Nutrient Management from Feeds to Manure: Diet Manipulation to Alter Manure Outputs and Characteristics in Lactating Dairy Cows

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Summary

Manure management affects farm profits and potential environmental impacts of dairy production. Therefore, good management of manure is necessary for the sustainable dairy operation. Manure management costs can be reduced by lowering manure outputs when the herd size and production are maintained and by decreasing nutrient losses from manure, i.e., maintaining good manure values as fertilizer. To reduce environmental impacts of manure, lowering ammonia emission during manure storage is critical. Manipulating diets (ingredients and nutrient composition) can affect manure outputs and characteristics to some degree. Diet manipulation is an attractive strategy because it does not add additional costs for manure management if successful. Several effective dietary manipulations are available to lower manure outputs. Forages, diet fermentability, and protein levels can significantly influence manure outputs.Depending on producers' current rations, appropriate use of available strategies can reduce man ure outputs by 20 lb/cow a day without negative effects on production. The main purpose of altering manure characteristics by diet manipulation is to lower ammonia emissions during storage. This is difficult to accomplish and more studies are needed. However, including corn distillers grain with solubles in a ration or reducing dietary cation and anion difference may have potential and are introduced in this article.

Why Altering Manure Outputs and Characteristics?

Manure management is an important component in the dairy operation and influences sustainability of dairy production. The goals of manure management are to: 1) lower environmental impacts, such as gas emissions and nutrient losses, and 2) maintaining good quality of manure as fertilizer. These goals can be achieved simultaneously because lowering nutrient losses from manure (e.g., ammonia emission and nitrogen **(N)** and phosphorus **(P)** leaching and runoff) means maintaining nutrients in manure that are needed for crops.

There is limited information about the costs for manure management on dairy farms. Previously, a survey study was conducted (22 dairy farms) to investigate the cost of different types of manure management in dairy farms (Bentley et al., 2016). The largest factor that affected the cost of manure management was the herd size (i.e., manure output). Although the cost varies among different operating systems (e.g., tie-stalls and free-stall barns with sand, waterbeds/mattresses, dried manure solids, etc.), the average cost for manure management was estimated to be $306/cow per year. This suggests that reducing manure output without changing the herd size and production can increase producers' profits. Regardless of the cost, many producers may face the necessity of lowering

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total manure outputs at farms to maintain the herd size. This is because productivity of individual cows (milk yield) has increased over the last 60 years (USDA NASS, 2019; https://www.nass.usda.gov/Data_and_Statistics/index.php) and manure production per cow has also increased as production increased. The increase in manure production per cow occurred because the genetic selection was based on production without considering nutrient use efficiency. For example, cows in 1960 consumed 32 lb/day of DM and produced 40 lb/day of milk, but current cows consume 55 lb/day of DM and produce 90 lb/day of milk (Figure 1). Because total tract digestibility of dietary DM has not changed or is even lower for current cows (Potts et al., 2017), total manure produced at dairy farms has increased over the last decades if the herd size has been maintained. For those farms, increasing the capacity of manure storage or reducing manure outputs (somehow) is necessary. Strategies of diet manipulations to reduce manure outputs will be further discussed later.

The purpose of altering manure characteristics is to mainly decrease gas emissions, i.e., lowering environmental impacts (ammonia, greenhouse gases, and hydrogen sulfide), and to maintain good nutritional value of manure as fertilizer. As previously discussed, the average manure management cost was $306/cow per year, but when manure nutritional value is considered, the cost dropped to $104/cow per year (Bentley et al., 2016). Maintaining a good value of manure as fertilizer can positively influence farm profits and also lower environmental impacts. In this article, the author will mainly focus on altering manure characteristics to lower ammonia emissions because this is one of the major local environmental concerns (odor, air quality, soil acidification, and eutrophication) in dairy production, and ammonia emissions results in a significant decrease in nutritional value (i.e., N) of manure.

Reducing Manure Outputs

In most large farms, the amount of manure produced may be larger than needed for crops. Therefore, separating solid and liquid from manure and using dried solid manure as alternative bedding could be a strategy to lower manure volume and reduce farm expenses (Schwarz et al., 2010) because the price of bedding sources has significantly increased (Smith et al., 2017). However, installation of the separating equipment at farm could be a large investment and burdensome for producers. Dietary manipulation should be a good practical strategy with small or no additional cost to reduce manure outputs if successful. The major factor that affects manure production of cows is dry matter intake (**DMI;** Weiss et al., 2009). The relationship between manure outputs and DMI is shown in Figure 2. As shown in the figure, despite the strong linear relationship between DMI and manure outputs, cow-to-cow variation exists. For example, one cow that consumed 50 lb of DMI produced 176 lb of manure, but another cow that consumed the same amount of DMI produced 110 lb of manure. This indicates that there is potential to lower manure outputs of cows and this can be achieved to some extent by dietary manipulation. Previously, an experiment was conducted at The Ohio State University (Weiss et al., 2009) to examine the effects of type of forage (corn silage and alfalfa silage), type of carbohydrate, and levels of protein supply in diets on manure excretion, i.e., feces, urine, and manure. In this experiment, total collection of feces and urine was conducted for individual cows (36 cows; 18 dietary treatments; total 108 observations) and the results are summarized below.

