mitigation within enclosed animal housing via urine-feces separation (von Bernuth et al., 2005; Panetta et al., 2004; Swierstra et al., 2001; Braam et al., 1997a, 1997b).

Ammonia emissions from the storage of RSU and RSF during the first 7 d of storage are shown in Fig. 2. Evidently,

Table 1. Average cumulative NH₃ emissions from the respective waste streams during the entire study period.

	ISF†	RSF†	ISU†	RSU†	Scrape manure
Cumulative NH ₃ emissions (mg)	76.1 ± 0.4	552.0 ± 44.3	2971.0 ± 738.0	2898.0 ± 88.0	2034.0 ± 106.5

† ISF, idealistically separated feces; RSF, realistically separated feces; ISU, idealistically separated urine; RSU, realistically separated urine.

Table 2. Characteristics of the respective waste streams at the beginning and end of the study.

Character	Initial†					End				
	RSF‡	RSU	ISU	ISF	Scrape	RSF	RSU	ISU§	ISF	Scrape
TS (mg/g)	1.73	0.57	0.41	1.98	1.35	1.97 ± 0.17	0.88 ± 0.16	0.62 ± 0.06	2.86 ± 0.30	1.44 ± 0.01
TVS (mg/g)	1.48	0.50	0.09	1.71	1.11	1.68 ± 0.19	0.52 ± 0.06	0.19 ± 0.06	2.26 ± 0.16	1.14 ± 0.01
pH	7.4	8.2	8.7	6.4	8.2	7.9 ± 0.1	9.7 ± 0	10.0 ± 0	6.3 ± 0	7.2 ± 0.1
TAN (mg)	1183	1506	219	256	4,803	273 ± 17.8	30 ± 7.8	9.0 ± 11.0	237 ± 18.7	2029 ± 107.0
TKN (mg)	5612	3670	4018	4136	10,796	3716 ± 306.6	611 ± 47.3	591 ± 817.4	2756 ± 339.3	6605 ± 468.2

† The three replicates were derived from 1 bulk sample of either urine, feces, or scrape manure at the beginning of the study (means and standard deviations not necessary).

‡ ISF, idealistically separated feces; RSF, realistically separated feces; ISU, idealistically separated urine; RSU, realistically separated urine.

§ Two replicates for the mean of ISU (i.e., $n = 2$; $n = 3$ for all the other means).

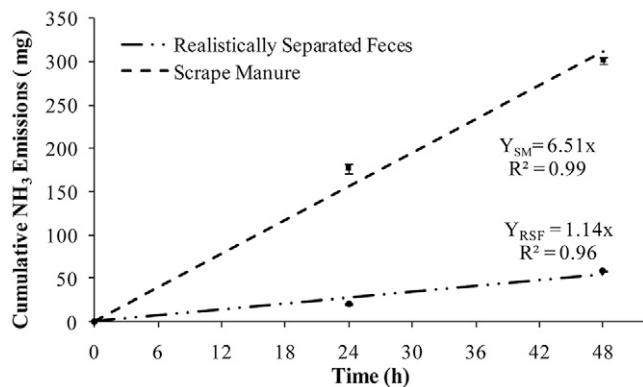


Fig. 1. Ammonia emissions from the realistically separated feces (RSF) and from the scrape manure (SM) in the first 48 hr after excretion.

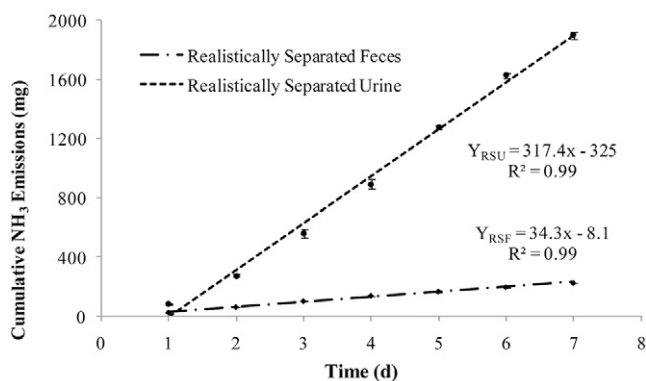


Fig. 2. Ammonia emissions within the first week from the realistically separated urine (RSU) and from the realistically separated feces (RSF).

