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Managing Manure Nitrogen to Reduce Losses

Definition of terms

Ammonia	NH_3 – an uncharged nitrogen gas molecule. It is formed from ammonium in manures and soils with a high pH.
Ammonium	NH_4^+ – a positively charged nitrogen molecule (dissolved in water) that binds to negatively charged soils and organic matter, reducing movement in soil.
Denitrification	The conversion of nitrate to nitrous oxide and dinitrogen, which occurs mainly in warm and wet soils.
Dinitrogen	N_2 – an uncharged nitrogen gas molecule that is very stable and benign. About 78% of the atmosphere near the Earth's surface is dinitrogen.
Nitrate	NO_3^- – a nitrogen molecule (dissolved in water) that is formed in soil by bacteria that oxidize ammonium (nitrification). As it is negatively charged, nitrate is soluble and can leach through the soil profile with water.
Leaching	The movement of water and its constituents (e.g., nitrogen) through the soil profile.
Mineralization	The conversion of organic nitrogen to inorganic plant available nitrogen.
Nitrification	The biological conversion of ammonium to nitrite and then to nitrate by bacteria.
Nitrous oxide	N_2O – an uncharged nitrogen gas molecule and one of the most potent greenhouse gases (265-298 times more effective than carbon dioxide in trapping heat) (IPCC 2014).
Urea	$(NH_2)_2CO$ – a water soluble nitrogen molecule. It is the main nitrogen component in urine, but it is also a commonly manufactured fertilizer. Urea is mobile in soil because it is not charged and rapidly disassociates into ammonium and carbon dioxide in the environment.
Volatilization	The loss of ammonia gas to the atmosphere.

Introduction

Manure is an important source of nutrients for crop production in dairy farms, but it can also contribute to losses of nitrogen (N) into the atmosphere, surface waters, and groundwater. Losses of N can pose health risks to humans and animals, contribute to environmental impacts, and cause economic losses to the farmer. Gaseous N losses of concern are ammonia and nitrous oxide. Ammonia can irritate the eyes and lungs in humans. It can also react with other compounds in the atmosphere to form particulate matter that can penetrate deep into the lungs. Ammonia emissions can also be deposited back onto the Earth's surface causing eutrophication of aquatic ecosystems (lakes and rivers), promoting algal growth and potentially affecting aquatic populations. In addition, deposited ammonia can be transformed to nitrous oxide, a greenhouse gas (GHG) that is 265-298 times more potent than carbon dioxide (IPCC 2014).

Gaseous N losses can occur from within the barn, during processing and storage, and after land application. In the barn, N from manure is mostly lost as ammonia through the process of volatilization. Manure processing can affect the form of N in the manure (organic N can be converted to ammonium), which could lead to greater N losses during downstream processes, such as storage and land application, without mitigation practices. During storage, N is mostly lost to the atmosphere through volatilization of ammonia and as nitrous oxide through the process of denitrification. After manure land application, gaseous N loss from soil can also occur through volatilization and denitrification. In addition, N can be lost through leaching, which represents a contamination risk to both surface and groundwater.