The ratio of corn silage to alfalfa silage affected manure outputs. Increasing proportion of corn silage from 25 to 75% by replacing alfalfa silage (i.e., 75 to 25%) decreased urine outputs, lowering total manure excretion. When a diet with 75% corn silage is compared with 75% alfalfa silage, manure output was decreased by about 20 lb/cow a day. The reason that alfalfa silage increases urine output is because of potassium content. Alfalfa silage contains high potassium (about 3.5% DM basis) compared with corn silage (1.0%) so that increasing proportion of alfalfa silage replacing corn silage increases dietary potassium concentration. Increased intake of potassium increases urine excretion (Bannink et al., 1999). However, no effect of corn silage vs. alfalfa silage on fecal outputs was observed. Therefore, a 1% unit increase in corn silage (i.e., 1 % unit decrease in alfalfa silage) decreased 0.4 lb of manure in this experiment. Increasing starch concentration in a ration can also decrease manure output as well. Dietary starch concentrations examined in this study ranged from 22 to 30% (DM basis). Decreased manure outputs with increasing dietary starch level occurs mainly due to changes in diet fermentability. To increase dietary starch level, dietary NDF concentration usually decreased and total tract digestibility of starch is > 92% but that of NDF is about 45%. Therefore, when starch concentration increased from 22 to 30% (i.e., decrease in NDF from 35 to 27%), manure production was decreased by 18 lb/cow a day. This decrease in manure output was caused by decreased fecal excretion but urine outputs were not affected by starch contents. Therefore, a 1%-unit increase in dietary starch decreased 1.9 lb of manure. Dietary crude protein **(CP)** concentration can also influence manure output as well. In this study, dietary CP concentration from 14.9 to 17.7% (DM basis) was examined. However, because proportion of rumen degradable protein **(RDP)** was maintained at 10.8% of dietary DM, this study actually evaluated the effect of rumen undegradable protein **(RUP)** or metabolizable protein (**MP** from 8.8 to 12%) rather than dietary CP. Increasing RUP with maintaining RDP supply altered both fecal and urine outputs but did not affect manure outputs in this study. This was because increasing RUP increased urine output but decreased fecal output. Increasing dietary CP, RDP, or RUP concentrations usually increases urine outputs (Broderick, 2003; Appuhamy et al., 2014) because it increases urinary N excretion and increases the volume of water to maintain osmolality. In addition, RDP usually has a greater impact on urine output compared with RUP (Reynal and Broderick, 2005; Nennich et al., 2006). Changes in fecal outputs by dietary RUP was observed in the study. However, changes in fecal outputs by dietary CP depends on nutrients replaced to alter dietary CP concentration. In the study by Weiss et al. (2009), fecal outputs increased with increasing RUP because it increased in expense of NDF (protein is more digestible than NDF). However, dietary CP concentration can be adjusted with starch [e.g., increasing soybean meal **(SBM)** in expense of corn grain], and if this is the case, changes in fecal outputs are usually not significant (Broderick, 2003). Therefore, manure outputs can be reduced by lowering dietary CP via reduced urine outputs. Weiss et al. (2009) observed a decrease in urine output by 8 lb/cow with reducing dietary CP from 17.7 to 14.9% (i.e., MP from 12 to 8.8%). However because deficient protein supply negatively affects production (Lee et al., 2011), dietary CP should be reduced when excessive (e.g., 18% to 16% CP; this is not applied to fresh cows). If dietary CP decreases by increasing starch, not NDF, then fecal outputs should not be affected and manure outputs can be decreased.

The dietary manipulation introduced above is summarized in Table 1. The strategies are effective and easy to apply at farms with minimal or no additional costs. If these strategies are used properly (not extreme changes), about 20 lb/cow of manure a day can be possibly reduced (e.g., daily 4,000 lb of manure at farm with 200 lactating cows) without negatively affecting production.

