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Ammonia Volatilization from Soil-Applied Organic Fertilizers

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ABSTRACT: A reliable quantification of nitrogen (N) losses by ammonia (NH_3) volatilization can contribute to identifying optimized strategies of fertilizer management. The objective of this study was to quantify ammonia volatilization from several organic N sources incorporated into or applied onto the soil surface. Two cultivation areas, under snap bean and corn, were evaluated at Embrapa Agrobiology, Seropédica, Rio de Janeiro (RJ). Both experiments used a randomized complete block design in split-plots, with four replications. The main plots consisted of four organic fertilizers (castor bean cake, bokashi, legume fertilizers, cattle manure), at rates of 200 kg ha^{-1} N, and a control treatment (without fertilization), and the subplots corresponded to the management forms (incorporated or surface-applied) of the fertilizers. In the first experiment, snap bean cv. Novirex was grown in winter/spring and in the second, corn cv. Catingueiro in summer/autumn. In each subplot, static semi-open NH_3 collectors were installed. We conclude that surface-applied castor cake was the organic fertilizer with highest N loss by NH_3 volatilization. A comparison of the management systems (incorporated or surface-applied) showed that volatilization from organic fertilizers incorporated into the soil was significantly lower, with a reduction of 80 % for castor cake, of 78 % for bokashi and 67 % for legume fertilizer. Nitrogen loss through ammonia volatilization varied, from rates of 3 to 25 % in winter/spring and from 2 to 38 % in summer/autumn, according to the organic fertilizer applied. The period required to recover 95 % of the N lost by NH_3-N volatilization was between 13 to 18 days for castor cake; 14 to 43 days for bokashi; 17 to 49 days for legume fertilizer and more than 43 days for cattle manure.

Keywords: NH_3 volatilization, organic fertilization, nitrogen dynamics.

INTRODUCTION

Nitrogen losses to the atmosphere by ammonia volatilization are estimated at 54 Tg yr^{-1}, most of which is the result of anthropogenic activities (Laegreid et al., 1999). Organic and mineral fertilizers account for about 20 % of the global ammonia emissions. The mean amount of ammonia lost worldwide by N volatilization from fertilizers is of the order of 14 %, with higher values in hot and humid climates (Bouwman et al., 2002). Some studies in Brazil report losses of 18-30 % of the total soil-applied N (Cantarella et al., 2008; Soares et al., 2012), although these losses may even exceed 50 % of the applied N (Rochette et al., 2009). Ammonia volatilization rates depend on several soil factors: cation exchange capacity (CEC), buffering capacity, temperature, and moisture and, mainly, on the pH and the fertilizer type (Miwa et al., 2007; Araújo et al., 2011; Viero et al., 2014). These N losses by ammonia volatilization reduce the N use efficiency and boost production costs in agricultural systems (Sangoi et al., 2016).

Advanced studies on ammonia volatilization from synthetic fertilizers such as urea are available. To reduce N losses through volatilization, urea has been applied together with urease inhibitors, with subsequent incorporation of fertilizer into the soil (Viero et al., 2017). However, other technologies such as urea-coating with micronutrients (Stafanato et al., 2013), compaction with sulfur and bentonite (Oliveira et al., 2014), and urea mixtures with more acidic fertilizers such as ammonium sulfate have been studied.

Concerning the legally approved organic fertilizers for agricultural production systems, there is a lack of studies investigating their volatilization rates. Among the main organic fertilizers sold in Brazil and permitted by legislation for organic production systems, castor cake, bokashi, cattle manure, and vegetal biomass, mostly applied on the surface or incorporated into the soil, are particularly noteworthy. However, the cost of N in these organic fertilizers is extremely high. Thus, a reliable quantification of N losses by NH_3 volatilization can help identify the best management strategies of organic fertilizers as well as in the development of new studies to mitigate losses and promote rational use of this resource (Araújo et al., 2009).

Therefore, the objective of this study was to quantify ammonia volatilization from several organic N sources incorporated into or applied onto the soil surface.