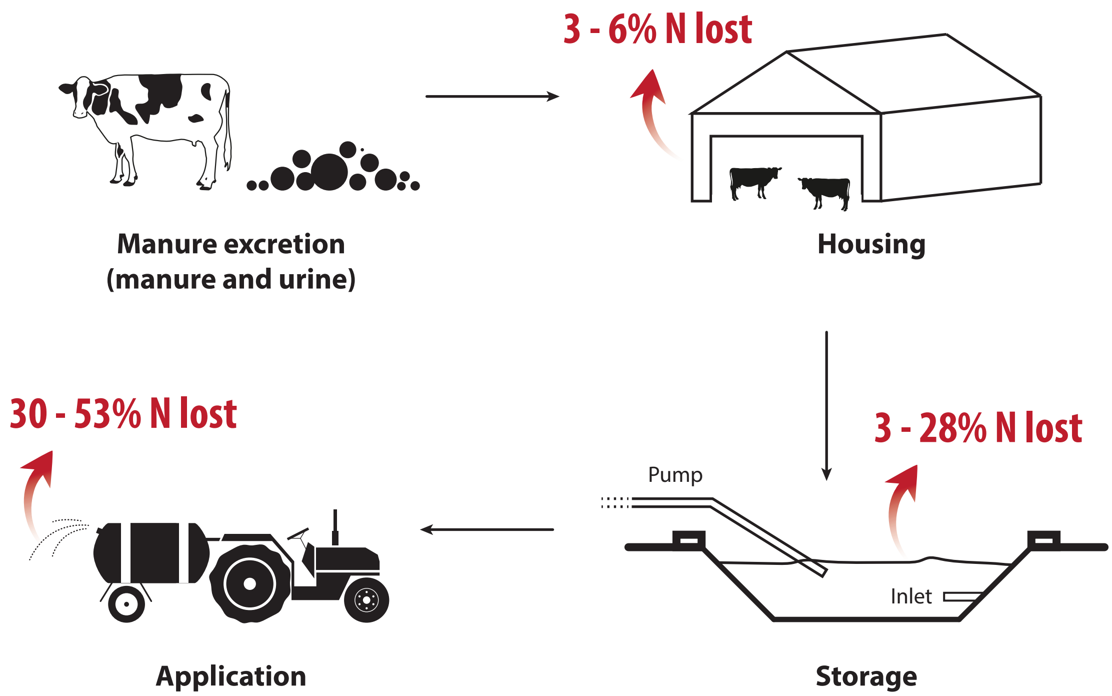

Figure 1. Average nitrogen emissions from manure management in dairy facilities (Adapted from Aguirre-Villegas et al. 2014).

Dairy producers can track manure N and its availability using nutrient management planning. Nutrient management planning can aid producers in determining manure application rates and additional fertilizer inputs needed to meet crop requirements. This allows producers to maximize crop yields while avoiding excess N applications. However, accurately predicting N availability in manure can be more challenging than predicting the availability of many other nutrients, such as phosphorus and potassium. This is because N can exist in many forms that can be lost to the atmosphere or water sources before it is applied to the land or before uptake by plants after land application. N losses can vary significantly by region and depend on farm practices. In permitted facilities in Wisconsin, these losses have been reported from 60-65% throughout manure collection, processing, storage, and land application (Figure 1) (Aguirre-Villegas et al. 2014). At current N fertilizer prices, this loss translates to an annual loss of nearly $100 per cow.

Ammonia emissions account for the majority of the manure N lost to the atmosphere. If proper management practices are not in place, more than half of the excreted ammonium can be lost as ammonia in the barn, during manure processing and storage, and after land application. It is important to understand the mechanisms governing manure N losses and the practices that are available to minimize these losses on the dairy farm. Different tools are available that provide advice on how to minimize N losses from livestock operations, including the Air Management Practices Assessment Tool (AMPAT 2016).

Manure nitrogen production

Nearly 28% of the N consumed in the dairy diet is excreted in milk, 38% in urine, and 33% in manure (Spek et al. 2013). Many factors affect the N content in both the manure and urine, such as breed, cow type (e.g., lactating cow, dry cow, heifer), and diet. Manure N comes from undigested fiber, bacterial cell walls, and sloughed intestinal tissue (Ferguson et al. 2001). Most of the N excreted in the manure is in the form of protein and is therefore less likely to be decomposed in the short-term by microorganisms. Urine also contains N from protein, but nearly 82% of urinary N is in the form of urea. The excretion of urea in the urine increases when excess crude protein is fed to the cow beyond her requirements for milk production and maintenance.

Predicting the N content in manure can be done using tables, predictive equations, or laboratory measurements. Tables, such as those produced by the American Society of Agricultural and Biological Engineers (ASABE 2005), Midwest Plan Service (Table 1) (Lorimor, Powers, and Sutton 2004), and university fertilizer guidelines (e.g., Laboski and Peters 2012) approximate the nutrient content in manure based on historical manure sampling data. While tables can be useful, they represent averages and do not account for the large variation in manure nutrient content. This can result in large errors when used for a specific operation. Equations can be used to predict nutrient excretion based on other measured parameters, such as ASABE (2005) and Nennich et al. (2005), and may be more accurate than table values. However, this additional information may not always be available. The

Table 1. Dairy manure characteristics as excreted daily per head (from Lorimor, Powers, and Sutton 2004).

