RESEARCH

Swine manure application methods effects on ammonia volatilization, forage quality, and yield in the Pre-Amazon Region of Brazil

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The use of swine manure (SM) as a nutrient source for pastures is increasingly common in Brazil, due to its low cost. However, this practice can cause N losses in agricultural soil, where ammonia (NH_3) volatilization may be the main drawback, generating undesirable economic and environmental consequences. The objective of this study was to evaluate SM application methods that retain N within the system and determine how these methods affect forage yield and quality. The study was conducted in the municipality of Chapadinha, Maranhão, Brazil, and the following SM application methods were evaluated: (1) surface application, (2) incorporation at 5-cm soil depth, (3) incorporation at 10-cm soil depth, and (4) control when SM was not applied. Lower N losses due to NH_3 volatilization and higher pasture yield and quality were found when SM was incorporated at 10-cm soil depth (83 kg N-NH_3 ha^{-1} and 6.3 Mg DM ha^{-1}, respectively, compared to 86 kg N-NH_3 ha^{-1} and 1.5 Mg DM ha^{-1} for the control), whereas higher N-NH_3 losses and lower pasture yield were observed when SM was applied to the soil surface (143 kg N-NH_3 ha^{-1} and 2.6 Mg ha^{-1}, respectively). Higher quality forage in terms of chemical composition was also observed when SM was incorporated at greater soil depth. Incorporating SM at 10-cm depth represents an efficient management to mitigate N-NH_3 volatilization, and this application method is associated with significantly increased in DM yield and improved chemical composition.

Key words: *Brachiaria brizantha*, manure management, nitrogen loss, semi-opened chamber.

INTRODUCTION

Approximately 36-million head of swine are raised in Brazil annually (IBGE, 2012), generating approximately 120 million tones of manure. This large volume of manure has aroused interest in new manure management technologies, with an emphasis on minimizing negative effects to the environment. Land application of swine manure (SM) is considered an optimum use of this by-product in Brazil, with considerable potential to meet the nation's row crop and pasture fertilizer requirement (Shigaki et al., 2006). In particular, there is interest in new technologies for applying animal manures that can improve nutrient use efficiency and minimize off-site losses of nutrients.

It is well established that fertilization with animal manure increases soil nutrient availability, crop yields, and pasture carrying capacity (Scherer et al., 2007). However, the use of manure as fertilizer can also lead to significant N losses from the system. Of the total N present in SM, approximately 65% is in ammoniacal form (NH_4). As a result, ammonia (NH_3) volatilization tends to be the primary N loss concern with manure application (Pfluke et al., 2011).

The volatilization of NH_3 from soils is affected by a host of environmental factors, including soil, air temperatures and soil moisture (Roelle and Aneja, 2005; Rochette et al., 2013), rainfall (Kissel et al., 2004), wind speed (Freney et al., 1983; Sommer et al., 1991), soil pH (Hafner et al., 2012), and soil cation exchange capacity (CEC) (Whitehead and Raistrick, 1993). From a management stand point, land application method represents one of the key opportunities to control NH_3 loss, with the largest emissions expected from technologies that broadcast or surface apply manure (Maguire et al., 2011). For instance, Smith et al. (2009) reported approximately 59% decrease in N losses due to NH_3 volatilization when injecting/tillage manure into the soil compared to surface application. Pfluke et al. (2011) observed that band spreading liquid manure reduced total NH_3 losses by 52% compared to surface broadcast application. Elsewhere, Dell et al. (2012) reported a range of NH_3 volatilization values with alternative technologies, with the degree and immediacy of manure incorporation representing the primary determinants affecting the efficacy of a technology.

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Conservation of NH_3 in land applied manure can significantly benefit crop yields, particularly in nutrient deficient systems. Loecke et al. (2004) found that corn grain yields increased on average by 17% over 2 yr as the result of incorporating 340 kg total N ha^{-1} (8.5% mineral N) into the soil in the form of the accumulated bedding from swine production. Laboski et al. (2013) found that injecting dairy liquid manure increased corn grain yield up to 12% over 4-yr experiment. These benefits to yield can translate into improved profitability of farms that directly incorporate manures. Rotz et al. (2011) concluded that shallow injection of dairy manure could significantly improve net farm returns relative to broadcast application due to greater manure N use efficiency.