Lowering Manure N and P Excretion

When environmental impacts of manure nutrients are considered, manure N and P are the 2 major nutrients that can cause public concerns. This is because when significant amounts of N and P are lost from the field, P can cause eutrophication and production of harmful algae bloom in water and N can contaminate air, soil, and water via volatilization, leaching, and runoff (USEPA, 2004). The largest factor that influences N and P excretion in manure is N and P intake, respectively. Increasing dietary N and P concentration increases manure N and P excretion (Nennich et al., 2006; Alvarez-Fuentes et al., 2016). Therefore, the simple but most effective strategy to lower N and P excretion in manure could be to lower dietary N and P concentration. However, because deficiency of dietary protein and P negatively affect production of cows (Lee et al., 2011; Puggaard et al., 2014), the recommendation is to formulate a diet for adequate protein and P supplies and avoid excessive supply. Protein concentrations of 15.5 to 16.5% CP can provide adequate protein (depending on production levels and feed ingredients) to lactating cows (not the fresh cows) and P concentration should be no more than 0.4% (DM basis) according to NRC (2001). To further reduce manure N excretion from manure, a protein deficient diet (protein supply below the requirement) was also examined (Lee et al., 2012b). However, because production is almost always compromised when protein supply is deficient, supplementing a deficient protein diet with rumen protected limiting amino acids (Met, Lys, and His) was necessary to maintain production (Lee et al., 2012a; Lee et al., 2012c).

If the quality of manure as fertilizer is considered, reducing dietary protein concentration described above may not be an ideal strategy because it decreases manure N concentration. In a typical dairy manure storing practice (i.e., storing manure in a lagoon for months before field application), actually no matter what level protein diet is fed, N content in aged manure (i.e., manure at the time of field application) should be about the same, i.e., similar N values as fertilizer. This is because changes in dietary protein concentration largely changes urinary N excretion (relative to fecal N excretion) and the major source of N that is easily and rapidly volatilized as ammonia from manure is urinary N (i.e., urea), and N losses via ammonia volatilization during manure storage are considerable. The considerable loss of N through ammonia emissions results in a large imbalance of nutrients in aged manure at the time of field application. This imbalance of nutrients in manure reduces the manure value as fertilizer and application of this manure may increase risk of nutrient losses from the field, contaminating the environment. For example, N losses through ammonia emission alters the ratio of N:P in manure. Fresh dairy manure contains N and P with a ratio of 7:1 (when a diet adequate in protein and P is fed) which is close to the ratio of N:P required for corn (this depends on soil N and P concentration), i.e., corn requires 1 unit of P when 6 units of N are taken. However, the ratio of N:P in aged manure becomes 3:1 at the time of application after considerable ammonia emissions during storage. If a producer applies this manure to meet both N and P for crops, excessive P will be applied and this increases risk of P losses from the field. Although the manure application rate is based on P supply to meet the requirement of crops, this will result in deficient N supply to crops and P may not be utilized effectively due to low N available, still increasing risk of P losses from the field. Therefore, the ideal strategy for manure management is to maintain a good balance of nutrients until the time of application, for which altering manure characteristics to lower ammonia emissions from manure during storage is the key.

Altering Manure Characteristics

The main interest in altering manure characteristics in this article is to lower ammonia volatilization from manure during storage. Various physical treatments to manure have been investigated (Hristov et al., 2011a). For example, treating manure with a urease inhibitor is an effective method. A urease inhibitor was originally designed to co-apply with commercial N fertilizer (urea) to lower ammonia volatilization after application and this strategy has been known to be effective for manure as well (Hagenkamp-Korth et al., 2015). However, in our preliminary study, the urease inhibitor activity of one particular product was effective only for a short period of time (< 24 h) after application (Figure 3). This suggests that frequent application of the urease inhibitor is required for effective ammonia emission abatement. Acidifying manure with strong acids is probably the most effective method to reduce ammonia emission where ammonia emissions can be reduced by 95% (Fangueiro et al., 2015). However, handling strong acid to apply to manure on a daily basis requires trained workers and is dangerous. Covering lagoons also has been introduced as an effective method (Guarino et al., 2006). Although the main purpose of covering a lagoon is to produce biogas, this is effective in lowering ammonia emission during storage as well. However, all these strategies above require costs to maintain the management system; acids and urease inhibitors are purchased to apply regularly and materials covering manure are expensive and have a lifespan (Lupis et al., 2012). Any strategies that increase expenses for manure management may not be preferred by producers. In this aspect, dietary manipulation to alter manure characteristics and then ammonia emissions from manure could be an attractive approach because it requires no or minimal costs. However, studies about diet manipulation to alter manure characteristics and ammonia emissions are limited. Although effective, the strategy is not as effective as physical manure treatments discussed above (acidification, urease inhibitor, and covering manure). However, the goal of diet manipulation is not 80 to 95% reduction of ammonia emission from manure as shown from physical manure treatments (e.g., acidification) but is reduction of ammonia emission by 20 to 40%. Potential strategies of diet manipulation are introduced in the following section based on our recent research.