Animal	Animal size (lb)	Manure (lb/day)	Water (%)	Density (lb/ft^3)	Total solids (lb/day)	Nitrogen (lb/day)
Calf	150	12	88	65	1.4	0.06
	250	20	88	65	2.4	0.11
Heifer	750	45	88	65	6.7	0.23
	1,000	60	88	65	8.9	0.30
Lactating cow	1,000	111	88	62	14.3	0.72
	1,400	155	88	62	20.0	1.01
Dry cow	1,000	51	88	62	6.5	0.30
	1,400	71	88	62	9.1	0.42
Veal	1,700	87	88	62	11.0	0.51
	250	6.6	96	62	0.3	0.03

most accurate method to determine the nutrient content in manure for a specific dairy operation is to sample and analyze manure regularly by an approved laboratory. While this method may best represent the manure constituents concentration produced at the farm, not all dairy operations use this method because it can be time consuming.

Forms of manure nitrogen

Nitrogen is present in both inorganic and organic forms in manure and urine but in different proportions. Inorganic N is readily available to plants and is mostly comprised of ammonium with some other N forms (e.g., nitrate, nitrite, and ammonia) typically in smaller quantities. Nearly half of the excreted N from the cow is in the form of ammonium, which is present in urine (Mikkelsen 2009).

Manure contains most of the excreted organic N. Organic forms of N in manure come from bedding materials, undigested feed, ruminal microorganisms, microbial cells, proteins, and amino acids (Russelle et al. 2008). Organic N converts to inorganic N over time once applied to land, making it available for plant uptake. Some of these organic N sources are more easily converted to available N than others. For example, N in undigested feed can take up to several years to become plant available. However, microbial ruminal cells can be converted into ammonium within weeks (Russelle et al. 2008). In general, moist and warm soils will mineralize organic N to ammonium faster than cooler and drier soils (Hernandez and Schmitt 2012). According to Laboski and Peters (2012), numerous research trials show that manure N available for plant uptake in the second and third year after manure application in Wisconsin are 10% and 5% of the total N applied, respectively, but can vary based on soil, manure characteristics, and environmental conditions.

Nitrogen loss mechanisms

The main manure N loss mechanisms include ammonia volatilization, denitrification, and nitrate leaching (Figure 2). After excretion, ammonium in manure can be used by the plants or undergo a series of chemical and biological conversions to other forms such as ammonia or nitrate. If ammonium is not quickly utilized by plants or soil bacteria, some ammonium will be converted into ammonia when exposed to air and quickly escape as ammonia gas (volatilization). This is true especially when manure is deposited on moist surfaces, under warm temperatures, or exposed to windy conditions.

Ammonium can be converted into nitrate by soil bacteria (nitrification). Nitrate is more readily available for plant uptake, but it is also more prone to water loss via leaching or emission to air due to denitrification. Poorly drained soils become easily saturated with water. These saturated conditions are ideal for denitrifying bacteria to live, reproduce, and reduce nitrate to dinitrogen or nitrous oxide gas (denitrification) (Hernandez and Schmitt 2012). Dinitrogen gas is the most abundant gas in the atmosphere, and its emission does not have environmental or health implications. Emission of this gas, however, reduces manure's N concentration.

Nitrate is highly soluble, creating the opportunity for movement through the soil profile and potential for groundwater contamination. There are many factors that promote nitrate leaching. These factors include soil N concentrations, rainfall timing and intensity, the presence of plants, and the type of soil and its characteristics (e.g., water retention capacity, infiltration rates, and temperature) (Trautmann et al. 1989). In general, leaching is more common in well-drained coarse soils.