Most research on manure application technologies has stemmed from the North America and Europe. As part of efforts to evaluate the potential to promote manure injection technologies in Brazilian cropping systems, this study sought to quantify differences in NH_3 losses from a Brazilian pasture at time of establishment. Specifically, broadcast and simulated injection methods of swine manure were compared. In addition, effects on pasture quality and sward yield were quantified.

MATERIALS AND METHODS

The study was conducted in April 2010 in the city of Chapadinha (3º44' S, 43º18' W), Maranhão, Brazil (Figure 1), on a sand clay loam soil, Red-Yellow Latossol. The region has a hot and semi-humid equatorial climate with an average annual precipitation of 2100 mm, and two well-defined seasons: a rainy season from January to June and a dry season marked by drought from July to December. Total rainfall during the experimental period was 339 mm. Soil samples from 0 to 20 cm depth were collected before swine manure (SM) application and analyzed for pH (0.01 M $CaCl_2$ suspension, 1:2.5 soil/solution, v/v), organic C (Walkley-Black), P and exchangeable Ca, Mg, K, and H+Al according to standard methods used by Embrapa (1999). Particle size analysis was performed using the pipette method (Robinson, 1967). The soil presented the following characteristics: pH 5.2 in water, 2.5 $cmol_c$ Ca dm^{-3}, 2.5 $cmol_c$ Mg dm^{-3}, 0.2 $cmol_c$ Na dm^{-3}, 0.11 $cmol_c$ K dm^{-3}; 0.6 $cmol_c$ Al dm^{-3}, 9.4 $cmol_c$ H+Al dm^{-3}, 2.5 mg P L^{-1}; 54% sand, 22% silt, and 25% clay.

Manure was obtained from a local swine farm, and it was collected on the same day of field application. Immediately before application, a sample was taken to determine DM content by drying in a forced ventilation oven at 65 °C to constant weight. Total N was analyzed with wet digestion, and ammonia N was determined by steam distillation with a semimicro Kjeldahl as described by Aita et al. (2007). The SM used in this study presented the following chemical attributes: 2.63 g N_{total} kg^{-1}, 3.7 g P kg^{-1}, 4.1 g K kg^{-1}, 20.90 g Ca kg^{-1}, 2.7 g Mg kg^{-1}, and 48 g DM kg^{-1}.

The experimental design was completely randomized with four treatments and four replicates, resulting in 16 experimental plots. The SM was applied to the soil in all experimental plots (7.5 m × 3.5 m) at a dose of 10 m^3 ha^{-1}, except for the control, using the following SM application methods: (1) application on the soil surface, (2) incorporation at 5-cm soil depth, (3) incorporation at 10-cm soil depth, and (4) control - no application of SM. For the soil surface treatment, SM was evenly spread on the soil surface of each plot; for the treatments where SM was incorporated, cutting discs of a planter were used to dig 5-cm- and 10-cm-deep trenches in the soil, and SM was subsequently applied and mixed with the exposed soil. Before this study, the site consisted of native vegetation, predominantly Babaçu (*Orbignya speciosa* [Mart. ex Spreng.] Barb. Rodr.) Ammonia volatilization rates were quantified using a semi-open static ammonia chamber, consisting of a 2-L transparent plastic bottle as described by Araújo et al. (2009). The base of the bottle was removed and placed on top, with a galvanized wire to protect the ammonia absorber system from rain and water irrigation (Figure 2). After the bottle removal, the chamber was 260 mm in length and 100 mm diameter. Inside of the chamber there was a 250 mm long wire designed with a hook in the top to support the ammonia absorber system, which consists of polyurethane foam

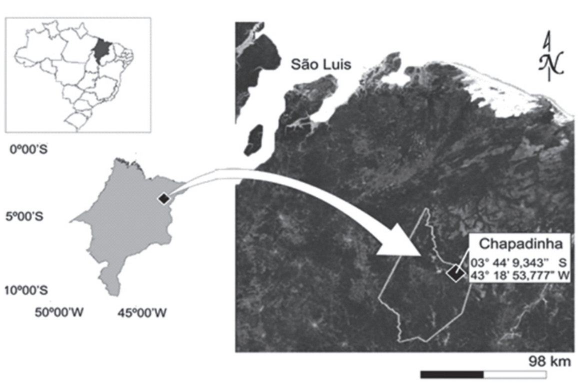

Figure 1. Experimental area location.