Inclusion of corn distillers grain with solubles **(DG)** in a ration has potential to alter manure characteristics and lower ammonia emissions. Because of its high protein content (30 to 40% CP) and relatively low price, DG has been widely used as a protein source in lactation diets. However, because of its high fat content (12%) and polyunsaturated fatty acid (PUFA) content, caution on milk fat depression has been suggested (Benchaar et al., 2013). In our study, a diet containing 30% DG (DM basis) was compared with a SBM-based diet where nutritional composition in the diets was similar (17.5% CP, 31% NDF, and 21% starch on a DM basis). The experiment was conducted with 24 cows in a randomized complete block design (n = 12 per treatment). We observed production of cows for 9 weeks and feces and urine were collected in the last week of the experiment. Feces and urine collected were used to reconstitute manures for individual cows. Randomly selected 9 manures (i.e., 9 cows) per treatment were incubated for gas emissions over 10 days in a continuous flux chamber system (Lee et al., 2020). As a result, DG manure decreased ammonia emissions by about 40% compared with SBM manure, which was a considerable decrease (Figure 4, A). There were 2 mechanisms to explain the ammonia mitigation. Although dietary protein concentration was about the same between the SBM and DG diets, the concentrations of RDP and RUP were different where the inclusion of DG decreased RDP (from 10.7 to 9.9% of DM) and increased RUP concentration (7.0 to 7.8%) in the diet compared with the SBM diet. Therefore, the DG diet with low RDP decreased urinary N contribution from 60 to 55% and increased fecal N contribution from 40 to 45% to manure N (Table 2). Again, because manure N originating from urine is the major form of N for volatilization (i.e., urea), lowering urinary N contribution to manure N decreases ammonia emission. Furthermore, inclusion of DG in a ration increases dietary S content due to high S content in DG, which decreases DCAD in a diet. In this study, the 30% DG diet had 65 mEq/kg of DCAD vs. 192 mEq/kg for the SBM diet. This resulted in a decrease in urine pH for DG from 8.5 to 7.5 which may have reduced manure pH as well to some extent. Although we did not measure initial manure pH at the start of the incubation, manure pH after the 10-day incubation was still lower (7.2 vs. 7.5; P = 0.02) for DG vs. SBM manure. The summary of the experiment results is shown in Table 2. Although feeding the 30% DG diet decreased ammonia emissions by 40%, our conclusion was that this is not an ideal strategy because it decreased about 9 lb/day of energy-corrected milk and fat and protein yields (Morris et al., 2018). In addition, due to high S content in manure, it increased manure hydrogen sulfide emissions by 66% compared with SBM manure (Figure 4, B). Although hydrogen sulfide emitted from manure is not likely large (0.8 g/cow over 10 days) to affect animal and human health, hydrogen sulfide is one of the dangerous gases produced from manure (Costigan, 2003). Further studies with lower inclusion of DG (10 to 20% of dietary DM) are needed to evaluate a DG diet on manipulating manure characteristics. However, from this study, we observed potential that a diet with reduced DCAD could be a strategy to lower ammonia emission from manure by reducing manure pH.

When a lactation diet is formulated to meet the requirements of all minerals (adequate, not excessive), DCAD should be around 200 mEq/kg DM (± 50). Traditionally, increasing DCAD has been recommended using additional supplementation of Na or K from that level (Sanchez and Beede, 1996; Iwaniuk and Erdman, 2015). This is mainly because cationic salts can increase rumen buffering capacity, resulting in improving feed fermentation and reducing risk of acidosis. A meta-analysis by Iwaniuk and Erdman (2015) showed increases in DMI, milk yield, milk fat, and nutrient digestibility as DCAD increases (-68 to 811 mEq/kg DM), suggesting that decreasing DCAD may negatively affect performance of lactating cows. However, no negative production responses were also observed in some designed experiments when DCAD was reduced but still positive (Apper-Bossard et al., 2006; Wildman et al., 2007). Furthermore, previous studies showed that reducing DCAD to < 50 mEq/kg DM can lower urine pH to as low as 6.5 in dairy cows and lambs (Apper-Bossard et al., 2010; Luebbe et al., 2011), which could be sufficient to lower manure pH and ammonia emissions from manure. Therefore, we conducted another experiment with 27 mid-lactating cows in a complete randomized block design (Zynda et al., unpublished). Cows were fed a diet with DCAD of about 192, 101, or 1 mEq/kg DM. The basal diet consisted of 53% corn silage, 7% alfalfa silage, and 40% concentrate (16% CP, 32% NDF, and 27% starch; DM basis). In this experiment, DMI, milk yield, and milk protein yield were not affected by decreasing DCAD.

