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Full Length Article

Mitigating Ammonia Volatilization from Urea in Waterlogged Condition Using Clinoptilolite Zeolite

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Abstract

Besides causing environmental pollution, ammonia volatilization from nitrogenous fertilizers such as urea reduce urea-N use efficiency in agriculture. Amending urea with Clinoptilolite zeolite may reduce ammonia loss from urea as well as improving chemical properties of soils. This study was conducted to determine the effects of amending an acid soil with Clinoptilolite zeolite on ammonia loss and selected soil chemical properties. An acid soil (Typic Paleudults) was mixed with three rates of Clinoptilolite zeolite. Treatments were evaluated using closed-dynamic airflow system. Standard procedures were used to determine soil pH, total nitrogen, exchangeable ammonium, available nitrate, available phosphorus, exchangeable cations, organic matter, total organic carbon, and cation exchange capacity (CEC). Application of Clinoptilolite zeolite significantly reduced ammonia loss up to 25.33%, increased soil pH, exchangeable ammonium, available nitrate (treatment with highest amount of Clinoptilolite zeolite) and exchangeable cations. However, there was reduction in total titratable acidity, exchangeable Al^{3+} and H^+ ions. Mixing acid soil (Typic Paleudults) with Clinoptilolite zeolite minimized ammonia loss from urea and improved selected soil chemical properties (under laboratory condition).

Keywords: Ammonia loss; Urea; Clinoptilolite zeolite; Soil chemical properties; Exchangeable ammonium; Available nitrate

Introduction

Unbalanced use of urea does not only lead to ammonia (NH_3) loss but it also causes eutrophication, groundwater pollution, acid rain, soil acidification, and greenhouse gas emissions (Tang *et al.*, 2008; Adesemoye and Kloepper, 2009; Ju *et al.*, 2009; Moose and Below, 2009). Furthermore, NH_3 volatilization from urea causes nutrients leaching from leaves of plants besides increasing plants' sensitivity to stress factors (Francis *et al.*, 2008). When urea is surface applied, approximately 90% of N is lost in sandy soils with low buffering capacity (Francis *et al.*, 2008). Ammonia loss from urea occurs when it is hydrolyzed to ammonium carbonate [$NH_2CONH_2 + 2H_2O \rightarrow (NH_4)_2CO_3$] by urease. Afterwards, ammonium carbonate decomposes into NH_3, CO_2, and H_2O. Ammonia loss is also high under warm-dry and cool-wet conditions (McGarry *et al.*, 1987). Ammonia loss is higher under waterlogged or anaerobic condition compared to aerobic condition (Zhengping *et al.,* 1991). For example, photosynthetic activities of aquatic organisms (photoautotroph) in rice fields (anaerobic condition) are reduced by rice canopy. As a result, it reduces carbon dioxide depletion in rice fields and increases the possibility of NH_3 loss (Fillery *et al.,* 1983). Application of algaecide in anaerobic condition reduces water pH.

Ammonia loss from urea can be reduced with application of materials which are high in CEC (Sommer *et al.*, 2006; Omar *et al.*, 2010; Latifah *et al.*, 2011a, b, c) or materials, which lower soil microsite pH (Stevens *et al.*, 1992), moisture, and temperature (Sommer *et al.,* 1991). In a study, zeolite was mixed with dairy slurry to reduce ammonia volatilization (Lefcourt and Meisinger, 2001). Zeolite has also been mixed with acid sulphate soil (Ahmed *et al.,* 2010) or cellulose (He *et al.,* 2002) or triple superphosphate and humic acids (Ahmed *et al.*, 2006a, b) to control ammonia loss from urea in non-waterlogged soils. Mixing zeolite with sago waste water and peat water reduced ammonia loss from urea in waterlogged soils (Omar *et al.,* 2010; Latifah *et al.,* 2011c). However, unlike previous studies where researchers used expensive acidic materials (corrosive and difficult to handle) such as acid sulphate soil, triple superphosphate and peat water to control ammonia loss, in this present study, an acid soil was mixed with Clinoptilolite zeolite alone to control ammonia loss in waterlogged condition. We hypothesized that mixing Clinoptilolite zeolite with an acid soil will effectively reduce ammonia loss from urea. This is possible because the high affinity of Clinoptilolite zeolite for cations such as ammonium will enhance retention of ammonium ions which are produced during urea hydrolysis and release these ions

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timely to minimize the rate of converting ammonium to NH_3. Therefore, this study was carried out to determine the effect of mixing an acid soil (Typic Paleudults) with Clinoptilolite zeolite at different rates on ammonia volatilization from urea, exchangeable ammonium, available nitrate, and other selected soil chemical properties.