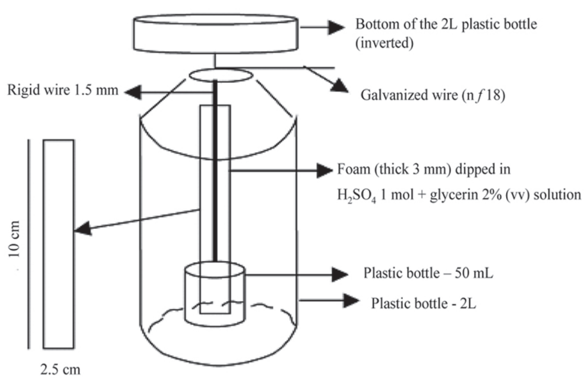

Figure 2. Scheme of the semi-open static ammonia collector (adopted from Araújo et al., 2009).

(0.017 g cm^{-3}) with 3 mm thick, 2.5 cm wide and 25 cm long. In the bottom end of this same wire where the foam was placed, a rubber band used to hold a plastic jar (50 mL) with 10 mL of the acid solution H_2SO_4 1 mol dm^{-3} + glycerin (2% v/v). Upon preparation of N-NH_3 absorber system, foam was packed into the plastic jar with acidic solution and then compressed to absorb most of the solution. The foam remains in the bottle closed until the moment of its placement inside of the chamber. Three collectors were placed in each plot, and samples were taken at 24, 48, 72, 96, 144, 216, and 264 h after SM application. The ammonia levels were quantified by distillation, and a correction factor of 1.74 was applied to the results to estimate the actual NH_3 volatilization according to Alves et al. (1994). Chambers remained in the same position during all the experimental period.

One week after SM application, a pasture of *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf 'Marandu' was planted. For weed control during the experiment we used manual weeding.

To determine forage yield, the pasture was cut at 45 d after planting, according to the point-quadrant method for directly determining sample cuts within a pre-defined square area of 0.50 m^2 (Spedding and Large, 1957). The samples were weighed and dried in a forced-draft oven (65 °C) until a constant weight was achieved. After drying, samples were weighed again to obtain DM. Dried samples were ground, and crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), hemicellulose (HC), and *in vitro* digestibility of *B. brizantha* 'Marandu' were determined. The CP content was obtained by determining total N extracted with sulfuric acid digestion using the semi-micro Kjeldahl method according to the formula % CP = % total N × 6.25 (Silva and Queiroz, 2002). Neutral detergent fiber and ADF were analyzed using the Van Soest method described by Silva and Queiroz (2002). Hemicellulose content was obtained using non-chemical methods and estimated from the difference between NDF and ADF levels. Neutral detergent fiber (cell walls) is a residue obtained after extracting cellular contents by boiling in a solution of sodium lauryl sulfate and EDTA (pH 7.0), after which cellulose, hemicellulose, and lignin were recovered. Acid detergent fiber is the residue obtained after extracting soluble compounds by boiling in a solution of sulfuric acid (1 N) and cetyltrimethylammonium bromide and subsequently recovering cellulose and lignin together with small quantities of contamination from pectin, minerals, and N compounds (Lana, 2005).

In vitro digestibility was analyzed according to method described by Tilley and Terry (1963), which remains the procedure most often used to predict and simulate ruminal degradability. This technique requires incubating the samples in a donor animal's ruminal fluid. Specifically, the method consists of leaving samples in contact with ruminal fluid inside a test tube, thereby attempting to reproduce the predominant conditions inside the rumen-reticulum.