However, milk fat yield tended to decrease linearly (1.00 to 0.86 kg/d; $P = 0.08$) as DCAD decreased. As expected, urine pH for the low DCAD diet decreased from 8.4 to 6.4 ($P < 0.01$; Figure 5, A). However, although the low DCAD diet decreased ammonia emission by 15% over a 5-day manure incubation compared with control, the decrease was not statistically significant ($P = 0.15$; Figure 5, B). The impact of reduced DCAD on ammonia emission observed was lower than expected. Further investigation indicated that the ratio of feces to urine that was used to reconstitute manures was 2.9:1 on average in this experiment and this ratio is quite larger than the ratio for modern dairy cows (< 2:1; Weiss et al., 2009; Hristov et al., 2011b). Because we estimated urine volume for individual cows using urine creatinine concentration, it may have been underestimated. When N balance was calculated, we obtained about 40 g/day of N retained (N intake – fecal N – urine N – milk N), which is the upper end in the range, supporting possible underestimation of urine volume. In addition, feces and urine collected were frozen until manure incubation. When urine was thawed before manure incubation, pH of urine was greater by 0.3 unit compared with pH at collection, which alleviated the effectiveness in reducing manure pH as well. We concluded that feeding a low DCAD diet (< 50 and > 0 mEq/kg DM) in mitigating ammonia from manure still has great potential to lower ammonia emission. This conclusion is supported by our preliminary study (Zynda et al., unpublished) where urine pH was manually reduced from 8.5 to 7.5, 6.5, and 5.5 and manure was reconstituted with 2:1 of the feces to urine ratio. In this preliminary study, ammonia emission was decreased significantly ($P < 0.01$) by 20, 33, and 36% for urine pH of 7.5, 6.5, and 5.5 compared with 8.5 of urine pH (Figure 6). However, we observed a tendency for decreased milk fat yield and numerical decreases in milk yield, suggesting that the DCAD level of 1 mEq/kg DM was too low. Further studies are needed if there is appropriate low level of DCAD (e.g., 50 mEq/kg DM) to sufficiently reduce urine pH without affecting production.

Conclusions

Dietary manipulation is a practical strategy to alter manure outputs because this strategy is effective and adds no or minimal costs to apply at farms. An increase in proportion of corn silage replacing alfalfa silage and increase in starch level by lowering NDF concentration can significantly lower manure output. If dietary protein supply is excessive, it needs to be reduced to an adequate level by increasing starch, not NDF. This will also lower manure outputs. Appropriate use of these manipulations can reduce manure outputs by 20 lb/cow a day without negatively affecting production. The main goal of manure management is to lower ammonia emissions from manure during storage, which will lower environmental impacts (odor, air quality, and soil acidification) and increase manure values as fertilizer. Diet manipulation has potential to alter manure characteristics and reduce ammonia emission from manure. Inclusion of corn distillers grain with solubles can lower ammonia emissions from manure by reducing urinary N contribution to manure N and reducing manure pH. However, it may compromise production and inclusion greater than 20% is not recommended. Reducing DCAD in a diet also has potential to reduce urine pH and then manure pH, resulting in ammonia mitigation from manure. However, these strategies need more research to confirm their effectiveness without compromising production of cows.

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Table 1. Dietary factors that can lower manure outputs in lactating cows[1,2]

Dietary factors	**Feces**	**Urine**	**Manure**
Increasing corn silage replacing alfalfa silage	-	Down	Down
Increasing starch by decreasing NDF	Down	-	Down
Decreasing dietary protein by increasing NDF	UP	Down	-
Decreasing dietary protein by increasing starch	-	Down	Down
Decreasing dietary DCAD to 200 mEq/kg DM	-	Down	Down

[1]Part of data from Weiss et al. (2009)
[2]-, no change; Down, decrease; UP, increase.

Table 2. Effects of a SBM- or DG-based diet on fecal, urine, and manure outputs and manure characteristics before and after incubation.[1]

	Diets[2]			
	SBM	DG	SEM	*P* - value
Before incubation				
Feces, lb/day as-is	112	113	5.5	0.86
Feces, lb/day DM	17	17	0.8	0.69
pH	6.66	6.41	0.092	0.09
N, g/day	190.4	187.8	7.09	0.80
Urine, lb/day	69	61	3.5	0.02
pH	8.53	7.48	0.125	< 0.01
N, g/day	287.2	231.4	12.72	< 0.01
Manure	181	174	7.3	0.42
N, g/day	477.6	419.2	15.8	0.02
Fecal N contribution, %	40.5	45.3	1.46	< 0.01
Urine N contribution, %	60.5	55.5	1.172	< 0.01
After incubation				
Manure pH	7.47	7.24	0.096	0.02
Manure N, % DM	2.96	3.18	0.071	< 0.01

[1]Data from Lee et al. (2020).
[2]SBM, manure from a soybean meal-based diet; DG, manure from a distillers grains-based diet.