Materials and Methods

Soil Sampling, Preparation and Characterization

Typic Paleudults (Bekenu Series) soil was sampled at 0 to 25 cm in an undisturbed area of Universiti Putra Malaysia Bintulu Sarawak Campus, Malaysia (latitude 3° 12' 14.6" N and longitude 113° 4' 16.0" E). The soil was air-dried, ground, and sieved to pass to a 5 mm sieve. The soil was analyzed before and after the incubation study for texture using a hydrometer method, pH in distilled water and 1 M KCl (at ratio of 1:2.5 soil:water or KCl) using a glass electrode (Peech, 1965), organic matter and total carbon using loss-on-ignition method (Piccolo, 1996), total N using Kjedahl method (Bremner, 1965), available NO_3^- and exchangeable NH_4^+ (Keeney and Nelson, 1982), exchangeable cations and available P were extracted using the Double Acid Method (Mehlich, 1953) and cations determined using Atomic Absorption Spectrometer (AAnalyst 800, Perkin Elmer Instruments, Norwalk, CT), whereas available P was determined using the Blue Method (Murphy and Riley, 1962). Cation exchange capacity of the soil was determined using the leaching method (Cottenie, 1980) followed by steam distillation (Bremner, 1965). Total titratable acidity, exchangeable H^+, and exchangeable Al^{3+} were determined using acid-base titration method (Rowell, 1994).

The selected chemical and physical properties of the soil (Table 1) used in this study were typical of Typic Paleudults (Bekenu series) and they are consistent with those reported by Paramananthan (2000) except for CEC, exchangeable calcium, and magnesium.

Clinoptilolite Zeolite Characterization

The Clinoptilolite zeolite used in this study was characterized for pH (Tan, 2005), CEC using CsCl method (Ming and Dixon, 1986), total N (Bremner, 1965) total P, and cations were extracted using the Aqua Regia method (Tan, 2005). Phosphorus in the extractant was determined using the Blue method (Murphy and Riley, 1962) total cations were determined using atomic absorption spectrophotometry. pH of the Clinoptilolite zeolite was higher as expected, but its CEC and total N content were lower (Table 2).

Treatments Evaluation for Ammonia Loss from Urea

The ammonia loss incubation study was conducted using close-dynamic air flow system (Siva *et al.*, 1999; Ahmed *et al.*, 2006a, b). Treatments were arranged in a Complete Randomized Design (CRD) with three replications for 33 days. The treatments per 250 g of soil evaluated in 500 mL conical flask were: T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite. The complete fertilization is equivalent to 1.31 g urea + 1.39 g ERP + 0.88 g MOP + 0.16 g Kieserite + 0.53 g chelated ZnCoBor per experimental unit. The amounts of the fertilizers used were a scaled down for plant density of 3 rice plants hill^{-1}. This fertilizer rate for macronutrients (151 kg ha^{-1} N, 97.8 kg ha^{-1} P_2O_5, 130 kg ha^{-1} K_2O, and 7.6 kg ha^{-1} MgO) (Muda Agricultural Development Authority, Malaysia) was based on the recommended fertilizer for rice whereas micronutrients (2.3 kg ha^{-1} B, 4 kg ha^{-1} Cu, and 4 kg ha^{-1} Zn) fertilization was based on the recommendation of Liew *et al.* (2010). The amounts of Clinoptilolite zeolite used were deduced from the literature (Kavoosi, 2007; Bernardi *et al.*, 2009; Gevrek *et al.*, 2009; Sepaskhah and Barzegar, 2010), where rates of 5, 10 and 15 tons ha^{-1} are equivalent to 20, 40 and 60 g hill^{-1}, respectively.