MATERIALS AND METHODS

The study was carried out on the farm Fazendinha Agroecológica km 47, at Embrapa Agrobiology, Seropédica, Rio de Janeiro (22° 46’ S and 43° 41’ W; 33 m a.s.l.). According to Köppen’s classification system, the regional climate is Aw, with wet summers and dry winters, a mean annual temperature of 24.6 °C and mean annual precipitation of 1,200 mm.

Two experiments with complementary irrigation were carried out. In the first, snap bean (*Phaseolus vulgaris L.)* cv. Novirex was cultivated in winter/spring (July to November 2015), on an 80-m^2 area. According to the Brazilian Soil Classification System (Santos et al., 2018), the soil is classified as a *Planossolo Háplico Distrófico* [Planosols (IUSS, 2015)], with the following chemical properties determined by the methodology recommended by Claessen (1997): pH(H_2O) = 6.35 (at a ratio of 1:2.5 v/v); Ca^{2+} = 2.60 $cmol_c$ dm^{-3} and Mg^{2+} = 0.96 $cmol_c$ dm^{-3} (extracted by KCl 1.0 mol L^{-1}); P = 1.94 mg dm^{-3} and K = 128 mg dm^{-3} (extracted by Mehlich-1); and C (%) = 0.66. Snap bean was sown on July 6, 2015, in furrows opened with a hoe, spaced 0.5 m apart, at a sowing density of seven seeds per meter. The area was fertilized with thermophosphate (60 kg ha^{-1} P_2O_5) and potassium sulphate (60 kg ha^{-1} K_2O), applied in the planting rows. Nitrogen fertilization at a rate of 200 kg ha^{-1} N, contained in the different fertilizer sources, was applied 25 days after sowing (DAS). The seeds were inoculated with crop-specific rhizobia strains.

The treatments were distributed in randomized blocks in split plots, with four replications. The main plots (2 × 2 m) consisted of four organic N fertilizers, applied at a rate of

200 kg ha^{-1} N (Table 1), and a control treatment (without N), and the subplots consisted of two management forms of organic fertilizer (surface-applied or incorporated). The organic fertilizers consisted of: castor cake; bokashi type fertilizer [fertilizer produced by mixing 40 % castor bean cake with 60 % wheat bran, inoculated with efficient microorganisms -EM (Embiotic®) and incubated in a closed container for anaerobic fermentation for 21 days]; legume fertilizer (ground legume leaves); and cattle manure.

After applying the fertilizers to the soil, the plots were divided into two 2 m^2 subplots. On that occasion, the fertilizer of one subplot was left on the soil surface and in the other, incorporated into the arable layer with a hoe. In each subplot, static semi-open NH_3 collectors were installed (Araújo et al., 2009), beneath which the N fertilizers were applied. Nitrogen losses by NH_3 volatilization were monitored for 96 days, during which the foams in the collector were exchanged 18 times.

After physiological grain maturation of snap bean, the pods were harvested from a 2 m^2 area per plot. Only the effect of the different fertilizer types was evaluated, without considering the management effect. The number of pods per plant, pod length, and green pod yield were evaluated.

In the second experiment, corn (*Zea mays)* cv. Catingueiro was cultivated in summer/autumn (February to May 2016), in an 80-m² area. According to the Brazilian Soil Classification System (Santos et al., 2018), the soil is classified as a of *Argissolo Vermelho Amarelo Distrófico* [Acrisols ((IUSS, 2015)], with the following chemical properties, determined by the methodology recommended by Claessen (1997): pH(H_2O)= 5.93 (at a ratio of 1:2.5 v/v); Ca^{2+} = 2.53 $cmol_c$ dm^{-3} and Mg^{2+} = 0.89 $cmol_c$ dm^{-3} (KCl 1.0 mol L^{-1} extractor); P = 9.70 mg dm^{-3} and K = 87 mg dm^{-3} (extracted with Mehlich-1). Corn was sown on February 3, 2016, in furrows spaced 1.0 m apart, at a sowing density of six seeds per meter. The area was fertilized with 60 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O as thermophosphate and potassium sulphate. Nitrogen fertilization was applied 21 days after sowing (DAS), at a rate of 200 kg ha^{-1} N, in the form of the different organic fertilizers (Table 1).