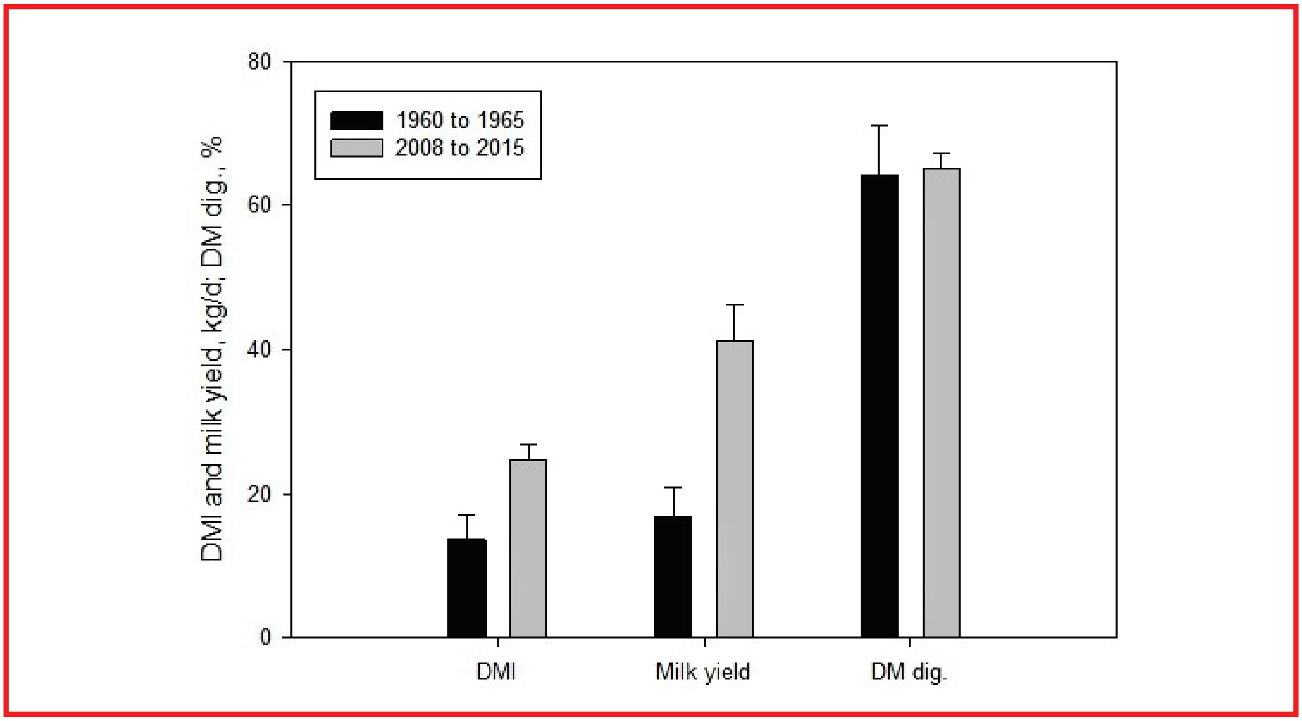

Figure 1. Comparisons of intake, milk yield, and total tract dry matter digestibility between cows in the past (studies with total collection published in Journal of Dairy Science from 1960 to 1965) and current cows (data from experiments at The Ohio State University from 2008 to 2015).