Statistical analyses were performed using Minitab 16. Data were analyzed for normality and were normally distributed, so it was not necessary to transform data; ANOVA were used to determine treatments effects. Comparisons of means were performed using Tukey's test at $P < 0.05$.

RESULTS AND DISCUSSION

Effect of climatic conditions on NH_3 volatilization

The mean temperature fluctuated only slightly throughout the experimental period, remaining at 32 °C on average. Rain was frequent, and approximately 30 mm of rainfall was recorded soon after SM application. Thereafter, rainfall events were less intense, except at 23 d after the study began when 120 mm of rainfall was recorded over a 24-h period (Figure 3).

The intensity of N losses due to ammonia volatilization was reduced by rainfall, especially during the first 72 h after SM application (64 kg N-NH_3 ha^{-1}, considering all treatments). During this period, rainfall of 34 mm contributed to decrease the accumulated losses of NH_3-N, which corresponded to only 13% of the accumulated losses throughout the entire experimental period (Figure 4). This trend is most likely the result of increased soil

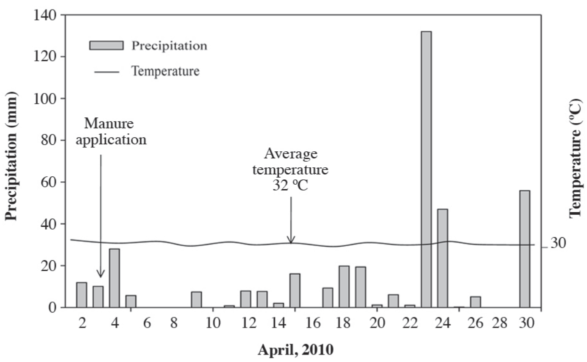

Figure 3. Temperature and rainfall during the experimental period.

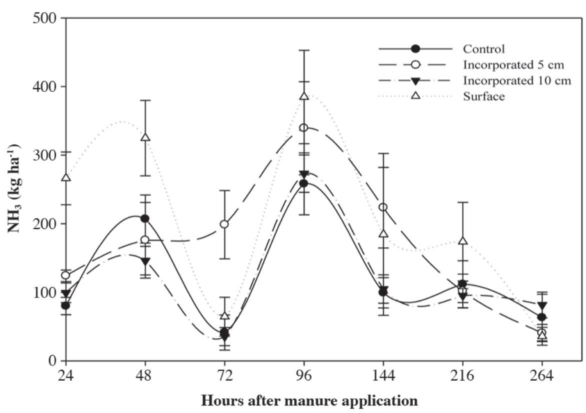

Figure 4. Ammonia volatilization after swine manure application.

moisture, which minimizes N losses due to ammonia volatilization when manure is incorporated (Sommer et al., 2006). According to Hargrove (1988), 10 to 20 mm rainfall is sufficient to minimize or even eliminate N-NH_3 loss due to volatilization. Rochette et al. (2001) observed a gradual decrease in N-NH_3 volatilization rates with no significant loss after 20 mm of rainfall while assessing reduced N-NH_3 volatilization resulting from the incorporation of SM into the soil. This decrease occurs because of the presence of water within the soil pore space following recent rainfall, favoring depletion of gas diffusion under such conditions. However, the timing and intensity of rainfall is also important to determine the magnitude of volatilization (Black et al., 1987). Low rainfall values do not favor manure incorporation because they may increase NH_3 losses by providing the necessary moisture for the hydrolysis of urea found in manure (Kong et al., 1991; Freney et al., 1992). The effect of rainfall in reducing ammonia volatilization has been well-documented (Sharpe et al., 2004; Paramasivam et al., 2009; Faria et al., 2013) and may be explained by the fact that rainwater dilutes superficial NH_4 (thereby reducing the partial pressure of NH_3) and also transports NH_4 deeper into the soil (thus increasing resistance to volatilization) (Van der Molen et al., 1990).

In several studies, the highest rates of ammonia volatilization were observed during the initial periods after applying both manure and mineral-based N fertilizers (Sharpe et al., 2004; Perala et al., 2006; Nyord et al., 2008; Rochette et al., 2009). According to Thompson et al. (1987) 50% or more of NH_3 emissions can be expect within 24 h of broadcast application. However, most of these studies were conducted under different climate and soil conditions; thus, it is apparent that N-NH_3 losses by volatilization are highly affected by a combination of soil and climatic factors.