The 80-m^2 experimental area for corn was subdivided into 2 × 2 m plots. The treatments were distributed in randomized blocks, split plots, with four replications. Similarly, to the first study, the main plots consisted of different organic N fertilizers applied at a rate of 200 kg ha^{-1} N (Table 1) and the subplots of management forms of organic manure (incorporated or spread on the soil surface).

The subplot size and fertilizer management were the same as in the first experiment. In each subplot, static semi-open NH_3 collectors were installed (Araújo et al., 2009), and losses by NH_3 volatilization were monitored for 72 days.

Samples of corn plants were collected in the milky grain stage, from 2 m^2 per plot, to evaluate green corn yield with and without leaves, number of ears per plant, green corn ear length, and green corn ear diameter.

Table 1. Nitrogen content and C:N ratio of organic N fertilizers

Treatments	N	C:N
	%	
Control (no N fertilization)	-	-
Castor cake	7.29	5.76
Bokashi	4.28	9.81
Legume fertilizer	3.48	12.07
Cattle manure	0.96	43.75

- = without N-fertilization; N = total nitrogen, determined by the Kjeldahl method; C = organic carbon, determined by the Walkley – Black method (Claessen, 1997).

The volatilization data were log-transformed to ensure normal distribution and subjected to analysis of variance. The F test was applied and the means compared by the Scott-Knott test at 5 % probability. SigmaPlot 12.3 software was used to fit a curve of ammonia volatilization data to time. The Gompertz (Equation 1), a model with three parameters, was selected:

$$Y = Ae^{-e^{-(x-x_0)^b}} \quad \text{Eq. 1}$$

in which "Y" is the proportion of fertilizer-N lost by ammonia volatilization (cumulative basis); "A" is the maximum proportion of fertilizer-N lost as ammonia; "x" is the time in days; "x_0" is the time in days when ammonia volatilization begins to decelerate (curve inflection); and "b" is the relative volatilization rate at x_0.

The adjusted model was rearranged to estimate the time (Y) required until 95 % of N was lost by ammonia volatilization for each fertilizer studied. This simplification was performed as described below (Equation 2). Setting Y = 0.95A,

$$0.95A = Ae^{-e^{-\left(\frac{x_{0.95}-x_0}{b}\right)}} \quad \text{Eq. 2}$$

in which $x_{0.95}$ is the time until 95 % of the maximum NH_3 volatilization is volatilized as NH_3-N (A).

Solving equation 2, A is canceled out, and after taking the natural log of both sides, equation 3 is obtained:

$$0.05129 = e^{\left(\frac{-x_{0.95}-x_0}{b}\right)} \quad \text{Eq. 3}$$

Taking the natural log of both sides again, the equation to calculate $x_{0.95}$ is simplified to the equation 4:

$$x_{0.95} = 2.97b + x_0 \quad \text{Eq. 4}$$

RESULTS AND DISCUSSION

In the winter/spring experiment with snap bean, no significant differences between N sources were observed for the number of pods per plant, pod length, and green pod yield (Table 2). This was probably due to the high N rates that induced luxury consumption in all treatments.

The overall mean pod yield was 4.95 Mg ha^{-1} (Table 2), similar to results of Vidal et al. (2007) in an experiment with snap bean in an organic production system.

Castor cake was the organic fertilizer with the highest potential of ammonia volatilization (25.52 % of the total applied N) when broadcast on the soil surface (Table 3). This was probably due to the low C/N ratio (Table 1), contributing to accelerated mineralization (Capuani et al., 2012) and consequent N availability. Mariano et al. (2012) when studying the volatilization of ammonia from synthetic fertilizer applied on sugarcane trash found similar results.

Table 2. Number of pods per plant; pod length, and green pod yield of snap bean cv. Novirex

Treatments	Number of pods	Pod length	Green pod yield
	pods per plant	cm	Mg ha^{-1}
Control (no N fertilization)	6.54 a	13.60 a	5.02 a
Castor cake	6.74 a	13.41 a	4.77 a
Bokashi	8.37 a	14.10 a	5.54 a
Legume fertilizer	7.78 a	13.83 a	4.67 a
Cattle manure	7.52 a	13.58 a	4.76 a
Mean	7.39	13.70	4.95
CV (%)	23.56	3.54	26.35

Means followed by the same letters do not differ by the Scott-Knott test at 5 % probability.