the cumulative NH_3 emissions within this duration increased linearly with time as manifested in the high linear correlation coefficient (R) of 0.99. It can thus be inferred that the daily rates of NH_3 emissions from the two storage treatments (RSU and RSF) in the first week were constant. Within this first week of monitoring, the rate of NH_3 emission from RSU was more than nine times higher than the rate of NH_3 emission from RSF. This significantly larger rate of NH_3 loss from RSU could be the result of hydrolysis of urinary urea resulting from the initial feces-urine contact. Alternatively, NH_3 losses from RSF within this duration may be attributed to the hydrolysis of trace urinary urea that could have been entrapped in the feces while the rest of the urine drained away.

Profiles of cumulative NH_3 losses from storage of combined realistically separated urine and feces (RSUF) and scrape manure for the first 7 d of postseparation storage are presented in Fig. 3. Aggregate NH_3 loss from separate storage of RSU and RSF (loss from RSU + loss from RSF) were much higher than the NH_3 loss from the storage of scraped manure. The aggregate rate of NH_3 loss from the storage of RSU and RSF was approximately 3.5 times more than the loss from storage of scraped manure. It is quite evident that the majority of the loss from the storage of RSU and RSF is predominantly from the storage of separated urine, which is individually higher than the total loss from the storage of the scrape manure. A possible explanation for this observation is that the fecal solids material reduces the NH_3 mass transfer characteristics of NH_3 from liquid into air; thus, it inhibits NH_3 release from the scrape manure storage.

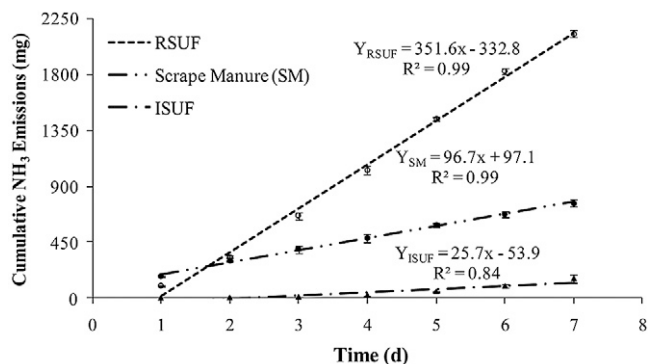


Fig. 3. Ammonia emissions from aggregate of realistically separated urine and feces (RSUF), aggregate of idealistically separated urine and feces, and conventional scrape manure (SM), within the first week.

In past research work, the dissociation constant (K_d) of NH_4^+ in dilute finishing swine manure with 1% TS and in concentrated chicken manure slurries have respectively been reported as being one-fifth and one-sixth that of NH_3 in water (Zhang et al., 1994; Hashimoto and Ludington, 1971), indicating possible mitigating effects of TS on NH_3 volatilization.

Details of cumulative NH_3 losses from storage of RSF and ISF within the first 2 wk are shown in Fig. 4a. It is clear that the rate of NH_3 loss from the storage of RSF is more than 20 times higher than that of the NH_3 losses from the storage of ISF. The latter observation indicates that after the urine has been drained away from the feces, some of the urine would be entrapped in the feces. This entrapped urine would quickly (minutes to a couple of hours) be hydrolyzed to NH_3 with assistance from urease present in the feces and subsequently released as NH_3 . In addition, NH_3 release is pH dependent. Generally the pH of urine is around 9 to 10, implying that the pH (6.4) of the feces (see Table 2) would be increased by the entrapped urine—a factor that could also increase NH_3 loss. The gradual NH_3 loss from ISF may be attributed to the slow breakdown rate of organic N by heterotrophic bacteria.