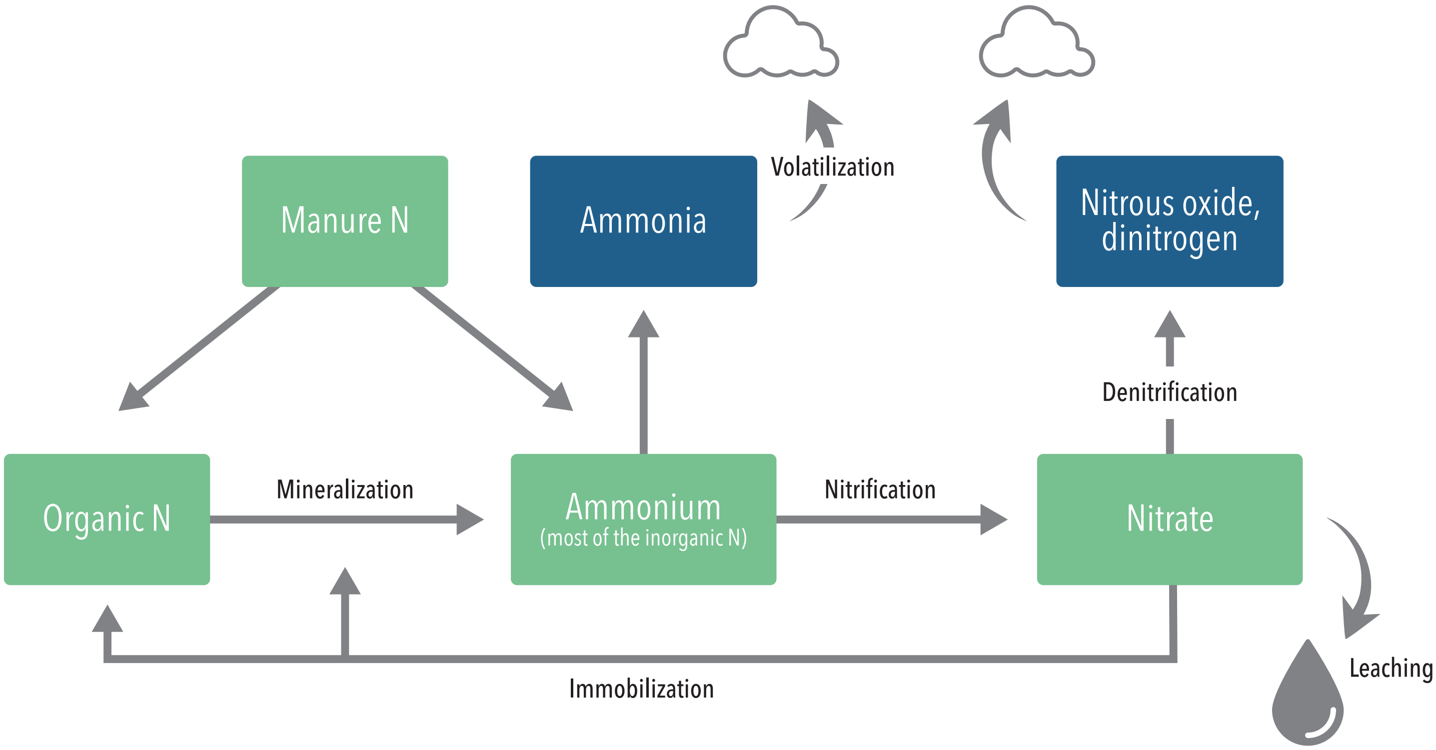

Figure 2. Nitrogen (N) formation and loss mechanisms after manure excretion (adapted from Hernandez and Schmitt 2012).

Nitrogen loss through manure management and mitigation practices

The extent to which N is lost from manure is directly related to the amount of N excreted from the cow. Reducing N excretion can therefore reduce the N available to be lost to the environment. Different management options have been evaluated to reduce N excretion, but reducing crude protein in the diet is perhaps the most common option. Reducing crude protein should be done with careful consideration of the metabolizable protein content in the diet to avoid any reductions in milk production (Aguirre-Villegas et al. 2017).