Table 3. Ammonia volatilization rate from different fertilizers applied to snap bean in winter/spring

Fertilizer sources	Management	
	Surface-applied	Soil-incorporated
	%	
Control (no N fertilization)	-	-
Castor cake	25.52 Aa	5.16 Ab
Bokashi	16.60 Ba	3.68 Ab
Legume fertilizer	8.25 Ca	2.73 Ab
Cattle manure	3.40 Da	3.06 Aa
CV Plot (%)	18.31	
CV Subplot (%)	16.63	

Means followed by the same lowercase letters in a row and uppercase letters in a column do not differ from each other by the F- and Scott-Knott tests at 5 % probability, respectively. - = no N volatilization was detected in the control treatment.

The ammonia volatilization rate from surface-applied bokashi was 16.60 % of the total N applied (Table 3). The significantly lower ammonia volatilization from bokashi than castor cake probably occurred due to the anaerobic fermentation during bokashi production (Carvalho and Rodrigues, 2007). Additionally, the N release rate from wheat bran (which accounts for about 60 % of the bokashi composition) to the soil is very slow (Oliveira and Borszowskei, 2012).

The ammonia volatilization rate from surface-applied legume fertilizer was 8.25 % of the total N applied (Table 3). This lower volatilization in relation to bokashi can be explained by the fact that the N of this fertilizer is not readily available to the plants, because it must undergo a decomposition process before mineralization (Ribas et al., 2010).

Surface-applied cattle manure was the organic fertilizer with lowest N losses by ammonia volatilization (Table 3). This is due to the about six times slower mineralization of manure than that of castor cake (Table 1) (Severino et al., 2004). Moreover, the potential N volatilization loss from stored manure is lower because after 120 days the presence of NH^{4+}-N is 50 % lower than in the beginning, and the initially released nitrate is immobilized (Azeez and Averbeke, 2010).

However, when the fertilizers were incorporated into the soil, ammonia volatilization did not differ statistically between the fertilizer types (Table 3).

A comparison of the management systems (surface-applied or incorporated), showed that volatilization from organic fertilizers incorporated into the soil was significantly lower (Table 3). This reduction was 80 % for castor cake, 78 % for bokashi, and 67 % for legume fertilizer, whereas no significant difference between the managements was observed for cattle manure.

With regard to the period of collection required to recover 95 % of the N lost by ammonia volatilization in the first experiment, according to equation 4, the time period to recover 95 % of the maximum NH_3 volatilization was 18, 43, and 49 days, respectively, for surface-applied castor cake, bokashi, and legume fertilizer (Figure 1). The slower NH_3 volatilization from cattle manure required 116 days to reach 95 % of the maximum NH_3-volatilization, which was out of the evaluation period. The volatilization rate of ammonia from legume fertilizer was not only lower than the observed rate for castor cake and bokashi but also slow and occurred gradually over more than 50 days.

In the second experiment, with corn grown in the summer/autumn, the number of ears per plant did not differ statistically among the treatments. However, the organic fertilizers increased the yield of green corn with and without leaves (by about 70 %) over the control treatment (without N application), regardless of the source (Table 4). This yield increase was mainly due to the longer ear length in the fertilized treatments. Santos et al. (2009) reported similar results in a study on the effect of organic fertilization on corn yield variables.

The mean yield of corn with leaves was 7.36 Mg ha^{-1} in the fertilized treatments and 4.18 Mg ha^{-1} without N fertilizer. Freire et al. (2010) reported different results in a study of response to N fertilization, with a maximum value of 14.8 Mg ha^{-1} for green corn yield. In our study, the yield was probably low because of cv. Catingueiro is a super-early corn cultivar.

In the second experiment, the volatilization rate from the castor cake treatment was 38.18 % of the total N applied (Table 5). This was probably due to the high temperature and precipitation during this period (Inmet, 2016; Castro et al., 2018). In a study addressing the volatilization of ammonia in mixed mineral fertilizers, Gurgel et al. (2016) found similar results. This underscores the importance of adequate castor cake management to reduce N losses by volatilization. In the treatments fertilized with surface-applied bokashi, legume fertilizer, and cattle manure, the ammonia volatilization rates were similar to those of the first study.

