NITROGEN RELEASE FROM LAND-APPLIED ANIMAL MANURES

M.L. Cabrera and R.M. Gordillo

AUTHORS: Crop and Soil Sciences Department, Plant Sciences Building, The University of Georgia, Athens, Georgia 30602.

REFERENCE: *Proceedings of the 1995 Georgia Water Resources Conference*, held April 11 and 12, 1995, at The University of Georgia, Kathryn J. Hatcher, Editor, Carl Vinson Institute of Government, The University of Georgia, Athens, Georgia.

Abstract. Animal manures are a valuable source of nitrogen (N) for crops. However, not all N in manure is available to plants. In general, manure N in inorganic form is immediately available to plants, although some inorganic N may be lost through ammonia volatilization and denitrification, and some may be immobilized by microorganisms. Another fraction of manure N available to plants is that proportion of organic N that is mineralized within a crop's growing season. This mineralized N is also susceptible to losses through ammonia volatilization and denitrification, and to immobilization by soil microorganisms. Thus, to determine the correct N-supplying capacity of animal manures it is necessary to know the amounts of inorganic and organic N present in the manure, the fraction of organic N that is mineralizable, and the magnitude of processes that decrease the availability of released N.

NEED FOR ESTIMATES OF N AVAILABILITY

Manures generated in confined animal production are a valuable source of nitrogen (N), phosphorus (P), and potassium (K) for crops. The application rate of these animal manures is typically based on the material's capacity to supply N. Consequently, good estimates of N availability are essential to determine correct application rates.

When applied at the rates required to supply adequate N, animal manures often provide more P than crops remove, leading to a buildup of soil P. Once soil available P reaches a threshold value, runoff water can carry excessive amounts of P to streams and lakes, causing eutrophication. When P reaches this threshold value, the rates of application should be based on the P requirement of the crop and on the material's capacity to supply P (Sharpley et al., 1994). When this situation arises, part of the N required by the crop is not met by the applied manure and has to be provided by supplemental fertilizer N. In that case, knowledge of the amount of N supplied by the applied manure is needed to estimate the amount of fertilizer N to add. Thus, independently of whether animal manures are applied for N or P, a correct estimation of their N-supplying capacity is needed to ensure adequate crop nutrition, and to avoid surface and ground water contamination with N.

A MODEL FOR ESTIMATING N AVAILABILITY

Sims (1986) proposed the following model for estimating available N in poultry manure: Available N = $A_i N_i + P_m N_o$, where N_i and N_o are inorganic and organic N in the manure, respectively, A_i is the fraction (0-1) of inorganic N that is available, and P_m is the fraction (0-1) of organic N that is mineralizable. A similar model was proposed by Beauchamp (1983) for liquid cattle manure. The relative importance of each of the terms of this equation depends on the relative proportion of organic and inorganic N in the manure.

INORGANIC N IN ANIMAL MANURES

Fresh and Composted Manures

In general, fresh and composted animal manures have a lower proportion of inorganic than organic N. For example, the proportion of inorganic N in cattle manure typically ranges from 1 to 11% (Table 1), although values as high as 34% have been reported (Paul and Beauchamp, 1993). Similarly, inorganic N in swine manure generally ranges from 4 to 15% of total N (Table 1). On the other hand, values reported for poultry manure have been as high as 50%, possibly suggesting a more mineralizable organic N fraction than that in cattle and swine manures (Table 1). Composted animal manures usually have low levels of inorganic N due to gaseous N losses (Martins and Dewes, 1992; Keener and Hansen, 1992) and to N immobilization during the composting process (Table 1).

Most of the inorganic N in fresh and composted manures is commonly found in NH_4 form, although relatively high NO_3 concentrations have been reported (Sims, 1986; Bitzer and Sims, 1988; Cabrera et al., 1994) . The amount of NO_3 in animal manures depends on the presence of nitrifiers, which are likely to be derived from soil. Thus, animal manures that have been in contact with soil are likely to have higher NO_3 contents than those that have not. Cabrera et al. (1994) found that two poultry litter samples from houses with "dirt" floors contained more than 2000 mg NO_3-N kg^{-1}, whereas a sample from a house with cement floor did not contain NO_3. The concentration of NO_3 in animal manures in which nitrifiers are active also depends on the existence of conditions that favor denitrification. Storage of animal manures with high moisture content may lead to large losses of NO_3 through denitrification (Cabrera and Chiang, 1994).