Profiles of short-term NH_3 losses from storage of RSU and RSF are shown in Fig. 4a and b. The rate of NH_3 loss from RSU is more than 12 times greater than that from storage of ISU in the first 7 d. This is probably because RSU had already picked up urease from the initial urine-feces contact, which immediately initiated and accelerated hydrolysis of urinary urea into NH_3 . In the first 7 d of storage, ISU had only marginally started losing some NH_3 (Fig. 4b). It appears that it would take at least 2 to 3 d for the urine to collect adequate mass of urease from the ambient environment to initiate discernable catalyses of urea hydrolysis.

Long-Term Studies

A comparison of NH_3 emissions from RSU and ISU for the entire study period is presented in Fig. 5a. Ammonia losses from RSU started right from the first day and continued throughout the first 2 wk, after which no further NH_3 loss was observed during the period of the study. The three replicate studies were fairly identical on the basis of the standard deviations from the mean of the three replicates (Table 1). On the other hand, NH_3 losses from two replicates of ISU showed completely different trends. We also had a third replicate, where very little NH_3 was

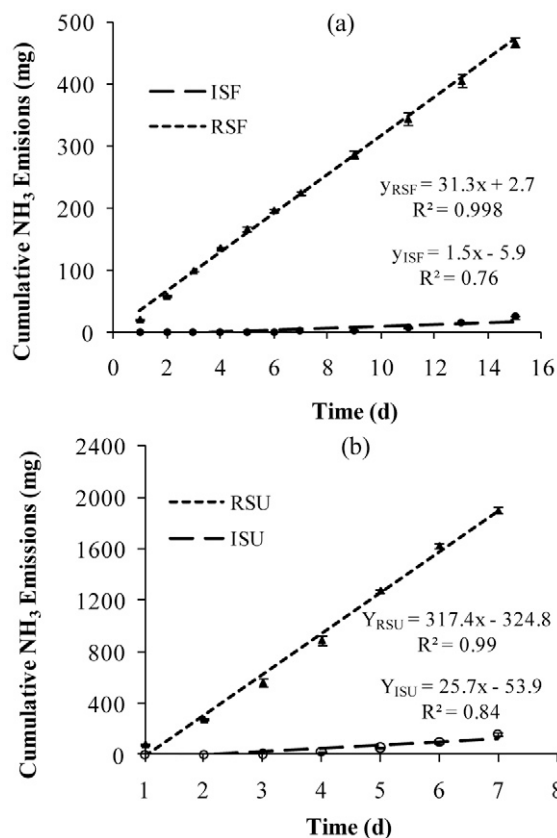


Fig. 4. Ammonia losses from (a) realistically separated feces (RSF) and idealistically separated feces (ISF) within first 2 wk; and (b) realistically separated urine (RSU) and idealistically separated urine (ISU) within first week.

lost (~750 mg over the 3-wk study period). Therefore, the third replicate was not included in data analyses. The authors believe the first replicate of ISU probably picked up the urease quicker than the second and third replicates because urease's presence in the environment is not evenly distributed. In general, the environmental conditions (temperature, pH, etc.) were the same in the laboratory. The earlier hydrolysis of urea in the first replicate explains the higher NH₃ loss within the 3-wk period. Ammonia loss from the first replicate was almost over by the end of the 23-d period, whereas the second replicate was evidently still losing NH₃. In general, however, from these results we could infer that NH₃ loss from the storage of ISU will be potentially higher than the NH₃ loss from the storage of RSU. A possible explanation for the higher NH₃ loss from ISU was the absence of fecal solids material to bind NH₃ or impede the mass transfer mechanism of NH₃. Another possible explanation is the higher pH of ISU (10.0) compared to that of RSU (9.7). In general, a higher pH increases the potential of NH₃ emissions.

