

## Reduction of Ammonia Loss by Mixing Urea with Liquid Humic and Fulvic Acids Isolated from Tropical Peat Soil

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**Abstract: Problem statement:** Fertilizer N use efficiency is reduced by ammonia volatilization. Under low soil CEC and high pH, N from soil solution is released to the atmosphere. Ammonia loss due to low worldwide N use efficiency (33%) has been implicated in global warming. Thus, the objectives of this laboratory study were to evaluate the effectiveness of liquid humic and fulvic acids, isolated from tropical peat soils in reducing N loss from urea fertilizer as well as to investigate the ability of these acids to retain  $\text{NH}_4^+$  and  $\text{NO}_3^-$  or reduce soil pH. **Approach:** Formulated liquid N fertilizers consisting of urea and different types of humic molecules (HA or FA or mixture of both), solid and liquid urea were surface applied to 250 g of soil. A closed dynamic air flow system was used to trap  $\text{NH}_3$  loss in boric acid after which samples were titrated with 0.01 M HCl to estimate  $\text{NH}_3$  loss. After 30 days of incubation, the soil was air dried and analysed for pH, exchangeable  $\text{NH}_4^+$ , available  $\text{NO}_3^-$  and exchangeable cations. The results were analysed using SAS and treatments means were compared using Duncan's New Multiple Range Test (DNMRT). **Results:** The use of humic molecules reduced  $\text{NH}_3$  loss and increased exchangeable  $\text{NH}_4^+$ . The high CEC of Humic Acids (HA) made the LHA treatment the best in reducing N loss after surface application. The presence of HA and Fulvic Acids (FA) increased  $\text{NH}_4^+$  recovery. Even though, the soil pH of all the treatments were high, significant reduction of N loss was observed for humic molecules treatments. **Conclusion:** The use of liquid organic N fertilizer has the ability to reduce  $\text{NH}_3$  volatilization in acid soil. The use of both humic and fulvic acids could be effective in promoting  $\text{NH}_4^+$  retention. Thus, it can be concluding that, humic substances, in general, have great ability in controlling  $\text{NH}_3$  loss and retaining  $\text{NH}_4^+$  in acid soils. It could be a cheapest, practical and easiest way to control N loss.

**Key words:** Ammonia volatilization, humic acids, fulvic acids, liquid N fertilizers, ammonium, nitrate

### INTRODUCTION

Ammonia ( $\text{NH}_3$ ) loss from volatilization processes reduces urea-N fertilizer use efficiency<sup>[1,2]</sup>. According to Raun and Johnson<sup>[3]</sup>, worldwide N Use Efficiency (NUE) was approximately 33%. This low value suggests the environmental problems associated with the use of unbalanced N fertilizers. In considering the economic aspect, 67% loss was estimated to cost USD 15.9 billion. This huge amount of money does not include that needed in maintaining a clean environment with the existence of problems created due to unbalanced use of N fertilizers.

Under normal conditions, ammonium ( $\text{NH}_4^+$ ), hydroxyl ( $\text{OH}^-$ ) and carbonate ( $\text{CO}_3^{2-}$ ) ions are produced rapidly (1 or 2 days) after surface application of urea by urease<sup>[4]</sup>. This leads to the accumulation of  $\text{NH}_4^+$ , which simultaneously increases the soil pH surrounding the application area or near the urea granule<sup>[1]</sup>. The increase of  $\text{OH}^-$ ,  $\text{HCO}_3^-$  and  $\text{NH}_4^+$  concentrations through this process plays a significant role in the rapid loss of N. Rapid liberation of ammoniacal N makes it more fragile, which promotes soluble N (e.g.,  $\text{NH}_4^+$ ) to react with other components in the soil solution and releases  $\text{NH}_3$  gas to the atmosphere<sup>[5]</sup>. Global estimation of N loss from urea

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alone has been estimated at 9 Tg N year<sup>-1</sup><sup>[6]</sup>. While, overall losses from all possible sources reaches up to 54 Mt (or 10<sup>-12</sup> g) NH<sub>3</sub>-N year<sup>-1</sup><sup>[7]</sup>. It must be stressed that, huge losses of N could be one of the critical environmental issues that contribute to global warming.