Manure Slurries

In contrast to fresh and composted manures, slurries typically contain more inorganic than organic N (Table 2). This is apparently the result of mineralization of organic N during storage. Nodar et al.(1992) found that the proportion of inorganic N in poultry slurry increased from 30% when fresh to 64% after 14 weeks of storage.

As in the case of fresh and composted manures, most of the inorganic N in slurries is present as NH_4. This is apparently due to the existence of conditions that favor denitrification and discourage nitrification within the slurries (Oenema and Velthof, 1993).

Table 1. Dry matter and total N contents, and proportion of total N present in inorganic form in manure samples

No of samples	Dry matter (g kg^{-1} wet manure)	Total N (g kg^{-1} dry manure)	Range Inorganic N (% of Total)	Mean Inorganic N (% of Total)	Ref.
a) cattle manure					
1	N.G.†	15.3	0.2	0.2	32
1	N.G.	23.2	0.9	0.9	23
1	N.G.	25.6	0.9	0.9	12
1	170	17.9	4.4	4.4	16
3	175-198	22.6-25.8	18.7-33.8	26.2	31
1	167	24.5	5.7	5.7	34
3	235-236	47-56	1.8-28	11.0	2
2	N.G.	19.9-28.7	1.9-2.7	2.3	12
1	N.G.	22.4	1.6	1.6	13
3	N.G.	10.5-12.8	0.7-6.1	2.7	37
b) swine manure					
1	271	39.7	14.9	14.9	34
1	N.G.†	38.6	3.7	3.7	12
1	N.G.	21.2	6.4	6.4	13
2	N.G.	23.1-28.5	0.4-1.1	0.8	37
1	N.G.	30.8	8.3	8.3	4
c) Poultry manure					
1	N.G.†	51	8	8	23
2	815-869	34-40	10-14	12	18
1	N.G.	45.9	3	3	12
1	N.G.	22	10	10	13
1	270	60.3	50	50	34
2	N.G.	21.3-31.2	3.5-4.5	4	37
19	N.G.	18.2-81.3	19-55	40	7
3	N.G.	43.9-58.5	6-18	12	10
3	770-840	27.7-45.9	11-13	12	11
3	N.G.	40.4-49.3	23-30	28	38
1	661	32.4	16	16	8
15	520-810	26.8-59.6	6.7-18	11	Un
1	N.G.	50.6	11	11	44
13	N.G.	34.8-46.5	20-25	22	45
d) Composted manure					
2	150-809	10.7-14.8	2.6-4.9	3.7	8
2	N.G.†	12.5-14.1	2.8-3.4	3.1	44
1	N.G.	17.0	12.6	12.6	12
1	N.G.	9.4	1.0	1.0	44
1	N.G.	19.1-19.7	1.5-1.6	1.5	12
3	158-216	22.7-27.7	3.1-5.1	4.1	31

† N.G. = Not given

Availability of Inorganic N in Animal Manures

According to the model proposed by Sims (1986), the availability of inorganic N in manures depends on the value of A_i. Beauchamp (1986) and Bitzer and Sims (1988) used A_i=0.8 for liquid cattle manure and poultry litter, respectively. This value was selected based on the assumption that 20% of the NH_4 would be lost through NH_3 volatilization. The authors concluded that in addition to NH_3 losses, it is necessary to consider losses through leaching, denitrification, and immobilization. Thus, the availability factor A_i could be defined as follows:

$$A_i = 1 - F_iNH_3 - F_iLch - F_iDen - F_iImm,$$

where F_iNH_3 is the fraction (0-1) of inorganic N that is volatilized as NH_3, F_iLch is the fraction (0-1) lost through leaching, F_iDen is the fraction (0-1) lost through denitrification, and F_iImm is the proportion of inorganic N that is immobilized. It should be noted that when estimating the availability of inorganic N in animal manures it is of interest to calculate the amount of manure inorganic N that would behave as N added with inorganic fertilizer. It is well known that leaching, denitrification, NH_3 volatilization, and immobilization losses also occur with fertilizer N, which is the reason why the efficiency of use is normally less than 100 %. The purpose of the factor A_i is to account for leaching, denitrification, NH_3 volatilization, and immobilization losses that occur in addition to those that normally occur with fertilizer N. That is, A_i should account for losses that occur due to the effect of compounds (other than the N) added in the manure. It is the decomposition of these added C compounds that cause the extra losses.