The incubation study was carried out by mixing soil with Clinoptilolite zeolite for the treatments with zeolite alone after which the mixture was moistened to 100% of field capacity and left over night to equilibrate. Before the fertilizers were applied, the water level in each conical flask was maintained at 3 cm from the soil surface to ensure the system was waterlogged. The water level was marked on the conical flasks. The water level in the conical flask was maintained throughout incubation period (33 days) by adding distilled water as the deficit of the original water level. The fertilizers were applied on the soil surface, air was passed through the volatilization system at a rate of 2.5 L min^{-1} and volatilized ammonia from urea was captured in 75 mL of 2% boric acid solution with bromocresol green and methyl red indicator. The rate of air flow was measured using a Gilmont flow meter (Gilmont Instrument, Great Neck, NY, USA). The boric acid solution was replaced every 24 h and back titrated with 0.05 M HCl to determine ammonia loss from urea. This measurement was continued until the ammonia loss decreased to 1% of the N added in the system (Ahmed *et al.*, 2006a, b, c). This incubation study was conducted in a laboratory with an average temperature of 29.7 ± 1.4°C and an average relative humidity of 70.1 ± 10.5%.

Statistical Analysis

Analysis of variance (ANOVA) was used to detect significant differences among treatments, whereas Tukey's HSD test was used to compare treatment means using Statistical Analysis System version 9.2 (SAS, 2008).

Table 1: Selected chemical and physical properties of Typic Paleudults (Bekenu Series) soil before incubation

Property	Soil
pH_{water}	4.41
pH_{KCl}	3.25
CEC ($cmol_c\ kg^{-1}$)	11.97
Total organic carbon (%)	2.43
Total N (%)	0.08
Exchangeable NH_4^+ ($mg\ kg^{-1}$)	21.02
Available NO_3^- ($mg\ kg^{-1}$)	7.01
Available P ($mg\ kg^{-1}$)	4.85
Exchangeable K^+ ($cmol_c\ kg^{-1}$)	0.10
Exchangeable Ca^{2+} ($cmol_c\ kg^{-1}$)	0.25
Exchangeable Mg^{2+} ($cmol_c\ kg^{-1}$)	0.34
Exchangeable Na^+ ($cmol_c\ kg^{-1}$)	0.22
Exchangeable Fe^{2+} ($cmol_c\ kg^{-1}$)	0.19
Exchangeable Cu^{2+} ($cmol_c\ kg^{-1}$)	Trace
Exchangeable Zn^{2+} ($cmol_c\ kg^{-1}$)	0.01
Exchangeable Mn^{2+} ($cmol_c\ kg^{-1}$)	0.02
Bulk density ($g\ cm^{-3}$)	1.16
Sand %	71.04
Silt %	14.58
Clay %	14.38

Table 2: Selected chemical properties of Clinoptilolite zeolite

Property	Clinoptilolite Zeolite
pH_{water}	8.20
CEC ($cmol_c\ kg^{-1}$)	71.30
Total N (%)	0.22
Total P (%)	0.01
Total K (%)	0.37
Total Ca (%)	0.67
Total Mg (%)	0.10
Total Na (%)	0.76
Total Fe (%)	0.11
Total Cu ($mg\ kg^{-1}$)	15.42
Total Zn ($mg\ kg^{-1}$)	16.75
Total Mn ($mg\ kg^{-1}$)	125.08

CEC: Cation Exchange Capacity

Results

Ammonia Volatilization

Ammonia volatilization was observed for complete fertilization without Clinoptilolite zeolite (T3) on the first day of incubation (Fig. 1). For T2, T4, T5, and T6, the ammonia volatilization started on the second day of incubation. At day 8 of incubation, the highest ammonia volatilization (9.58%) occurred in urea alone (T2). Ammonia loss from urea alone (T2) lasted for 23 days, whereas those of T3, T4, T5 and T6 lasted for 32, 30, 29, and 29 days, respectively. Ammonia volatilization decreased at 12 and 19 days of incubation and it has increased at 13 and 20 days of incubation in all the treatments except for T1. No ammonia volatilization was observed in soil alone (T1). Treatments with Clinoptilolite zeolite (T4, T5 and T6) significantly decreased total NH_3 loss and available P compared to treatments without Clinoptilolite zeolite (T2 and T3) (Fig. 2). The total NH_3