There are many factors involved in NH<sub>3</sub> volatilization, which can be grouped into soil (e.g., pH, CEC), environment (e.g., temperature, humidity) and management (e.g., surface application, drilling). A number of studies with different approaches has reduced NH<sub>3</sub> loss<sup>[1,2,8-11]</sup>. Acidic materials alone, organic and inorganic additives, mixture of acidic materials and additives could reduce N loss by 60, 38.5 and 49%, respectively<sup>[1,2,9-11]</sup>. Generally, the main concerns for the above mixtures are that they create an acidic environment from acidic materials used and inhibit ureolytic microorganisms' activities which in effect slows down the release of NH<sub>4</sub><sup>+</sup> into the soil and indirectly reduces N loss<sup>[12]</sup>.

In this regard, a new or better fertilizer formulation needs to be developed from organic based materials, which have the capability to retain NH<sub>4</sub><sup>+</sup> (due to high CEC) as well as maintaining low soil pH. Thus, the objectives of this laboratory study were to evaluate the effectiveness of liquid humic and fulvic acids, isolated from tropical peat soils, in reducing N loss from urea fertilizer as well as to investigate the ability of these acids to retain NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> or reduce soil pH.

## MATERIALS AND METHODS

Mineral and peat soil samples were collected at 0-25 cm depth from minimal disturbed area of Universiti Putra Malaysia Bintulu Campus, Sarawak and Kuala Tatau, Sarawak, Malaysia respectively. The mineral soil was a sandy clay loam Typic Paleudults (Nyalau series) and the peat soil was Sapristis (well decomposed humic matter). Both soils were air dried, ground and sieved to pass through 2 mm size.

The soil pH was analyzed using a glass electrode, organic carbon by combustion method<sup>[12]</sup>, CEC by leaching with ammonium acetate at pH 7 before steam distillation<sup>[13]</sup> and exchangeable cations (K, Ca and Mg) using Atomic Absorption Spectrophotometry (AAS). Prior to treatments preparation, humic acid (HA) was isolated according to the method of Susilawati *et al.*<sup>[14]</sup>. Extraction time of 4.5 h using a mechanical shaker at 188 rpm, acidification with 6 N HCl, fractionation under room temperature for 2 h and centrifugation time of 15 min were adopted for preparation of liquid humic acid (LHA) and Liquid Fulvic Acid (LFA). The mixture of LHA+LFA (acidified) and LHA+LFA (unacidified)

were prepared by including or excluding the acidification step and without centrifugation. All treatments had a ratio of 4:50 [urea (g): Distilled water (mL)]. Treatments evaluated in this study were; T0-soil alone, T1-urea (liquid), T2-urea (solid), T3-LHA+Urea, T4-LFA+urea, T5-LHA+LFA (acidified)+urea, T6-LHA+LFA (unacidified)+urea and (T7) ammonium sulphate (liquid).

Ammonia volatilization from the formulated fertilizers was evaluated in a laboratory incubation experiment. A closed dynamic air flow system with modification was used to measure the volatilized NH<sub>3</sub><sup>[15]</sup>. The system consisted of: (1) Air pump with the flow rates ranging from 1-2 L min<sup>-1</sup> and (2) An exchange chamber (500 mL Erlenmeyer flask) and a trap (250 mL Erlenmeyer flask), both stoppered and fitted with an inlet/outlet. An inlet was connected to the chamber with air pump, whilst the outlet was connected to the trap containing boric acid using polyethylene tube. A 250 g of mineral soil was placed in the exchange chamber to a depth of 3 cm. The soils were then moistened with liquid organic fertilizers (as treatments) or liquid urea and/or distilled water up to 75% field capacity. The moisture was maintained throughout the experiment by weighing the samples daily and distilled water was used to top up the difference.