Losses of manure N through NH_3 volatilization.

Many studies have shown that surface application of animal manures may lead to losses of N through NH_3 volatilization (Beauchamp et al., 1982; Pain et al., 1989; Thompson et al., 1987; Nathan and Malzer, 1994). These losses are due to the alkalinity already present in the manure (Husted et al., 1991) and to the increase in alkalinity caused by mineralization of the manure N (Tyson and Cabrera, 1993). It is this extra NH_3 loss caused by the added alkalinity that should be accounted for by A_i.

Ammonia volatilization losses are commonly high during the first 5 to 10 d after application (Thompson et al., 1990; Cabrera et al., 1993) and show diurnal fluctuations caused by diurnal soil temperature cycles (Nathan and Malzer, 1994). In addition, the occurrence of rains right after application may reduce NH_3 losses due to dilution of the ammoniacal N present in solution, and to incorporation of part of the N into the soil (Whitehead and Raistrick, 1991).

The magnitude of NH_3 losses can be very significant with certain manures. For example, surface application of swine slurry has resulted in losses ranging from 11.2 % (Hoff et al.,1991) to 78% of the NH_4-N applied (Pain et al., 1989). Similarly, losses of 38 to 70% of the NH_4-N have been reported as a result of surface applications of cattle slurry (Thompson et al, 1987; Pain et al., 1989; Thompson et al., 1990).

Data on NH_3 volatilization from fresh manures are scarce, but laboratory studies with poultry manure have shown losses ranging from 37 to 60 % of the surface-applied N (Wolf et al., 1988; Cabrera et al., 1993). In a field study, Nathan and Malzer (1994) found that the application of turkey manure to the soil surface caused an NH_3 loss equivalent to 5.7% of the applied N. Bernal and Kirchmann (1992) measured NH_3 losses equivalent to 2.3, 14.3, and 4.0 % of the total N content of surface-applied fresh, anaerobic, and aerobic swine manure, respectively.

In contrast, NH_3 volatilization from composted manures is relatively low due to the low NH_4 content and to the low rate of mineralization of the organic N (Brinson et al., 1994). It is clear that more field research is needed, especially with manures that have shown high NH_3 volatilization losses in laboratory studies.

Losses of manure N through denitrification

The application of animal manures or slurries to soil may enhance losses of N through denitrification due to the addition of easily decomposable organic compounds (Paul and Beauchamp, 1989). The aerobic decomposition of these compounds causes a fast depletion of oxygen in the soil atmosphere, which favors the development of anoxic microsites adequate for denitrification (Rice et al., 1988). In addition, the organic compounds present in the manure provide the C required for denitrifiers to function. It is this extra denitrification loss, caused by the addition of organic compounds, that sould be accounted for by A_i.

Losses through denitrification are usually lower than those through NH_3 volatilization. Egginton and Smith (1986) made several applications of cattle slurry (100 to 200 kg N ha^{-1}) to grassland during one year, and measured denitrification losses similar to those of control microplots, which were not fertilized. Comfort et al. (1990) injected dairy slurry into soil and measured denitrification losses that accounted for 2.5 to 3.2 % of the slurry's NH_4-N, or 1.0 to 1.3 % of the total applied N. In a laboratory study, Cabrera et al. (1993) measured denitrification losses from pelletized and nonpelletized poultry litter applied to the soil surface. Losses ranged from 0.2 to 0.6 % of the applied N for nonpelletized litter, and from 6.2 to 7.9 % of the applied N for pelletized litter. Thompson et al. (1987) estimated denitrification losses that accounted for 7 to 21 % of the N applied with injected cattle slurry.