Soil drying occurred in samples taken from 72 to 96 h after manure application; during this period, there was no heavy rain, and the maximum temperature remained at 32 °C on average, which contributed to the higher N-NH_3 losses, observed for all treatments, with an average of 146 kg N-NH_3 ha^{-1}. These results corroborate those obtained by Cantarella et al. (2003), who claim that N-NH_3 losses under wet soil conditions and high temperatures, which are typical of the Brazilian summer, usually peak at 2 or 3 d after fertilization. The soil drying may accelerate losses due to N-NH_3 volatilization. These losses are directly related to the speed and duration of soil drying, i.e., the level of NH_3 lost from the soil is positively correlated with the evaporation rate, and appreciable amounts of NH_3 are lost from the soil only when water loss occurs, which is favored by high temperatures and wind (Sommer and Hutchings, 2001; Cantarella, 2007). Thus, the application of manure when the soil is notably wet does not prevent volatilization from occurring but rather slows its release to the atmosphere.

Application methods and NH_3 volatilization

Cumulative losses of volatilized N-NH_3 (Figure 4) were usually higher ($P < 0.05$) for SM surface application, with total of 143 kg N-NH_3 ha^{-1} at 264 h after SM application (Figure 4). This value is, on average, 40% and 41% higher than those observed for the control and SM incorporation, respectively, at 10-cm soil depth. This notable difference between application methods can be explained by the greater surface area exposed to the atmosphere when manure is surface applied, encouraging higher volatilization rates. Pfluke et al. (2011) observed higher N-NH_3 emissions when manure was broadcast in the first few hours after spreading, followed by a rapid reduction to low levels, while for band treatments the same pattern was observed, however, with initial rates substantially lower.

Incorporation of SM at 10-cm soil depth presented similar ($P < 0.05$) N-NH_3 losses compared to the control (83 and 86 kg N-NH_3 ha^{-1}, respectively). This significant decrease in N-NH_3 emissions resulting from the incorporation of manure has been reported in several studies (Chadwick et al., 2001; Sogaard et al., 2002; Smith et al., 2009; Webb et al., 2010), and it is attributed to ammonia's higher reactivity with H^+ ions present in the soil that shifts the chemical equilibrium to the cationic form of NH_4^+, which is temporarily retained in the liquid and solid phases of the soil, thereby hindering its transformation to N-NH_3. Mechanical incorporation at 5 cm depth or deeper is an efficient way to reduce losses by volatilization. Several field studies conducted in other regions of Brazil (Cantarella et al., 1999; Basso et al., 2004; Giacomini and Aita, 2008) and in other countries (Bless et al., 1991; Tao et al., 2008; Webb et al., 2010) have confirmed the effectiveness of this practice. For example, Dell et al. (2012) found that total N-NH_3 emissions after broadcasting (without incorporation) averaged 70% and 55% of the N-NH_4 content of applied dairy and SM respectively. Rochette et al. (2001) observed that the efficiency in reducing NH_3 volatilization resulting from incorporation linearly decreases with time, and may be further influenced by rainfall; comparing six periods in which incorporation failed to reduce N-NH_3 emissions, five of these periods occurred after rain.

At 144 h after SM application, N-NH_3 emissions decreased by approximately 65% for all treatments, and the average values remained less than 5 kg N-NH_3 ha^{-1} of until the end of the experiment. Results suggest that nitrification and immobilization processes were more active during this period because a higher amount of mineral N is expected when losses of volatilized N-NH_3 are low. Furthermore, a decrease in the volatilization rate over time is natural because the manure infiltrates the soil. In addition, broadcast treatments appeared to dry faster, forming a surface crust, which further helped to decrease N-NH_3 loss.