Ammonia was collected in boric acid by air flow circulation, which passed through the exchange chamber into the trapping flask containing 100 mL boric acid with bromocresol green and methyl red indicator. It was then titrated with 0.01 M HCl to estimate the NH<sub>3</sub> released. The data was collected every 24 h for 30 days. At the end of the experiment, the soil samples were removed and air dried. The soil samples were then analyzed for pH (water and KCl), exchangeable NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> and cations (double acid method) (K, Ca and Mg) using atomic absorption spectrometer (AAS-800). The experiment was conducted using a Completely Randomized Design (CRD), with three replications. Treatment effects were assessed using analysis of variance while treatment means were compared using Duncan's New Multiple Range Test (DNMRT). Statistical Analysis System (SAS) version 9.1 was used for the statistical analysis.

## RESULTS

The mineral soil (Nyalau series) pH was acidic in water and KCl (Table 1). The soil contained 0.26% N, 2.99% total organic carbon and 5.16% organic matter. Low exchangeable cations (K, Ca and Mg) was recorded (Table 1). The CEC was 24.5 cmol kg<sup>-1</sup>.

These information are consistent with those reported by Paramananthan<sup>[16]</sup>.

Table 1: Selected chemical properties of nyalau series

Property	Values
pH <sub>w</sub>	4.040
pH <sub>KCl</sub>	3.490
Exchangeable K <sup>+</sup> (cmol kg <sup>-1</sup> )	0.113
Exchangeable Ca <sup>2+</sup> (cmol kg <sup>-1</sup> )	1.002
Exchangeable Mg <sup>2+</sup> (cmol kg <sup>-1</sup> )	1.001
CEC (cmol kg <sup>-1</sup> )	24.500
Total nitrogen (%)	0.260
Total organic carbon (%)	2.990
Organic matter (%)	5.160
C/N ratio	11.500

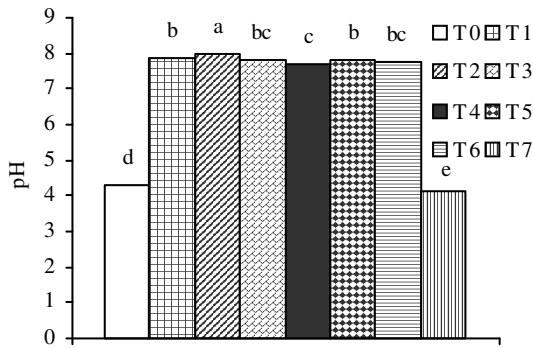


Fig. 1: Soil pH<sub>w</sub> after 30 days of incubation. (Different letter indicate significant difference between means using Duncan's New Multiple Range Test (DNMRT) at p = 0.05)

The pH (water and KCl) recorded for treated soils were significantly different between treatments (Fig. 1 and 2). Soil treated with T1 or T2 gave higher pH<sub>w</sub> value as compared to other treatments; the highest was noted for T2. T5 was the third highest. Statistically it was not different from T1. As compared to T0 and T7, the pH<sub>w</sub> of the treated soil with urea (T1 and T2) and organically based liquid N fertilizers (T3 to T6) was significantly higher. Interestingly, T3 gave almost similar pH<sub>w</sub> values with T6; and these two treatments only showed their differences from T2, T0 and T7. Even though T3 gave the highest pH value (9.04) during liquid organic fertilizer formulation (Table 2), its effect was temporary. After 30 days of incubation, the pH recorded for T3 was among the lowest, among organically based liquid N fertilizers treatments. The lowest pH<sub>w</sub> was recorded for T7 treatment followed by T0 and T4. In considering the effect of humic substances in reducing pH<sub>w</sub>, treated with urea, LFA was better among liquid organic N fertilizer treatments.