Decreases in Nitrogen availability through Immobilization

Animal manures or slurries may increase N immobilization if they contain easily decomposable C compounds with low N contents (King, 1984). Kirchmann (1991) found that part of the inorganic N present in anaerobically treated manure was immobilized after application to soil. This N immobilization was attributed to the fast decomposition of organic compounds generated during the anaerobic treatment. The amounts immobilized, expressed as a percentage of the initial NH_4-N, were 76% for swine manure, 64 % for cattle manure, and 21% for poultry manure. It is this extra N immobilization, caused by the decomposition of organic compounds added with the manure, that should be accounted for by A_i.

MINERALIZABLE ORGANIC N IN MANURES

Estimation of Mineralizable N from Laboratory Incubations

The second part of the N availability model proposed by Sims (1986) refers to the amount of organic N that becomes available through the process of N mineralization. This fraction of the organic N is indicated by the factor P_m in the equation previously described. Typically, P_m is estimated with laboratory studies in which animal manures are mixed with soil and incubated at optimum temperature and moisture conditions for periods that range from one to several months. Although limited in scope, the data available suggest that in general, P_m is smaller for swine and cattle manures than for poultry manures (Table 3). However, much more additional work is needed to better define P_m values for the different types of manure available.

Table 2. Dry matter and total N contents, and proportion of total N present in inorganic form in slurry samples

No of samples	Dry matter (g kg^{-1} wet slurry)	Total N (g kg^{-1} dry slurry)	Range Inorganic N (% of Total)	Mean Inorganic N (% of Total)	Ref.
a) Cattle slurry					
3	80-93	45.1-59.1	56-60	58	39
6	60.8-85.2	46.9-69.6†	60-79	65	40
7	5.6-123.2	29.2-80.1†	30-56	43	14
2	68-71	38.2-53.5	42-58	50	2
1	58.5	67.9	61	61	20
1	113	64.6	59	59	28
1	56-62	46.8-57.6	57-76	64	31
1	113	35.6	26	26	43
b) Swine slurry samples					
9	1.6-123.9	27.7-360.6†	18-92	62	14
8	7.6-68.8	51.1-172.3	45-85	69	5
10	10.5-81.3	66.7-265.9†	68-89	78	40
1	131.6	44.9	38	38	6
1	101.4	87.2	51	51	24
4	26.4-31.1	96.4-136.4	67-78	75	35
c) Poultry slurry samples					
1	12.2	167.3†	87	87	14
2	130-147	51-61.5	84-95	89	2
1	83.9	46.9	30	30	27
1	83.3	46.1	37	37	27
1	83.4	42.2	64	64	27
1	82.5	38.0	64	64	27

† Converted from g N L^{-1} to g kg^{-1} dry slurry with a relationship by Chescheir et al. (1985).

Limited research results have shown that the mineralization of organic N from manures may differ between soils. Castellanos and Pratt (1981) reported that N mineralization from several fresh and composted animal manures was consistently higher in one of the two soils they studied. Similarly, Chae and Tabatabai (1986) observed that the mineralization of N from four animal manures was very low in one of the four soils they used. In some of our recent, unpublished work, we observed differences in the kinetics of N mineralization of the same sample of broiler litter decomposing in 15 different soils. Reasons for these differences between soils are not clear. Therefore, additional work is needed to identify soil characteristics that affect the mineralization of manure N.

Estimation of Mineralizable N from Quick Indices

The estimation of P_m with laboratory incubations is time-consuming and therefore impractical to provide farmers with a quick assessment of the fertilizer value of a given manure. Consequently, some research efforts have been spent on the search for quick indices of mineralizable N.

Castellanos and Pratt (1981) tested total N, NH_4 released by alkaline and acid KMnO4, N released by pepsin, and NH_4 released by 6N HCl as indices of available N in 10 samples of fresh and composted animal manures. They found that the N released by pepsin could explain slightly more than 80% of the variation in available N. Similarly, Serna and Pomares (1991) reported that N released by pepsin could explain 64% of the variation in available N measured in 10 dry manure sample (including sheep, poultry, swine, and cow manures). In addition, Serna and Pomares (1991) found that N released by autoclaving and by acid $KMnO_4$ showed good correlation with N uptake by maize in a 6-week period, and with N mineralized during 6- and 16-week incubations. In a recent, unpublished study, we found that a fast pool of mineralizable N in 15 poultry litter samples correlated well with uric acid content ($r=0.78;p<0.01$) and with soluble organic N in the litter ($r=0.75;p<0.01$).