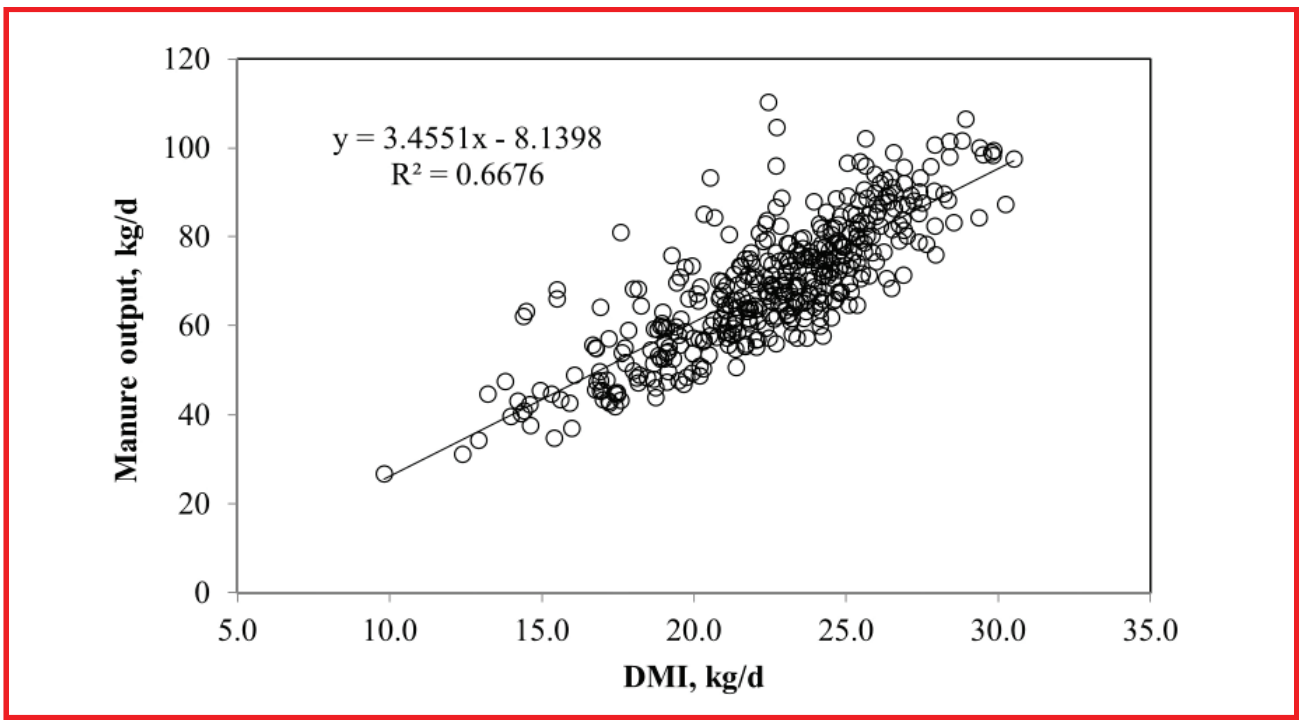

Figure 2. The relationship between manure production and dry matter intake. Data from total collection trials conducted at The Ohio State University were used (20 trials with various diets and 409 observations).

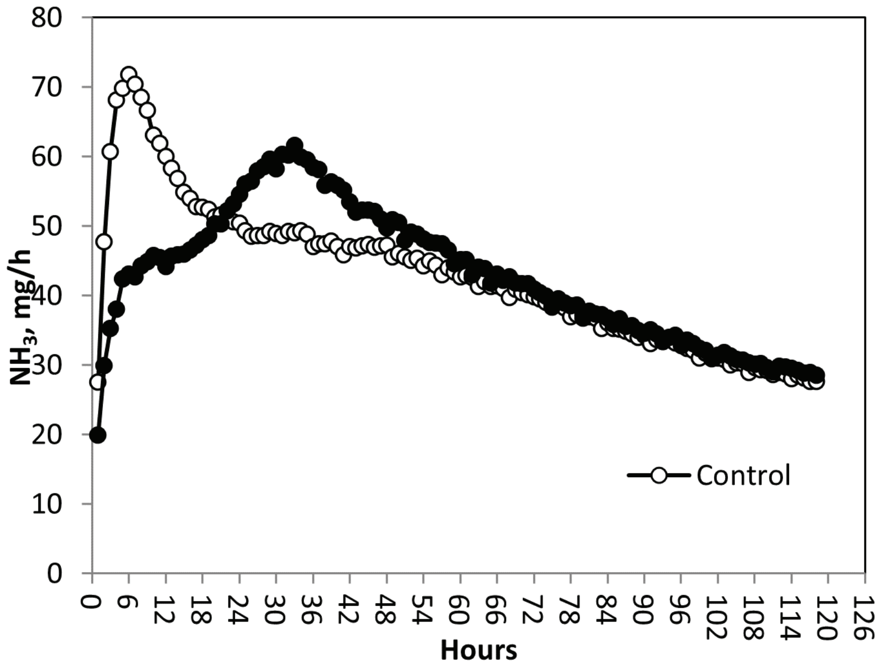

Figure 3. Ammonia emissions from dairy manure treated with or without a urease inhibitor.

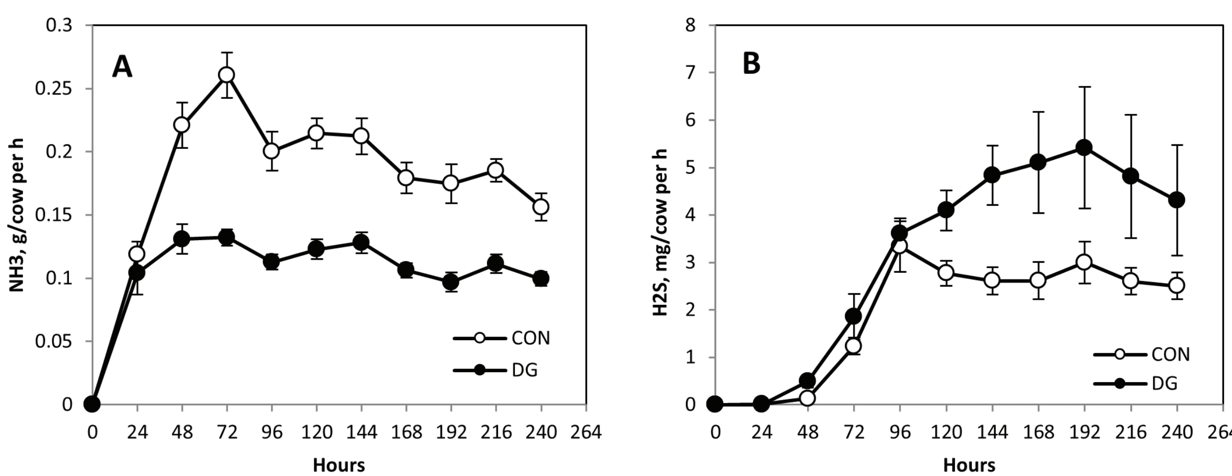

Figure 4. Ammonia (A) and hydrogen sulfide (B) emissions from manure of cows fed a diet containing soybean meal (CON) or corn distillers grains with solubles (DG) (30% of DM; Lee et al., 2020).