In KCl solution, the treatments gave different results. The highest pH<sub>KCl</sub> was recorded for T5, followed by T1, T2 and T4 (Fig. 2). These four

treatments were not significantly different. However, they were significantly different from T6 and T3.

Table 2: Average pH values of formulated liquid fertilizers

Code	Treatment	pH	
		Without urea	With urea
F1	Urea (liquid)	Nd	8.14
F2	HA	1.89	9.04
F3	FA	1.02	1.64
F4	HA+FA (acidified)	0.98	1.60
F5	HA+FA (unacidified)	6.56	6.89

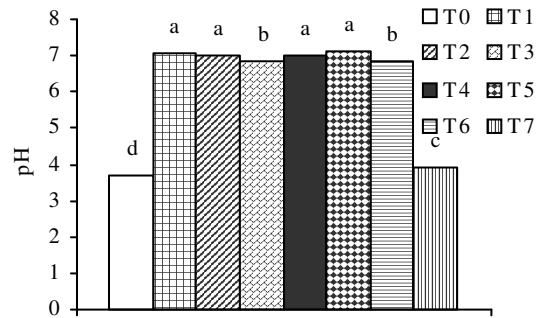


Fig. 2: Soil pH<sub>KCl</sub> after 30 days of incubation. (Different letter indicate significant difference between means using Duncan's New Multiple Range Test (DNMRT) at p = 0.05)

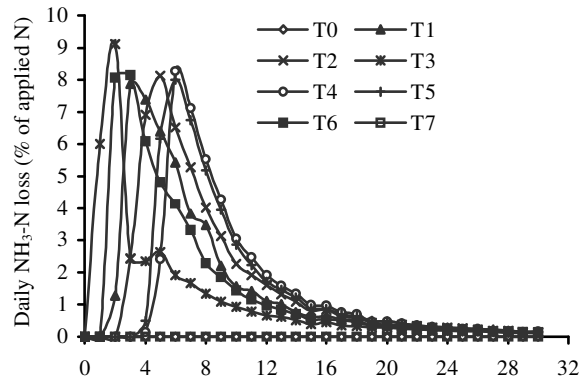


Fig. 3: Daily loss of ammonia for 30 days of incubation

As compared to T0 and T7, all the treatments with liquid organic based N fertilizers showed higher and significant results.

Daily NH<sub>3</sub> loss from T1 and T2 was maximum at day 3 (7.89%) and day 5 (8.12%), respectively (Fig. 3). T4 and T5 recorded similar peaks of NH<sub>3</sub> loss (6 days after treatments application). However, T6 and T3 showed a different trend.

T4 delayed N loss by 1-2 days as compared to T2 and T1, respectively. Similar result was noted for T5 treatment. T6 had no effect in delaying the N loss. In

the case of T3 treatment, N loss occurred a day earlier compared to T2 and 2 days earlier compared to T1.

Table 3: Cumulative NH<sub>3</sub> loss for 30 days of incubation

Label	Treatment	N loss (%)	Reduction obtained as compared to T2 (%)
T0	Control	0 <sup>c</sup>	nd
T1	Urea (liquid)	48.74 <sup>ab</sup>	3.88
T2	Urea (solid)	50.71 <sup>a</sup>	nd
T3	LHA plus urea	35.90 <sup>c</sup>	29.21
T4	LFA plus urea	44.91 <sup>b</sup>	11.44
T5	LHA+LFA (acidified)+urea	46.60 <sup>ab</sup>	8.11
T6	LHA+LFA (unacidified)+urea	48.65 <sup>ab</sup>	4.06
T7	Ammonium sulphate (liquid)	0 <sup>d</sup>	100

Different letter indicate significant difference between means using Duncan's New Multiple Range Test (DNMRT) at p = 0.05; \*nd = Not Determine

Table 4: Soil exchangeable NH<sub>4</sub><sup>+</sup> and available NO<sub>3</sub><sup>-</sup> contents for 30 days of incubation