Working with manures, sewage sludges, and soil amendments, Douglas and Magdoff (1991) found good correlation between the fraction of organic N mineralized and N released into the Walkely-Black acid-dichromate digest ($r=0.91;p<0.05$). In a study with municipal and industrial wastes, King (1984) was able to predict potentially available N with a regression equation that included organic N, total N, and C contents as independent variables. These results indicate that certain manure or waste characteristics play a significant role in determining the ease with which the organic N will mineralize once in contact with soil. Thus, further work in this area seems warranted.

Availability of Inorganic N Released through Mineralization

The availability of N released through mineralization is affected by the same processes discused for inorganic N initially present in manure (i.e. leaching, NH_3 volatilization, denitrification, and immobilization). Therefore, a more complete version of the model of N availability may be as follows:

Available N = $A_iN_i + A_mP_mN_o$, where A_m is the fraction of mineralized N that is available. The term A_m could be defined as follows: $A_m = 1 - F_mNH_3 - F_mLeach - F_mDen - F_mImm$, where the different F_m factors represent fractions (0-1) lost through NH_3 volatilization, leaching, denitrification, and immobilization, respectively. As indicated previously for the inorganic N initially present in the manure, A_m should account for the extra losses that occur as a result of the addition of manure compounds to the soil.

It would be difficult if not impossible to estimate values for all the parameters that make up A_i and A_m from the data available in the current literature. However, consideration of this model in future studies may help to arrive at better estimates of N availability from land-applied animal manures.

CONCLUSIONS

To determine the correct N-supplying capacity of animal manures, it is necessary to know the amounts of inorganic and organic N in the manure, the fraction of organic N that is mineralizable, and the magnitude of processes that decrease the availability of released N. Work is currently needed to identify manure and soil characteristics that determine the fraction of mineralizable organic N in manure. Further work is also needed to better estimate NH_3 volatilization and N immobilization following land application of animal manures.

Table 3. Percent organic N mineralized in incubations of animal manures with soils.

Sample Type	No of samples	Incub Length (d)	Temp (C)	Range Organic N Min. (%)	Mean Organic N Min. (%)	Ref.
swine	2	112	25	8-25	17	37
swine	1	182	30	16-52	39	13
cow	3	112	25	0-13	6	37
cow	1	182	30	13-51	35	13
chicken	1	182	30	21-67	53	13
broiler	3	150	25	25-40	34	38
broiler	3	150	40	17-64	44	38
broiler	19	140	23	21-110	67	7
broiler	15	112	25	41-85	60	Unp
broiler	1	56	25	25-37	31	44
broiler	1	56	25	43-51	47	8
broiler	1	35	25	60-73	67	9
compost	2	56	25	3-6	4	44
compost	2	56	25	0.3- (-4)	-1	8

LITERATURE CITED

1. Beauchamp, E.G., Response of corn to nitrogen in preplant and sidedress applications of liquid dairy cattle manure, *Can. J. Soil Sci.* (63), 377, 1983.
2. Beauchamp, E.G., Availability of nitrogen from three manures to corn in the field, *Can. J. Soil Sci.* (66), 713, 1986.
3. Beauchamp, E.G., Kidd, G.E. and Thurtell, G., Ammonia volatilization from liquid dairy cattle manure in the field, *Can. J. Soil Sci.* (62), 11, 1982.
4. Bernal, P.M. and Kirchmann, H., Carbon and nitrogen mineralization and ammonia volatilization from fresh, aerobically and anaerobically treated pig manure during incubation with soil, *Biol. Fertil. Soils,* (13), 135, 1992.
5. Bernal, P.M., Roig, A., Lax, A. and Navarro, A., Effect of the application of pig slurry on some physico-chemical and physical properties of calcareous soils, *Bioresource Technol.,* (42), 233, 1992.
6. Bernal, P.M. and Roig, A., Nitrogen transformations in calcareous soils amended with pig slurry under aerobic incubation, *Agric. Sci.,* (120), 89, 1993.
7. Bitzer, C.C and Sims, J. T., Estimating the availability of nitrogen in poultry manure through laboratory and field studies, *J. Environ. Qual.* (17), 47, 1988.
8. Brinson, S.E., Cabrera, M.L. and Tyson, S.C., Ammonia volatilization from surface-applied, fresh and composted poultry litter, *Plant and Soil*, (167), 213, 1994.