The results of NH₃ emissions from storage of waste streams from these three scenarios are summarized in Fig. 5b. Given the same exposed surface areas for all storages, the NH₃ loss from the combined RSU and RSF was the highest during the first 3 wk of storage. The combined emissions of ISU and ISF from the postseparation storages would be the next highest. However, from the observations, initiation of NH₃ loss from ISU would be delayed for about a week (while acquiring ambient urease) but will eventually exceed that from the other two storages. In general, NH₃ losses in descending order were: real-

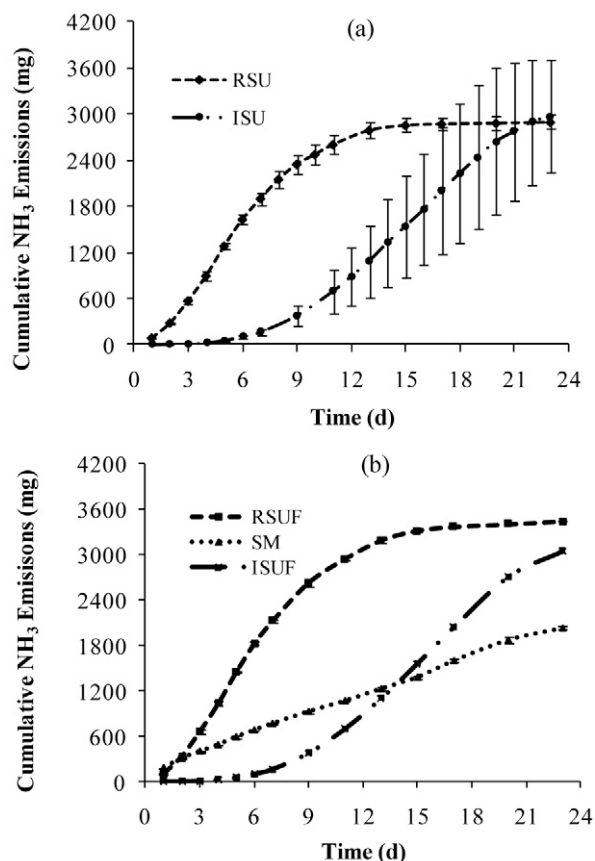


Fig. 5. Ammonia emissions from the (a) realistically separated urine (RSU) and idealistically separated urine (ISU); and (b) combined realistically separated urine and feces (RSUF), combined idealistically separated urine and feces (ISUF), and scrape manure storage (SM); over the entire study period.

istically separated urine and feces, idealistically separated urine and feces, and scrape manure storages. Therefore, on the basis of these studies, it is evident that avoiding contact between urine and feces would not necessarily result in more mitigation of NH₃ emissions. It appears that the effort of avoiding absolute contact of urine and feces will just delay the initiation of NH₃ loss by only a few days. In addition, extra efforts to separate urine and feces will result in more capital costs and operational costs for the producer. Thus, this study suggests that the conventional method of scraping cattle excretions from barns would be a better strategy for reducing NH₃ emissions from postcollection storages compared to the urine-feces separation approaches. Although urine-feces separation mitigates NH₃ emissions in barns based on our studies and previous studies (von Bernuth et al., 2005; Swierstra et al., 2001; Braam et al., 1997a, 1997b), the results from our studies also indicate that separation of urine and feces could potentially exacerbate NH₃ emissions during postseparation storages.

Summary and Conclusions

The overall goal of this study was to determine if urine-feces separation could mitigate NH₃ emissions during postseparation storage of the separated urine and feces. This study examined NH₃ emissions from three scenarios: (i) realistically separated urine and feces, (ii) idealistically separated urine and feces, and (iii) scrape manure (as the control). From the results of these

studies, NH₃ emission from postseparation storage of realistically separated urine and feces within the first week was greater than that from the storage of the idealistically separated urine and feces. However, the idealistically separated urine eventually lost NH₃ rapidly in the next 2 wk, resulting in higher NH₃ loss than from storage of the realistically separated urine and feces by the end of the third week.

Therefore, on the basis of these studies, it is evident that avoiding the contact of urine and feces would not necessarily result in reduced NH₃ emissions. It appears that the effort of avoiding absolute contact of urine and feces will just delay the initiation of NH₃ loss by only a few days. This study indicates that the conventional method of scraping urine and feces from the barn floor would be a better strategy for reducing NH₃ emissions from postcollection storage compared to urine-feces separation approaches.