Barn nitrogen losses

After excretion, ammonia emissions can occur during housing of dairy cows. Ammonium quickly turns into ammonia after urea in urine interacts with urease bacteria excreted with the manure. These losses from the barn environment occur as ammonium is exposed to the atmosphere with limited opportunity to bind to the soil in this setting. In addition, studies have found that ammonia emissions increase when manure is deposited over a larger surface area (e.g., alleyways or storage structures) (Rotz et al. 2016). Some strategies to reduce ammonia emissions during housing include frequent collection of manure, avoiding porous housing floor materials that can trap ammonium, and providing an organic bedding source, such as straw, so ammonium can bind thereby reducing losses (Herbert et al. 2009).

Segregating manure and urine could also reduce ammonia emissions from the barn by preventing fecal bacteria from contacting urea in urine. Within a few hours of excretion, urea in urine is converted into ammonium by urease enzymes, which can quickly volatilize as ammonia from the barn floor (Ndegwa et al. 2008). Urease enzymes are found only in manure and not in urine, explaining the mechanism behind reduced ammonia emissions when manure and urine are separated immediately after excretion. Separation of urine and manure has been achieved by using a conveyor belt and draining urine immediately after discharge. Laboratory studies have found ammonia emission reductions of nearly 99% by separating urine and manure, but pilot and full case systems achieved 20-65% reductions because complete separation is difficult to achieve (Ndegwa et al. 2008). Despite its potential to minimize ammonia N emissions, this method is expensive.

Contrary to ammonia, nitrous oxide is not commonly emitted from animal housing facilities. There is limited opportunity for manure to contact nitrifying and denitrifying bacteria on the barn floor. These bacteria are needed to break down the manure into forms that produce nitrous oxide.

Storage nitrogen losses

During manure storage, N can be lost to water through leaching or to the atmosphere via ammonia and nitrous oxide, which are the gases of most concern. Generally, more