9. Cabrera, M.L., Chiang, S.C., Merka, W.C., Thompson, S.a. and Pancorbo, O.C., Nitrogen transformations in surface-applied poultry litter: effect of litter physical characteristics, *Soil Sci. Soc. Am. J.*, (57), 1519, 1993.
10. Cabrera, M.L., Tyson, S.C., Kelley, T.R., Pancorbo, O.C., Merka, W.C., and Thompson, S.A., Nitrogen mineralization and ammonia volatilization from fractionated poultry litter, *Soil Sci. Soc. Am. J.* (58), 367, 1994.
11. Cabrera, M.L. and Chiang, S.C., Water content effect on denitrification and ammonia volatilization in poultry litter, *Soil Sci. Soc. Am. J.* (58), 811, 1994.
12. Castellanos, J.Z. and Pratt, P.F., Mineralization of manure nitrogen-correlation with laboratory indexes, *Soil Sci. Soc. Am. J.*, (45), 354, 1981.
13. Chae, Y.M. and Tabatabai, M.A., Mineralization of nitrogen in soils amended with organic wastes, *J. Environ. Qual.*, (15), 193, 1986.
14. Chescheir, III, G.M., Westerman, P.W. and Safley, Jr., L.M., Rapid methods for determining nutrients in livestock manures, *Trans. ASAE*, (28), 1817, 1985.
15. Comfort, S.D., Kelling, K.A., Keeney, D.R. and Converse, J.C., Nitrous oxide production from injected liquid dairy manure, *Soil Sci. Soc. Am. J.*, (54), 421, 1990.
16. Douglas, B.F. and Magdoff, F.R., An evaluation of nitrogen mineralization indices for organic residues, *J. Environ. Qual.*,(20), 368, 1991.
17. Egginton, G.M. and Smith, K.A., Losses of nitrogen by denitrification from a grassland soil fertilized with cattle slurry and calcium nitrate, *J. Soil Sci.*, (37), 69, 1986.
18. Hadas, A., Bar-Yosef, B., Davidov, S. and Sofer, M., Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures, *Soil Sci. Soc. Am. J.*, (47), 1129, 1983.
19. Hoff, J.D., Nelson, D.W. and Sutton, A. L., Ammonia volatilization from liquid swine manure applied to cropland, *J. Environ. Qual.*, (10), 90, 1991.
20. Husted, S., Jensen, L.S. and Jørgensen, S.S., Reducing ammonia loss from cattle slurry by the use of acidifying additives: the role of the buffer system, *J. Sci. Food Agric.* (57), 335, 1991.
21. Keener, H.M. and Hansen, R.C, Practical implications for the composting of poultry manure, paper presented at the 1992 National Poultry Waste Management Symposium, Birmingham, AL, October 6-8, 1992.
22. King, L.D., Availability of nitrogen in municipal, industrial, and animal wastes, *J. Environ. Qual.*, (13), 609, 1984.
23. Kirchmann, H., Carbon and nitrogen mineralization of fresh, aerobic and anaerobic animal manures during incubation with soil, *Swedish, J. Agric. Res*, (21), 165, 1991.
24. Kirchmann, H. and Lundvall, A., Relationship between N immobilization and volatile fatty acids in soil after application of pig and cattle slurry, *Biol. Fertil. Soils*, (15), 161, 1993.
25. Martins, O. and Dewes, T., Loss of nitrogenous compounds during composting of animal wastes, *Bioresource Technology*, (42), 103, 1992.
26. Nathan, M.V. and Malzer, G.L., Dynamics of ammonia volatilization from turkey manure and urea applied to soil, *Soil Sci. Soc. Am. J.*, (58), 985, 1994.
27. Nodar, R., Acea, M.J, and Carballas, T., Poultry slurry microbial population: composition and evolution during storage, *Bioresource Technology*, (40), 29, 1992.
28. Oenema, O. and Velthof, G.L., Denitrification in nitric-acid-treated cattle slurry during storage, *Neth. J. Agric. Sci.* (41), 63, 1993.