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References

- APHA. 1992. Standard methods for the examination of water and wastewater. 18th ed. American Public Health Assoc., NW, Washington, DC.
- APHA. 1998. Standard methods for the examination of water and wastewater. 20th ed. American Public Health Assoc., NW, Washington, DC.
- Aneja, V.P., J.P. Chauhan, and J.T. Walker. 2000. Characterization of atmospheric ammonia emissions from swine waste storage and treatment lagoons. *J. Geophys. Res.* 105:11535–11545.
- Battye, R., W. Battye, C. Overcash, and S. Fudge. 1994. Development and selection of ammonia emission factors. EPA/600/R-94/190. Final report prepared for USEPA, Office of Research and Development.
- Becker, J.G., and R.E. Graves. 2004. Ammonia Emissions and Animal Agriculture. Available at <http://www.mawaterquality.org> (verified 7 July 2010).
- Beline, F., J. Martinez, C. Marol, and G. Guiraud. 1998. Nitrogen transformations during anaerobically stored 15N-labeled pig slurry. *Bioresour. Technol.* 64:83–88.
- Braam, C.R., J.J.M.H. Ketelars, and M.C.J. Smits. 1997a. Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Neth. J. Agric. Sci.* 45:49–64.
- Braam, C.R., M.C.J. Smits, H. Gunnink, and D. Swierstra. 1997b. Ammonia emission from a double-sloped solid floor in a cubicle house for dairy cows. *J. Agric. Eng. Res.* 68:375–386.
- Bussink, D.W., and O. Oenema. 1998. Ammonia volatilization from dairy farming systems in temperate areas: A review. *Nutr. Cycling Agroecosyst.* 51:19–33.
- Buijsman, E., H.E.M. Maas, and W.A.H. Asman. 1987. Anthropogenic ammonia emissions in Europe. *Atmos. Environ.* 21:1009–1022.
- de Boer, I.J.M., M.C.J. Smits, H. Mollenhorst, G. van Duinkerken, and G.J. Monteny. 2002. Prediction of ammonia emission from dairy barns using feed characteristics. Part 1: Relation between feed characteristics and urinary urea concentration. *J. Dairy Sci.* 85:3382–3388.
- Elzing, A., and G.J. Monteny. 1997. Modeling and experimental determination of ammonia emission rates from a scale model dairy-cow house. *Trans. ASAE* 40:721–726.
- Gay, S.W., and K.F. Knowlton. 2005. Ammonia emissions and animal agriculture. Virginia Cooperative Extension, Pub. 442–110.
- Hashimoto, A.G., and D.C. Ludington. 1971. Ammonia desorption from concentrated chicken manure slurries: Livestock waste management and pollution abatement. p. 117–121. *In* Proceedings of the Int. Symp. on Livest. Wastes. ASAE, St. Joseph, MI.
- Hristov, A.N., M. Vander Pol, M. Agle, S. Zaman, C. Schneider, P. Ndegwa, V.K. Vaddella, K. Johnson, K.J. Shingfield, and S.K.R. Karnati. 2009. Effect of lauric acid and coconut oil on ruminal fermentation, digestion, ammonia losses from manure, and milk fatty acid composition in lactating cows. *J. Dairy Sci.* 92:5561–5582.
- Kertz, A.F., L.F. Reutzel, B.A. Barton, and R.L. Ely. 1997. Body weight, body condition score, and wither height of prepartum Holstein cows and birth weight and sex of calves by parity: A database and summary. *J. Dairy Sci.* 80:525–529.
- Lachance, I., Jr., S. Godbout, S.P. Lemay, J.P. Larouche, and F. Pouliot. 2005. Separation of pig manure under slats: To reduce releases in the environment. Paper 054159. 2005 ASAE Annual Meeting, Tampa, FL. 17–20 July 2005. ASAE, St. Joseph, MI.
- Liang, Z.S., P.W. Westerman, and J. Arogo. 2002. Modeling ammonia emission from swine anaerobic lagoons. *Trans. ASAE* 45:787–798.