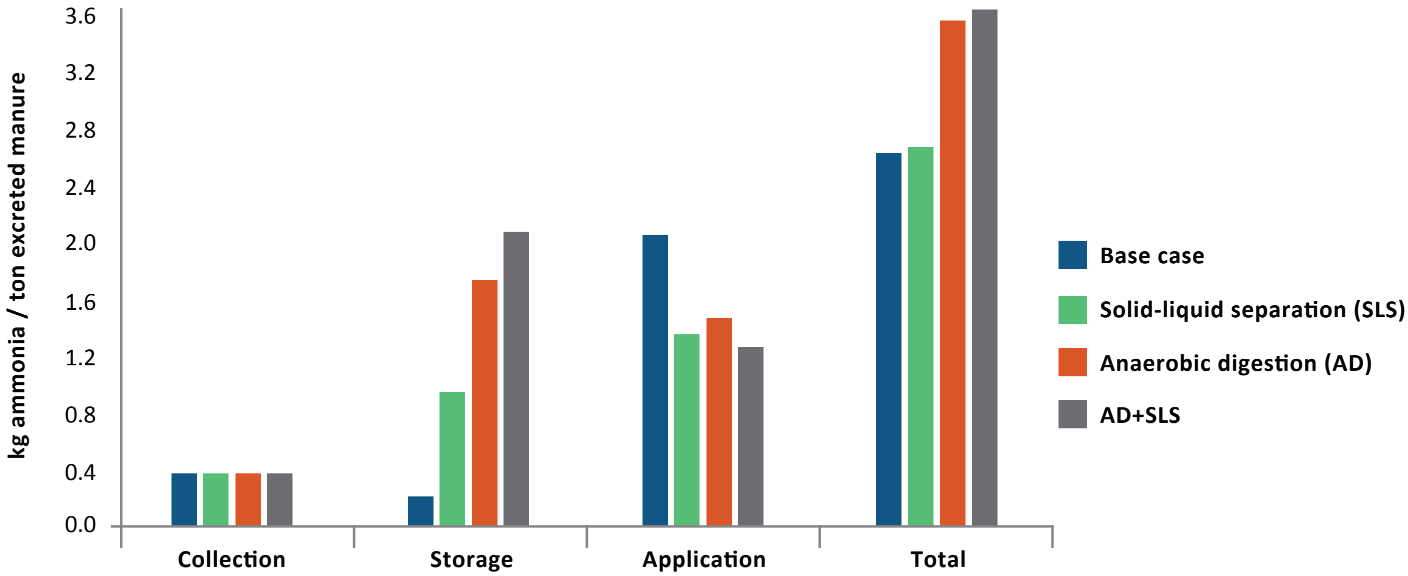

Figure 3. Modeled ammonia losses from manure management in a dairy system with no manure processing (base case), a system with solid-liquid separation (SLS), a system with anaerobic digestion (AD), and a system combining solid-liquid separation and anaerobic digestion (AD+SLS) (Aguirre-Villegas et al. 2014).

N is lost to leaching when compared to manure storages that are designed to current standards which reduce leaching losses. Storage systems are designed to avoid leaching risks with the use of liners such as concrete and compacted clay liners, among others. The primary concern for manure N leaching is ensuring proper storage designs are used. The IPCC (2006) reports N losses through leaching and runoff range from 1-20% during storage of solid and liquid manure. This is likely in systems that do not incorporate a liner and other designs for environmental protection.

Ammonia emissions during storage will increase as the following factors increase (Rotz et al. 2016):

- Ammonia N concentration of the manure being stored
- Storage surface area
- Ambient temperature
- Wind velocity near the storage surface
- Storage surface pH

As many of these factors involve the storage surface, a common ammonia reduction strategy is to use a storage cover. Storage covers can be permeable (e.g., straw or geotextile) or impermeable (e.g., synthetic liner, wood, or fiberglass) with the latter being more effective in reducing ammonia emissions but also more expensive. With higher manure solids, the formation of a natural crust on top of the storage also helps to reduce ammonia emissions, as the exposure to wind is reduced. Filling storage tanks from the bottom promotes the formation of this natural organic crust (Herbert et al. 2009). However, this crust promotes nitrous oxide emissions, as it creates aerobic conditions for nitrification and nitrate formation. Nitrate can then undergo denitrification where N is emitted as nitrous oxide. Maintaining anaerobic storage conditions will prevent nitrate from forming and thus reduce nitrous oxide emissions, but it can also increase the formation of methane. Finally, storing manure under conditions promoting drying (or reducing moisture) can increase the risk of ammonia emissions.

In the last decade, it has become increasingly common for dairy facilities to implement manure processing to increase the value of manure or reduce operational burdens. Anaerobic digestion (AD) generates biogas as a renewable source of energy, but it also promotes mineralization of organic N to ammonium. If the manure storage is not covered or manure is not injected or incorporated into the soil, ammonia losses can be even greater than without the digester (Figure 3).

Solid-liquid separation can also impact N losses. On one hand, the reduction of total solids in the liquid fraction of separated manure avoids a natural crust formation. This can increase ammonia emissions if the storage is not covered. The lack of a natural crust, however, can also reduce nitrous oxide emissions during storage because there is no opportunity for nitrification. On the other hand, a reduction in total solids can reduce ammonia losses during land application because a more liquid manure infiltrates better into the soil and becomes more stable. However, in coarse soils this could also represent an opportunity for leaching.

Land application nitrogen losses

Manure land application is perhaps the most studied stage of N losses from the manure system. Here, manure is exposed to soil bacteria that transform N into different forms, creating opportunities for N loss. Nitrate is susceptible to loss to water via leaching, especially after excessive rain and other scenarios where water exceeds the soils water holding capacity. Nitrate can also undergo denitrification and be lost as nitrous oxide and dinitrogen. Finally, ammonium can be lost to the air through volatilization within a few hours of application if it does not bind to the soil.

Nitrate is soluble with a negative charge, which impedes binding to negatively charged soil particles. As a result, if nitrate is not assimilated by the crop's root system, it can rapidly leach through the soil layers to groundwater. This poses significant environmental and health risks for humans and animals. Leaching is most likely to occur in coarsely textured soils, which do not have as much water-holding capacity as finely textured soils. The leaching risk is most acute in these soils when intense rainfall or irrigation moves water beyond the root zone (Lamb et al. 2014). To avoid nitrate leaching, N fertilizers should not be land applied when it is raining or intense irrigation is being used.