Label	Treatment	NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg kg <sup>-1</sup> )
T0	Control	12.60 <sup>d</sup>	10.27 <sup>c</sup>
T1	Urea (liquid)	170.80 <sup>c</sup>	12.13 <sup>bc</sup>
T2	Urea (solid)	170.80 <sup>c</sup>	12.13 <sup>bc</sup>
T3	LHA plus urea	179.67 <sup>c</sup>	11.20 <sup>bc</sup>
T4	LFA plus urea	224.00 <sup>b</sup>	12.13 <sup>bc</sup>
T5	LHA+LFA (acidified)+urea	217.00 <sup>b</sup>	18.67 <sup>ab</sup>
T6	LHA+LFA (unacidified)+urea	172.20 <sup>c</sup>	12.13 <sup>bc</sup>
T7	Ammonium sulphate (liquid)	774.20 <sup>a</sup>	21.00 <sup>a</sup>

Different letter indicate significant difference between means using Duncan's New Multiple Range Test (DNMRT) at p = 0.05

The minimum period for maintaining significant N loss (1% from added N, as urea) was different for all the treatments. Generally effects of organically based N fertilizers were different, vis a vis organic molecules type used in fertilizer formulation. In this study, presence of LHA (T3) required a minimum of 10 days to reach 1% N loss, whilst T6 required 12 days. Thirteen and 15 days were recorded for T1 and T2, respectively.

In general, the used of organic additives (e.g., LHA or LFA separately or their mixture) significantly reduced N loss (Table 3). Significant reduction of cumulative N loss, of 29.21% was recorded for T3 followed by T4 (Table 3). Other liquid organic N fertilizers treatments gave no significant effect as compared to T1.

Exchangeable NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> content in the soil were significantly different among treatments. The highest NH<sub>4</sub><sup>+</sup> recovery was recorded for T7 treatment (Table 4). It was followed by T4 and T5. Lowest NH<sub>4</sub><sup>+</sup> recovery was recorded for T1 and T2 followed by T3. Other organic additives did not result in any significant difference as compared to T1 and T2. The effect of T0, T1, T2, T3, T4, T5 and T6 on soil available NO<sub>3</sub><sup>-</sup> was

not significantly different from T7 (Table 4). The NO<sub>3</sub><sup>-</sup> was generally low in the soil after 30 days of incubation (Table 4).

Table 5: Soil exchangeable K, Ca, Mg and Na for 30 days of incubation

Label	Exchangeable cations (cmol kg <sup>-1</sup> )			
	K	Ca	Mg	Na
T0	0.119 <sup>c</sup>	0.754 <sup>a</sup>	0.715 <sup>a</sup>	0.138 <sup>b</sup>
T1	0.113 <sup>c</sup>	0.565 <sup>b</sup>	0.399 <sup>cd</sup>	0.120 <sup>b</sup>
T2	0.117 <sup>c</sup>	0.592 <sup>b</sup>	0.376 <sup>d</sup>	0.121 <sup>b</sup>
T3	0.127 <sup>c</sup>	0.588 <sup>b</sup>	0.412 <sup>bcd</sup>	0.137 <sup>b</sup>
T4	0.199 <sup>b</sup>	0.628 <sup>b</sup>	0.419 <sup>bc</sup>	0.126 <sup>b</sup>
T5	0.221 <sup>a</sup>	0.633 <sup>b</sup>	0.445 <sup>b</sup>	0.130 <sup>b</sup>
T6	0.215 <sup>ab</sup>	0.640 <sup>b</sup>	0.407 <sup>bcd</sup>	0.135 <sup>b</sup>
T7	0.123 <sup>c</sup>	0.817 <sup>a</sup>	0.684 <sup>a</sup>	0.333 <sup>a</sup>

Different letter indicate significant difference between means using Duncan's New Multiple Range Test (DNMRT) at p = 0.05