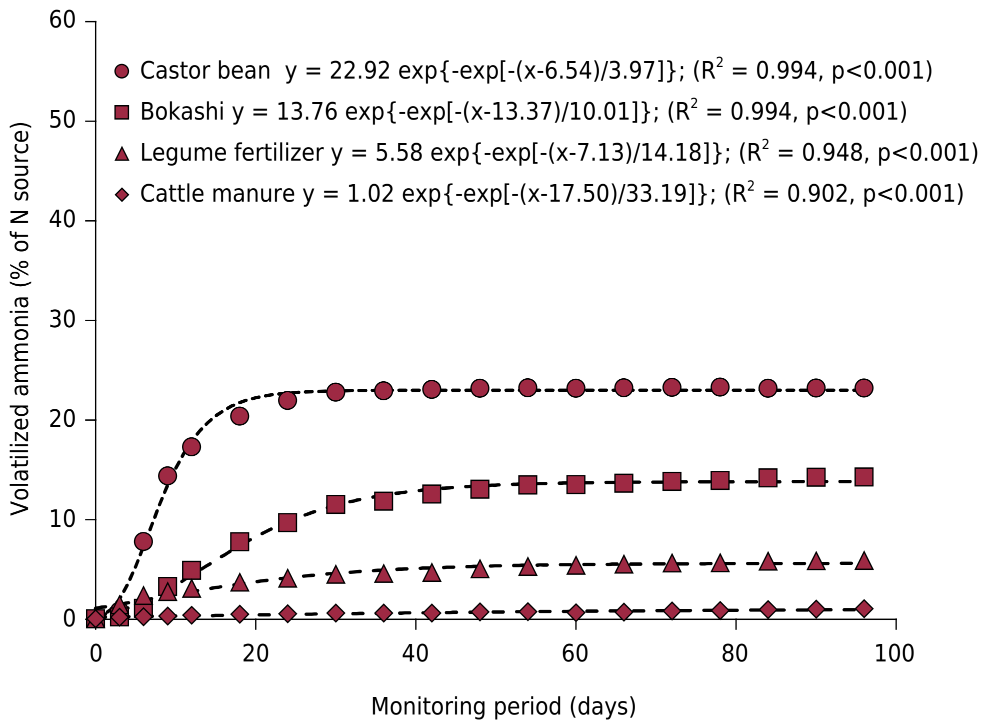

Figure 1. Ammonia volatilized from different surface-applied fertilizer sources (castor bean, bokashi, legume fertilizer and cattle manure) in snap bean cultivation, within 96 days.

Table 4. Yield of green corn with and without leaves; number of ears per plant; ear diameter

Treatments	Yield		Ear	EarL	EarDM
	with leaves	without leaves			
	Mg ha^{-1}		ears per plant	cm	mm
Control (no N fertilization)	4.18 b	2.67 b	1.06 a	10.37 b	28.67 b
Castor cake	8.02 a	5.18 a	1.25 a	13.12 a	34.10 a
Bokashi	7.23 a	4.64 a	1.05 a	13.89 a	34.73 a
Legume fertilizer	7.06 a	4.37 a	0.96 a	13.32 a	33.44 a
Cattle manure	7.13 a	4.29 a	1.11 a	11.48 b	31.38 b
Mean	6.72	4.23	1.09	12.44	32.46
CV (%)	22.49	18.99	13.70	8.14	7.41

Means followed by the same letters do not differ by the Scott-Knott test at 5 % probability. EarL = ear length; EarDM = ear diameter.

In the second experiment, similarly to the first study, volatilization was significantly reduced by organic fertilizer incorporation into the soil, except in the case of cattle manure (Table 5), with reductions of 92 % for castor cake, 85 % for bokashi, and 83 % for legume fertilizer. These results confirmed that the incorporation of organic fertilizers into the soil mitigates N losses by ammonia volatilization.