As with storage, ammonia emissions from land application depend on factors such as manure characteristics (e.g., ammonium concentration, dry matter content), soil characteristics (e.g., pH, temperature, moisture content), environmental factors (e.g., temperature, wind, and rainfall), and management practices (e.g., application method). Some of the strategies available to minimize ammonia emissions from land application are:

Time of application

- It is recommended to apply N when soil temperatures are cold enough to avoid or slow nitrifying biological activity and subsequent N loss via leaching or denitrification. Soil temperatures should be below 10°C (50°F) to minimize nitrification (Hernandez and Schmitt 2012). However, winter application is discouraged because the freezing temperature impedes N binding in the soil and decreases infiltration, which can result in runoff. In terms of ammonia, land application of manure with little or no wind and in cold temperatures reduces ammonia emissions. However, avoid periods with frozen soils, which promote runoff. If winter application cannot be avoided, it is recommended to apply to fields away from environmentally sensitive features like waterways.
- Match N application with plant N uptake. Generally, spring application results in the least amount of N losses through ammonia volatilization, as there is limited time for losses to occur before N crop uptake. However, this also means there is less time for the organic N to break down, resulting in less available N for crop production in the first year. Application to a growing crop when the N is needed most can reduce N losses; however, this requires costly and special manure application equipment.

Application method

- Many dairy farms, especially smaller facilities, land apply manure by broadcast or surface spreading, which is less costly than injection. However, broadcast application can result in significant N losses through volatilization if manure is not quickly incorporated. To avoid N losses via ammonia emission, either incorporate manure the same day as surface spreading or inject the manure.
- Injection favors denitrification conditions and potential loss of N as nitrous oxide or dinitrogen gas (Hernandez and Schmitt 2012). In terms of N quantity, the denitrification losses are less than the volatilization losses that occur when manure is left on the soil surface (Aguirre-Villegas et al. 2014). However, the impact is different because nitrous oxide is the most potent agricultural GHG. To minimize the opportunity for denitrification, the use of sweep knife injection systems is recommended, as they minimize the concentration of manure in the soil (Hernandez and Schmitt 2012).

Rate of application

- Applying nutrients at agronomic rates reduces N losses because there are fewer excess nutrients lost to air or water. Following a nutrient management plan helps ensure application at an appropriate manure rate on each field and prevents over- or under-application of N.

Apply manure to growing crops or cover crops

- The roots of established plants can immediately uptake the applied N, thereby minimizing the potential for leaching or runoff (Hernandez and Schmitt 2012).

Soil and environmental conditions

- Soil and manure below pH 7 will reduce microbial activity that promotes nitrate formation and N loss.
- Ammonia emissions are reduced in moist but not saturated soils. Dry conditions have been cited to increase ammonia emissions (Herbert et al. 2009) and wet soils tend to promote nitrous oxide emissions (Montes et al. 2013).

Summary

Manure is a valuable resource for agricultural systems due to its nutrient content. Nitrogen can be lost to air and water, posing environmental and health concerns if proper management practices are not in place. Ammonia and nitrous oxide are the main gases of concern in terms of atmospheric emissions. Ammonia can irritate eyes and lungs in humans and can contribute to eutrophication in lakes and rivers and endanger aquatic species. Nitrous oxide is one of the most potent GHGs, which are the main contributors to climate change. After excretion, different strategies can be adopted to minimize N losses. In the barn, frequent manure collection from the barn floor and segregating manure from urine can reduce ammonia emissions. During storage, a cover can be used to reduce wind exposure to the manure surface and reduce ammonia volatilization. This practice is especially important in systems with anaerobic digestion because digestate contains a greater amount of ammonium (which is more susceptible to losses) after the digestion process due to mineralization. Nitrogen losses to air and water can be significant after manure land application. Injecting manure into the soil can reduce ammonia emissions. An effective strategy for minimizing N losses includes applying manure when crops need N and at the amounts they need it. Avoiding manure land application during rain events or in saturated soils can also reduce N losses.

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