Pasture yield

Pasture yield was affected by the application method, as observed from the difference in yield between all treatments ($P < 0.05$). Also, fertilization with SM generally promoted increased yields of *Brachiaria brizantha* 'Marandu' by 45%, 62%, and 77% compared to the control for soil surface application, incorporation at 5-cm and incorporation at 10-cm soil depth, respectively (Figure 5).

Swine manure incorporation into the soil at both depths (5 and 10 cm) led to higher DM yields, and this increase was proportional to the depth of application; yields of 4.0 and 6.3 Mg ha^{-1} were obtained for treatments incorporated at 5- and 10-cm depths, respectively, compared to 1.5 and 2.6 Mg ha^{-1} for the control and soil surface application, respectively. According to Huijsmans et al. (2003), the incorporation of manure involves greater contact with soil particles, thereby accelerating such processes as nitrification because greater contact is achieved between nitrifying bacteria and ammoniacal N; consequently, nutrient availability for plants is increased, thereby increasing the efficiency of the manure used as a fertilizer. Furthermore, these results may be attributed to decreased losses resulting from volatilization in the plots where SM was incorporated, thereby retaining this nutrient more effectively within the system for improved use by plants. Maguire et al. (2011) report that total N available for crops is generally higher after injecting or incorporating manure into the soil compared to soil surface application.

Soil surface application shown lower pasture yield compared to other treatments (2.6 Mg ha^{-1}), indicating less efficiency in retaining N within the system. Fertilization with SM generally provided significantly increased DM yield. Barnabé et al. (2007) found that applying 150 m^3 ha^{-1} SM resulted in 156% higher DM yield compared to the unamended treatment when evaluating 'Marandu' grass yields on fertilization with SM. Medeiros et al. (2007) concluded that annually applying 180 m^3 ha^{-1} of pig slurry allowed for a similar DM yield of 'Marandu' grass to that obtained with mineral fertilizer with an average yield of 3.0 Mg ha^{-1}. In addition, Sutton et al.

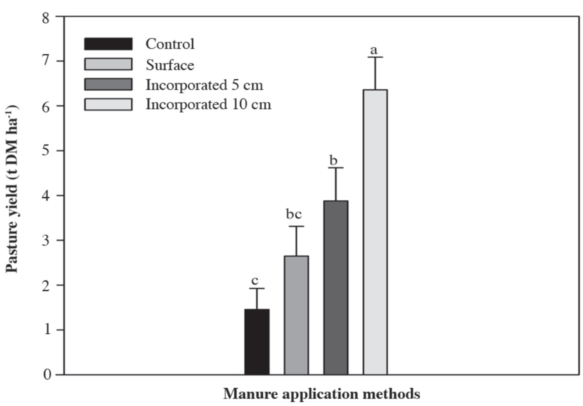

Figure 5. Pasture yield for different manure application methods.

(1982) found that injecting SM increased corn grain yield in 2.1 kg ha^{-1} compared with broadcasting application. Furthermore, Groot et al. (2007) in a 4-yr study in The Netherlands found that shallow manure injection resulted in greater N recovery by the grass crop (42% recovery) than with surface application (26% recovery).

These results validate the use of SM to increase forage yield and confirm that incorporating this manure can amplify the effects on yield and reduce the loss of N from the system. However, crop response can also be affected by specific environmental conditions such as rainfall, temperature, and soil properties.

Chemical composition and *in vitro* digestibility of forage

In general, SM application methods affected CP, ADF, and the *in vitro* digestibility of forage DM (IVDDM) (Table 1). Higher CP content (6.8%) was obtained by incorporating SM at 10-cm soil depth. Because this treatment ensured the lowest N-NH_3 volatilization rates, this higher CP content observed may be related to the increase in soil N availability for use by forage. The CP content observed with incorporation to 10-cm soil depth is also similar to those found by Freitas et al. (2005) studying the use of SM fertilizer in 'Marandu' grass, and are within the range recommended by Van Soest (1994) (6% to 6.5% CP in the minimum) for the fermentation of structural carbohydrates in the rumen.