To recover 95 % of the N lost by NH_3-N volatilization, it took 13 days for castor cake, 14 days for bokashi, 17 days for legume fertilizer, and 43 days for cattle manure (Figure 2). These data show that the ammonia volatilization rate in the summer/autumn is more accelerated than that observed in the winter/spring, which is probably due to the higher temperatures in this period of the year.

Table 5. Ammonia volatilization rate from different fertilizers applied to summer/autumn corn

Fertilizer sources	Management	
	Surface-applied	Soil-incorporated
	%	
Control	-	-
Castor cake	38.18 Aa	3.06 Ab
Bokashi	13.77 Ba	2.08 Bb
Legume fertilizer	8.82 Ba	1.48 Bb
Cattle manure	2.44 Ca	1.88 Ba
CV Plot (%)	19.36	
CV Sub-plot (%)	23.64	

Means followed by the same lowercase letters in a row and uppercase letters in a column do not differ from each other by the F-test and Scott-Knott test at 5 % probability, respectively. - = no N volatilization detected in the control treatment.

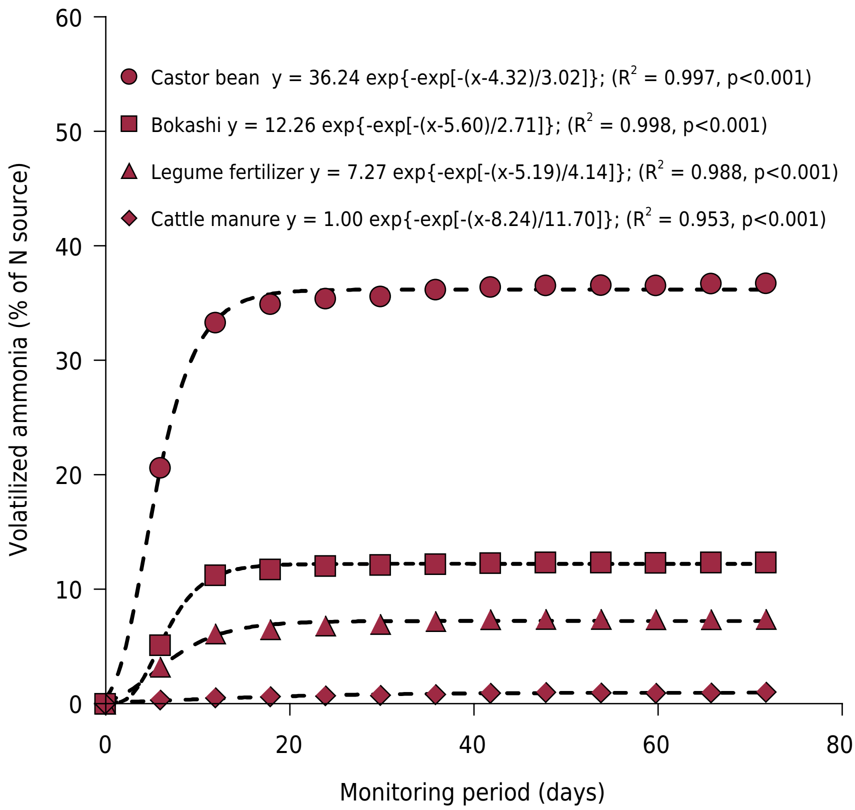

Figure 2. Ammonia volatilized from different surface-applied fertilizer sources (castor bean, bokashi, legume fertilizer, and cattle manure) in corn cultivation, within 72 days.

CONCLUSIONS

Castor cake is the organic fertilizer with the highest nitrogen loss through NH_3 volatilization when surface-applied, both in winter/spring and summer/autumn cultivation.

The incorporation of organic fertilizers significantly reduces N losses by NH_3 volatilization, compared to fertilizers spread on the soil.

The N loss rate by ammonia volatilization varies from 3 to 25 % in winter/spring and 2 to 38 % in summer/autumn among the studied organic fertilizers.

The period required to recover 95 % of N lost as NH_3-N volatilization varies from 13 to 18 days for castor cake; 14 to 43 days for bokashi; 17 to 49 for legume fertilizer; and more than 43 days for cattle manure.

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