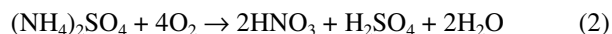
Increase of exchangeable K was recorded for all of the liquid organic N fertilizers (Table 5). As compared to T1, T4, T5 and T6 gave a range of 76 to 95% increase in exchangeable K. Other treatments [including (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] gave no significant results, as compared to T0 or T1 and T2. Exchangeable Ca and Mg from T1, T2, T3, T4, T5 and T6 treatments were lower compared to T0 and T7. They did not show any statistical difference among them. The highest content of exchangeable Na was noted for T7 treatment. It was significantly different from those of T0, urea (T1 and T2) and all organically based liquid N fertilizers (T3 to T6). The Na contents of the other treatments were only significantly different from that of T0.

## DISCUSSION

As expected, solid form of urea resulted in higher pH<sub>w</sub> value compared to other treatments. This was probably due to hydrolysis processes that occurred just after application of urea fertilizer. Hydrogen released mainly by hydrolysis of Al, non-exchangeable hydroxyl Al and Fe and dissolution of organic matter, could be used during urea hydrolysis. This process generates OH<sup>-</sup> which accumulate not only at the microsite but completely in the soil [17]. This may have contributed to the increase of pH. Even though some of the fertilizer mixtures [e.g; T5 (1.60), T4 (1.64)] (Table 2), used in this study were acidic, the pH increased sharply after 30 days of incubation. Higher quantity of H<sup>+</sup> (due to HCl during fractionation stage) in these mixtures could have facilitated urea hydrolysis and promoted the production of OH<sup>-</sup>.

Ammonium sulphate was the effective fertilizer in reducing the soil pH because N fertilizer, in the form of NH<sub>4</sub><sup>+</sup> has the ability to react during nitrification in soils

(equations 1 and 2) to produce acidic residues in the form of  $H^+$ ,  $NO_3^-$  and even  $SO_4^{2-}$ . According to Foth and Ellis<sup>[18]</sup>, almost 12 kg of  $CaCO_3$  will be needed in recovering the acidity by  $(NH_4)_2SO_4$  in 1 kg soil:



The CEC provided by HA, which ranged between 417-583  $cmol\ kg^{-1}$  (based on our previous study) may have contributed to ammonia loss reduction. The negative sites due to ionization of carboxylic (COOH) and phenolic (OH) might have improved  $NH_4^+$  retention hence reduction in N loss<sup>[19]</sup>. These negative charges could develop with the level of salt and pH, that occurred in soil<sup>[20,21]</sup>. More salt will produce more negative charge in soil. A similar situation will occur at high pH. Thus, the presence of KOH (residues by extraction procedure), as a source of salt, could enhance HA charges and indirectly reducing the N loss.

The high pH recorded for water and KCl could be another factor for the efficient use of humic molecules in controlling N loss, due to high pH recorded and could increase the CEC<sup>[21,22]</sup>. Humic molecules have the ability to retain cations at their surfaces. The retention of  $NH_4^+$  might be a factor for the low available  $NO_3^-$  in soil. Reduction conversion of  $NH_4^+$  to  $NO_3^-$  would then occur due to lack of  $NH_4^+$  in soil solution. A similar observation has been reported by Ahmed *et al.*<sup>[23]</sup>.

The information on exchangeable Ca and Mg supports  $NH_3$  loss reduction. The increase in these two cations suggests that there was some replacement and retention of  $NH_4^+$  in the soil treated with liquid organic fertilizers<sup>[23]</sup>. Even though, no statistical difference was observed, the trend of  $NH_3$  loss provides early information on the relationship between  $NH_4^+$  retention, reduction of N loss and exchangeable cations.

T7 caused the highest exchangeable Ca, Mg and Na in this study. This was expected for  $NH_4^+$ -N fertilized soils. Since the exchange sites of soils saturated with cations such as Ca, Mg, Na and K in the order of  $Ca > Mg > K > Na$ , more  $NH_4^+$  in particular is expected to be in soil solution for T7<sup>[18]</sup>.