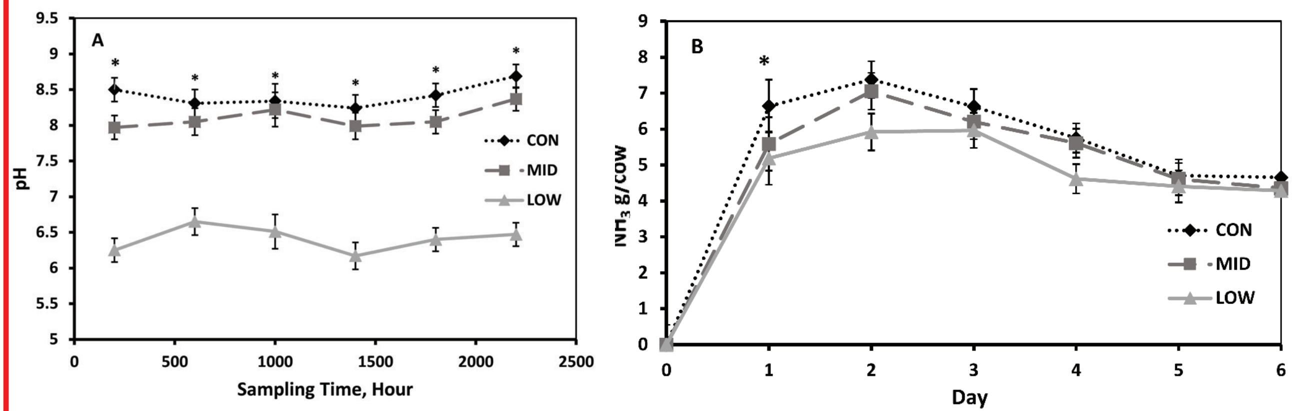

Figure 5. Urine pH (A) and ammonia emissions (g/cow) from manure (B) of cows fed a diet with DCAD of 200 (CON), 100 (MID), or 1 (LOW) mEq/kg DM (Zynda et al., unpublished).

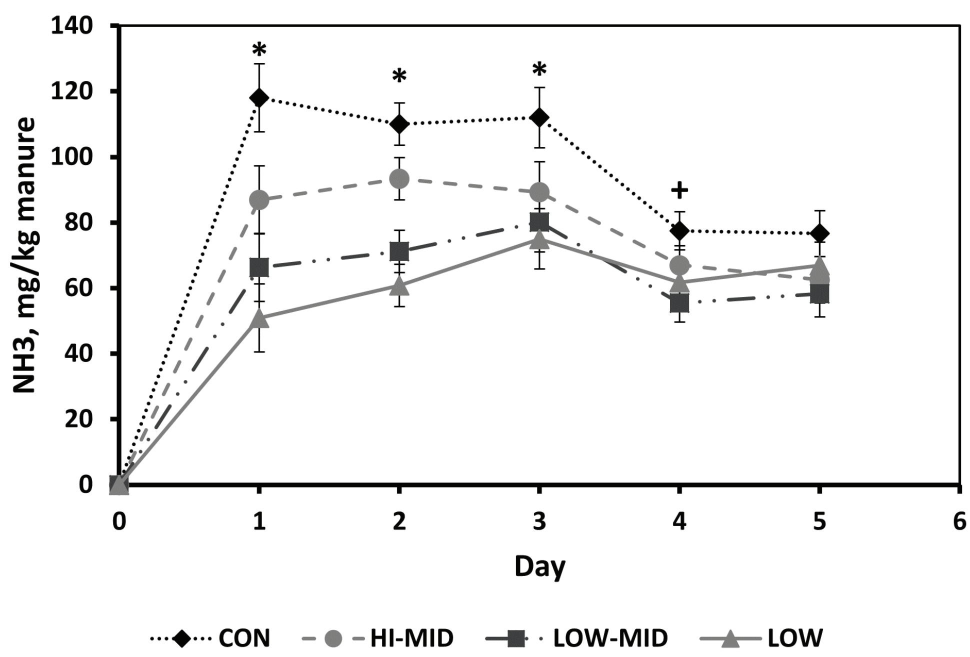

Figure 6. Ammonia emissions from manure with reduced urine pH. Urine pH was manually reduced from 8.5 (CON) to 7.5 (HI-MID), 6.5 (LOW-MID), and 5.5 (LOW) (Zynda et al., unpublished).