- Misselbrook, T.H., J.M. Powell, G.A. Broderick, and J.H. Grabber. 2005a. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence of ammonia emissions. *J. Dairy Sci.* 88:1765–1777.
- Moncrief, J.F. 1999. Generic environmental impact statement on animal agriculture: A summary of the literature related to manure and crop nutrients (J). Prepared for the Minnesota Environmental Quality Board. Available at www.eqb.state.mn.us/geis/LS_Manure.pdf (verified 12 July 2010).
- Morse, D., R.A. Nordstedt, H.H. Head, and H.H. Van Horn. 1994. Production and characteristics of manure from lactating dairy cows in Florida. *Trans. ASAE*, 37: 275–279.
- Ndegwa, P.M., A.N. Hristov, J. Arogo, and R.E. Sheffield. 2008. A review of ammonia emission mitigation techniques for concentrated animal feeding operations. *Biosyst. Eng.* 100:453–469.
- Ndegwa, P.M., V.K. Vaddella, A.N. Hristov, and H.S. Joo. 2009. Measuring concentrations of ammonia in ambient air or exhaust air stream using acid traps. *J. Environ. Qual.* 38:647–653.
- Panetta, D.M., W.J. Powers, and J.C. Lorimor. 2004. Direct measurement of management strategy impacts on ammonia volatilization from swine manure. Paper 044107. 2004 ASAE Annual Meeting, Ottawa, ON, Canada. 1–4 Aug. 2004. ASAE, St. Joseph, MI.
- Shi, Y., D.B. Parker, N.A. Cole, B.W. Auvermann, and J.E. Mehlhorn. 2001. Surface amendments to minimize ammonia emissions from beef cattle feedlots. *Trans. ASAE* 44:677–682.
- Sommer, S.G., and N. Hutchings. 1995. Techniques and strategies for the reduction of ammonia emission from agriculture. *Water Air Soil Pollut.* 85:237–248.
- Stewart, K.J., S.P. Lemay, E.M. Barber, C. Lague, and T. Crowe. 2004. Experimental manure handling systems for reducing airborne contamination of fecal origin. Paper 044132. *In* 2004 ASAE Annual Meeting, Ottawa, ON, Canada. 1–4 Aug. 2004. ASAE, St. Joseph, MI.
- Swierstra, D., C.R. Braam, and M.C. Smits. 2001. Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. *Appl. Eng. Agric.* 17:85–90.
- Tamminga, S., W.M. Van Straalen, A.P.J. Subnel, R.G.M. Meijer, A. Steg, C.J.G. Wever, and M.C. Blok. 1994. The Dutch protein evaluation system: The DVE/OEB system. *Livest. Prod. Sci.* 40:139–155.
- USEPA. 2002. Review of emission factors and methodologies to estimate ammonia emissions from animal waste handling (EPA/600/R-02/017 April 2002). National Risk Management, Research Laboratory, Research Triangle Park, NC.
- USEPA. 2009. Common manure handling systems. Available at <http://www.epa.gov/agriculture/ag101/dairymanure.html> (verified 7 July 2010).
- Vander Pol, M., A.N. Hristov, S. Zaman, N. Delano, and C. Schneider. 2008. Effect of inclusion of peas in dairy cow diets on ruminal fermentation, digestibility, and nitrogen losses. *Anim. Feed Sci. Technol.* 150:95–105.
- Vander Pol, M., A.N. Hristov, S. Zaman, and N. Delano. 2007. Peas can replace soybean meal and corn grain in dairy cow diets. *J. Dairy Sci.* 91:698–703.
- Varel, V. H. 1997. Use of urease inhibitors to control nitrogen loss from livestock waste. *Bioresour. Technol.* 62(1):11–17.
- von Bernuth, R.D., J.D. Hill, E. Henderson, S. Godbout, D. Hamel, and F. Pouliot. 2005. Efficacy of a liquid/solid isolation system for swine manure. *Trans. ASAE* 48:1537–1546.
- Zhang, R.H., D.L. Day, L.L. Christianson, and W.P. Jepson. 1994. A computer model for predicting ammonia release rates from swine manure pits. *J. Agric. Eng. Res.* 58:223–229.
- Zhao, D.W., and A.P. Wang. 1994. Estimation of anthropogenic ammonia emissions in Asia. *Atmos. Environ.* 28:689–694.