Higher exchangeable K recorded in some of the treatments was probably due to higher content of K associated with them. Based on our analysis, the content of K in fulvic acid solution was high, almost 2000 ppm in 50 mL. This value was 20 times higher as compared to LHA [previous paper, almost 100 ppm in 50 mL (after 1st washing)]. In the case of T4,

splitting LHA and LFA reduced the K content in LFA solution and this could be the reason why LFA gave lower exchangeable K as compared to T5 and T6 treatments.

## CONCLUSION

Liquid organic N fertilizer has the ability to reduce  $NH_3$  volatilization in an acid soil. Even though, the amount used was small as compared to the quantity of soil used, the effect on  $NH_3$  loss cannot be ignored. HA was the most effective material that effectively controlled  $NH_3$  loss. The use of both humic and fulvic acids is effective in promoting  $NH_4^+$  retention. Thus, it can be concluded that, humic substances, in general, have a great ability in controlling  $NH_3$  loss and retaining  $NH_4^+$  in an acid soil. It could be one of the cheapest, easiest and practical ways in controlling N loss. However, the rate or amount that is most effective together with its possibility to be used as foliar fertilizer needs to be investigated in detail in future research.

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## REFERENCES

1. Fan, M.X. and A.F. MacKenzie, 1993. Urea and phosphate interactions in fertilizer microsites: ammonia volatilization and pH changes. *Soil Sci. Soc. Am. J.* 57: 839-845. <http://soil.scijournals.org/cgi/reprint/57/3/839>
2. Al-Kanani, T., A.F. MacKenzie and H. Blenkhorn, 1990. Volatilization of ammonia from urea-ammonium nitrate solutions as influenced by organic and inorganic additives. *Fertil. Res.*, 23: 113-119. DOI: 10.1007/BF01063338
3. Raun, W.R. and G.V. Johnson, 1999. Improving nitrogen use efficiency for cereal production. *Agron. J.*, 91: 357-363. <http://agron.scijournals.org/cgi/reprint/91/3/357>
4. Zhengping, W., O. Van Cleemput, L. Liantie and L. Baert, 1991. Effect of urease inhibitors on urea hydrolysis and ammonia volatilization. *Biol. Fertil. Soils*, 11: 43-47. DOI: 10.1007/BF00335833
5. Hayashi, K., S. Nishimura and K. Yagi, 2008. Ammonia volatilization from a paddy field following applications of urea: Rice plants are both an absorber and an emitter for atmospheric ammonia. *Sci. Total Environ.*, 390: 485-494. DOI: 10.1016/j.scitotenv.2007.10.037