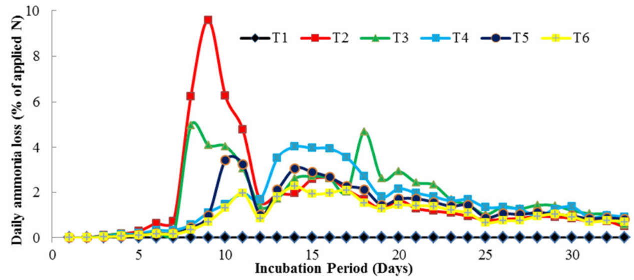

Fig. 1: Daily NH_3 loss for different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) over 33 days of incubation

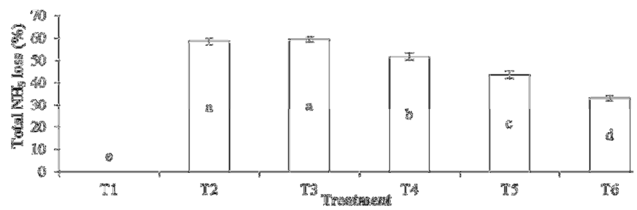

Fig. 2: Total NH_3 loss for different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) over 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at $P \leq 0.05$. The error bars are the ± standard error of triplicates

loss and available P decreased (T4 > T5 > T6) with increasing rate of Clinoptilolite zeolite.

Soil Chemical Properties

Clinoptilolite zeolite in T4, T5, and T6 increased soil pH_{water}, pH_{KCl}, and exchangeable NH_4^+ compared with T1, T2, and T3 (Fig. 3 and 4). The treatment with the highest amount of Clinoptilolite zeolite (T6) showed higher available NO_3^- compared with T3 (Fig. 5). There were no significant differences among treatments in terms of organic matter and total carbon contents after incubation (Table 3). Soil alone (T1) showed the highest total titratable acidity, exchangeable H^+, and exchangeable Al^{3+} compared with other treatments. At 33 days of incubation, the treatments with Clinoptilolite zeolite (T4, T5, and T6) showed higher exchangeable Ca, Mg, Na, Fe, and Mn compared with treatment T3 (complete fertilization without Clinoptilolite zeolite) (Fig. 6, 7, 8 and 9). The contents of exchangeable Ca, Na, Fe, and Mn increased with increasing rate of Clinoptilolite zeolite (T4, T5 and T6).

Table 3: Selected soil chemical properties over 33 days of incubation

Property	T1	T2	T3	T4	T5	T6
Decrease in total NH_3 loss as compared to T2 (%)	nd	nd	nd	6.75	14.90	25.33
OM (%)	4.00^{a} (±0.12)	4.33^{a} (±0.13)	4.07^{a} (±0.18)	3.87^{a} (±0.18)	3.73^{a} (±0.07)	3.93^{a} (±0.18)
TOC (%)	2.32^{a} (±0.07)	2.52^{a} (±0.08)	2.36^{a} (±0.10)	2.24^{a} (±0.10)	2.16^{a} (±0.04)	2.28^{a} (±0.10)
Total N (%)	0.10^{b} (±0.01)	0.15^{ab} (±0.01)	0.13^{ab} (±0.01)	0.16^{a} (±0.01)	0.18^{a} (±0.01)	0.18^{a} (±0.01)
Available P (ppm)	0.35^{e} (±0.02)	23.14^{d} (±2.36)	110.24^{a} (±5.70)	44.89^{bc} (±2.82)	52.25^{b} (±0.81)	29.45^{cd} (±3.28)
Total titratable acidity (meq)	0.37^{a} (±0.01)	0.20^{b} (±0.01)	0.15^{c} (±0.00)	0.21^{b} (±0.01)	0.22^{b} (±0.01)	0.21^{b} (±0.00)
Exchangeable H^+ (meq)	0.27^{a} (±0.01)	0.20^{b} (±0.01)	0.15^{c} (±0.00)	0.21^{b} (±0.01)	0.22^{b} (±0.01)	0.21^{b} (±0.00)
Exchangeable Al^{3+} (meq)	0.11^{a} (±0.01)	0.00^{b} (±0.00)	0.00^{b} (±0.00)	0.00^{b} (±0.00)	0.00^{b} (±0.00)	0.00^{b} (±0.00)