According to data obtained in this study, there was no effect of application method ($P < 0.05$) on ADF levels, and a higher value for this parameter was observed only in the control (50.7%). In this way, application of SM reduced this parameter in average by 11% compared to the control, regardless of the method used. These results can be attributed to the lower nutrient availability for plants in this treatment, leading to premature senescence compared to the other treatments. According to Noronha and Rosa (2001), a lack of nutrients for forage plants provokes changes in the chemical composition in plants, such as the translocation of nutrients from leaves, and increases the proportion of structural constituents, mainly lignin.

The NDF levels found are considered high (81.7% on average) for ruminant nutrition because they are greater than 70%, which causes low voluntary intake because intake is inversely proportional to NDF content in the diet according to Van Soest (1994). However, other authors found similar NDF values in studies with *B. brizantha* 'Marandu' (Malafaia et al., 1997; Costa et al., 2005), indicating that this value may be characteristic of the forage because neither SM fertilization nor the application method used had the same effect on its levels.

The IVDDM values ranged from 57.8% to 80.4%, and the highest coefficient was observed when SM was incorporated at depth 10 cm. These results were expected and are consistent with results observed for CP levels (Table 1), possibly indicating a positive

Table 1. **Average levels (% DM) of neutral detergent fiber (NDF), acid detergent fiber (ADF), hemicellulose (HC), and crude protein (CP), and *in vitro* digestibility of DM (IVDDM) of the grass *Brachiaria brizantha* 'Marandu' fertilized using various swine manure application methods.**

Application method	ADF	NDF	HC	CP	IVDDM
	%				
Control	50.7 (3.9)a	81.7 (3.2)a	31.0 (7.6)a	5.5 (0.42)b	59.5 (5.0)c
Incorporated 5 cm	42.3 (4.7)b	81.7 (2.6)a	39.4 (6.7)a	5.8 (0.21)b	75.4 (0.88)b
Incorporated 10 cm	47.1 (4.2)b	81.8 (2.9)a	34.7 (5.4)a	6.8 (0.12)a	80.4 (2.15)a
Surface	46.7 (3.8)b	81.5 (2.7)a	34.8 (3.9)a	5.3 (0.29)b	57.8 (2.52)c

relationship between these variables. The higher values for IVDDM is most likely because of the lower N-NH_3 volatilization, leading to higher nutrient levels in soil for plant uptake (mainly in N form) when this SM application method was used. Furthermore, it appears that placement of manure at some depth closer to the root zone may potentially increase nutrient availability in soil for plant use. Sutton et al. (1982) found that volatile losses of N-NH_3 from surface applied SM were reflected in lower corn yield response, lower corn-leaf N content, and lower soil NH_4 and NO_3 levels when comparing these parameters with injection treatment. Klausner and Guest, (1981) also reported higher N uptake in corn from injected dairy manure when compared with surface applied dairy.

Hemicellulose content, which is calculated based on the difference between NDF and ADF levels found for 'Marandu' grass (Table 1), shows no significant difference between different SM application methods with values between 31.0% and 39.4%. Similar values were found by Freitas et al. (2005) (from 32.22% to 36.73%).

Sutton et al. (1982) found that volatile losses of N-NH_3 from surface-applied SM resulted in lower corn yield response, lower corn-leaf N content comparing these parameters with injected treatment. Overall, Medeiros et al. (2007) reported that SM fertilization improved chemical attributes of *B. brizantha* 'Marandu', and this improvement was also observed in this study.

CONCLUSIONS

Results of this research clearly show the influence of swine manure application methods on ammonia volatilization, forage yield, and quality. Swine manure incorporation at a soil depth of 10 cm resulted in lower N losses due lower ammonia volatilization, thereby promoting higher forage yield by preserving a higher fertilizing potential. Additionally, N maintained within the system resulted in increased forage nutritional value, increasing crude protein content and digestibility.

In the Pre-Amazon region of Brazil there is still a lack of information about the efficiency of manure use as fertilizers, and all the variables analyzed in this study, particularly concerning manure application methods, since the N losses due volatilization vary according to the method of application, soil type and moisture, temperature, and the interaction of these factors. Using the information obtained in this research, it may be possible to make manure management decisions on which swine manure could be properly applied. For that, continued research to improve crop N use by conservation of N-NH_3 in the system is needed.

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