29. Pain, B.F., Phillips, V.R., Clarkson, C.R. and Karenbeck, J.V., Loss of nitrogen through ammonia volatilization during and following the application of pig or cattle slurry to grassland, *J. Sci. Food Agric.* (47), 1, 1989.
30. Paul, J.W. and Beauchamp, E.G., Effect of carbon constituents in manure on denitrification in soil, *Can. J. Soil Sci.*, (69), 49, 1989.
31. Paul, J.W., and Beauchamp, E.G., Nitrogen availability for corn in soils amended with urea, cattle slurry and composted animal manures, *Can. J. Soil Sci.* (73), 253, 1993.
32. Pomares, F. and Pratt, P.F., Value of manure and sewage sludge as a N fertilizer, *Agron. J.*, (70), 1065, 1978.
33. Rice, C.W., Sierzega, P.E., Tiedje, J.M. and Jacobs, L.W., Stimulated denitrification in the microenvironment of a biodegradable organic waste injected into soil, *Soil Sci. Soc. Am. J.*, (52), 102, 1988.
34. Reddy, K.R., Khaleel, R. and Overcash, M.R., Nitrogen, phosphorus and carbon transformations in a Coastal plain soil treated with animal manures, *Agric. Wastes*, (2), 225, 1980.
35. Rees, Y.J., Pain, B.F., Phillips, V.R. and Misselbrook, T.H., The influence of surface and sub-surface application method for pig slurry on herbage yields and nitrogen recovery, *Grass and Forage Sci.*, (48), 38, 1993.
36. Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C., and Reddy, K.R., Managing agricultural phosphorus for protection of surface waters: issues and options, *J. Environ. Qual.* (23), 437, 1994.
37. Serna, M.D. and Pomares, F., Comparison of biological and chemical methods to predict nitrogen mineralization in animal wastes, *Biol. Fertil. Soils*, (12), 89, 1991.
38. Sims, J.T., Nitrogen transformations in a poultry manure amended soil: temperature and moisture effects, *J. Environ. Qual.* (15), 59, 1986.
39. Stevens, R.J., Laughlin, R.J., Frost, J.P. and Anderson, R., Evaluation of separation plus acidification with nitric acid and separation plus dilution to make cattle slurry a balanced, efficient fertilizer for grass and silage, *J. Agric. Sci.*, (119), 391, 1992.
40. Sommer, S.G., Kjelleru, V. and Kristjansen, O., Determination of total ammonium nitrogen in pig and cattle slurry: sample preparation and analysis, *Acta Agric. Scand., Sect. B*, (42), 146, 1992.
41. Thompson, R.B., Ryden, J.C. and Lockyer, D.R., Fate of nitrogen in cattle slurry following surface application or injection to grassland, *J. Soil Sci.* (38), 189, 1987.
42. Thompson, R.B., Pain, B.F. and Lockyer, D.R., Ammonia volatilization from cattle slurry following surface application to grassland, *Plant and Soil*, (125), 109, 1990.
43. Trehan, S.P., Immobilization of $^{15}NH_4$ by cattle slurry decomposing in soil, *Soil Biol. Biochem.*, (26), 743, 1994.
44. Tyson, S.C. and Cabrera M.L., Nitrogen mineralization in soils amended with composted and uncomposted poultry litter, *Commun. Soil Sci. Plant Anal.* (24), 2361, 1993.
45. Westerman, P.W., Safley, Jr., L.M. and Barker, J.C., Available nitrogen in broiler and turkey litter, *Trans. ASAE*, (31), 1070, 1988.
46. Whitehead, D.C. and Raistrick, N., Effects of some environmental factors on ammonia volatilization from simulated livestock urine applied to soil, *Biol. Fertil. Soils* (11), 279, 1991.
47. Wolf, D.C., Gilmour, J.T. and Gale, P.M., Estimating potential ground and surface water pollution from land application of poultry litter - II. Publ. no. 137, *Arkansas Water Resourc. Res. Center*, Fayetteville, AR, 1988.