6. Oliver, J.G., A.F. Bouwman, K.W. Van der Hoek and J.J.M. berdowski, 1998. Global air emission inventories for anthropogenic sources of NO<sub>x</sub>, NH<sub>3</sub> and N<sub>2</sub>O in 1990. *Environ. Pollut.*, 102: 135-148. DOI: 10.1016/S0269-7491(98)80026-2
7. Van Cleemput, O. and P. Boeckx, 2006. Nitrogen and its Transformations. In: *Encyclopedia of Soil Science*. Vol. 2, Lal, R. (Ed.). Taylor and Francis, New York, ISBN: 082470634X, pp: 1125.
8. Purakayastha, T.J. and J.C. Katyal, 1998. Evaluation of compacted urea fertilizers prepared with acid and non-acid producing chemical additives in three soils varying in pH and cation exchange capacity. *Nutr. Cycl. Agroecosyst.*, 51: 117-121.  
<http://www.springerlink.com/content/xqqr91766k66045/fulltext.pdf>
9. Lethbridge, G. and R.G. Burns, 1976. Inhibition of soil urease by organophosphorus insecticides. *Soil Biol. Biochem.*, 8: 99-102. DOI: 10.1016/0038-0717(76)90072-9
10. Watson, C.J., H. Miller, P. Poland, D.J. Kilpatrick, M.D.B. Allen, M.K. Garrett and C.B. Christianson, 1994. Soil properties and the ability of urease inhibitors N-(n-Butyl) thiophosphoric triamide (nBTPT) to reduce ammonia volatilization from surface-applied urea. *Soil Biol. Biochem.*, 26: 1165-1171. DOI: 10.1016/0038-0717(94)90139-2
11. Zaman, M., M.L. Nguyen, J.D. Blennerhassett and B.F. Quin, 2007. Reducing NH<sub>3</sub>, N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup>-N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. *Biol. Fertil. Soils*. DOI: 10.1007/s00374-007-0252-4
12. Cheftetz, B., P.H. Hatcher, Y. Hadar and Y. Chen, 1996. Chemical and biological characterization of organic matter during composting of municipal solid waste. *J. Environ. Qual.*, 25: 776-785.  
<http://jeq.scijournals.org/cgi/reprint/25/4/776>
13. Keeney, D.R. and D.W. Nelson, 1982. Nitrogen-Inorganic Forms. In: *Methods of Soil Analysis*, Part 2, Page, A.L., D.R. Keeney, D.E. Baker, R.H. Miller, R. Ellis and J.D. Rhoades (Eds.). 2nd Edn., Agron. Monogr. 9. ASA and SSSA, Madison, WI., ISBN: 0891180729 (pt. 2).
14. Susilawati, K., O.H. Ahmed, A.B. Nik Muhamad and M.Y. Khanif, 2007. Effects of extraction and fractionation period on the yield of a tropical peat soil (Hemists) humic acids. *Am. J. Agric. Biol. Sci.*, 2: 202-205.
15. Siva, K.B., H. Aminuddin, M.H.A. Husni and A.R. Manas, 1999. Ammonia volatilization from urea as affected by tropical-based palm oil mill effluent (pome) and peat. *Commun. Soil Sci. Plant Anal.*, 30: 785-804.  
DOI: 10.1080/00103629909370246
16. Paramanathan, S., 2000. *Soils of Malaysia: Their Characteristics and Identification*. Vol. 1. Academy of Sciences Malaysia, Kuala Lumpur, ISBN: 9839445065.
17. Thomas, G.W. and W.L. Hargrove, 1984. The Chemistry of Soil Acidity. In: *Soil Acidity and Liming*, Fred Adams (Ed.). 2nd Edn., Agron. Monogr. 12. ASA, Madison, WI., ISBN: 0-89118-080-X, pp: 3-55.
18. Foth, H.D. and B.G. Ellis, 1988. *Soil and Fertilizer Nitrogen*. In: *Soil Fertility*. John Wiley and Sons, Inc., United States of America, ISBN: 978-0471825074.
19. Stevenson, F.H., 1994. *Humus chemistry: Genesis, Composition, Reactions*. 2nd Edn., Wiley, New York, ISBN: 978-0-471-59474-1, pp: 378-486.
20. Campitelli, P.A., M.I. Velasco and S.B. Ceppi, 2003. Charge development and acid-base characteristics of soil and compost humic acids. *J. Chil. Chem. Soc.*, 48: 91-96.
21. Tan, K.H., 2003. *Electrochemical Properties of Humic Matter*. In: *Humic Matter in Soil and the Environment: Principles and Controversies*, Marcel Dekker, (Ed.). Inc., New York, ISBN: 0-8247-4272-9, pp: 386.
22. Bache, B.W., 2006. Ion Exchange. In: *Encyclopedia of Soil Science*, Vol. 1, Lal, R. (Ed.). Taylor and Francis, New York, ISBN: 082470634X, pp: 916-919.
23. Ahmed, O.H., H. Aminuddin, M.H.A. Husni, A.R. Anuar and A.M. Nik Muhamad, 2008. Enhancing the urea-N use efficiency in Maize (*Zea mays*) cultivation on acid soils amended with zeolite and TSP. *Sci. World J.*, 8: 394-399. DOI: 10.1100/tsw.2008.68