Note: Different alphabets within a row indicate significant difference between means using Tukey's HSD test at P≤0.05; ( ) values in parenthesis represent standard error of triplicates. T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite

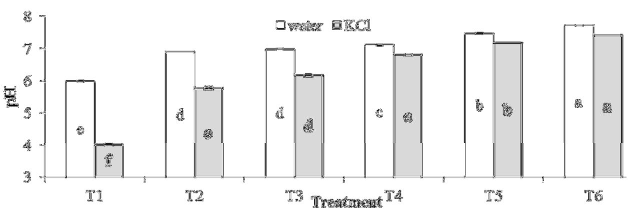

Fig. 3: Soil pH_{water} and pH_{KCL} of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) after 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

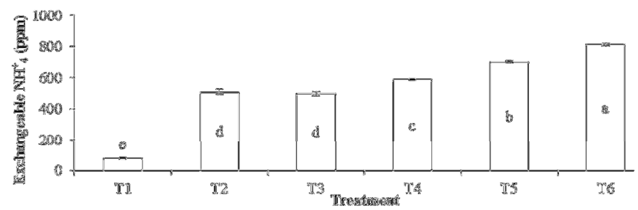

Fig. 4: Soil exchangeable NH_4^+ of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

However, T3 (complete fertilization without Clinoptilolite zeolite) showed the highest exchangeable K, Cu and Zn compared with other treatments (Table 4). Exchangeable K, Cu, and Zn contents in the soil with Clinoptilolite zeolite decreased with increasing rate of Clinoptilolite zeolite.

Discussion

Higher evolution of ammonia from the treatment with urea alone (T2) suggests that urea hydrolyzed and volatilized rapidly. Inclusion of rock phosphate in T3, T4, T5 and T6 delayed ammonia volatilization compared with T2, because of phosphoric acid from acidic phosphate hydrolysis. This reaction may have reduced urea hydrolysis and ammonia volatilization (Ahmed *et al.*, 2006b).

The fluctuation of ammonia volatilization during the incubation study was caused by the reaction between urea and soil water to form NH_4^+. As the soil surface rapidly dried due to air velocity in the chamber, NH_3 from urea decreased at 12 and 19 days of incubation. Ammonia loss decreased when soil water was insufficient for the chemical reaction but it increased at 13 and 20 days of incubation upon addition of water. This observation is consistent with that of Bundan *et al.* (2011). No ammonia volatilization in T1 suggests that the soil alone did not contribute to ammonia loss. This observation is consistent with findings reported in previous studies (Siva *et al.*, 1999; Ahmed *et al.*, 2006a, b, c; Omar *et al.*, 2010; Bundan *et al.*, 2011).

The treatments with Clinoptilolite zeolite (T4, T5 and T6) increased soil pH because of the basic cations in the Clinoptilolite zeolite (Fig. 6, 7 and 8). CEC of the Clinoptilolite zeolite may have partly contributed to reduction of NH_3 loss because of the improvement in the retention of NH_4^+ and NO_3^- (Ahmed *et al.,* 2010). No change in organic matter and total carbon contents regardless of treatment was because there was no addition of organic matter rich materials to the soil. Total titratable acidity, exchangeable H^+, and exchangeable Al^{3+} of the soil alone (T1) were higher, because this treatment showed lowest soil pH and highest exchangeable Fe compared with the other treatments (Gotoh and Patrick, 1974; Williams, 1980). At lower pH, H^+ activity and exchangeable Al^{3+} are higher. Hence, increase in soil pH to 5.2 or higher normally reduces H^+ activity and precipitates exchangeable Al^{3+} (Zhu *et al.*, 2009; Azura *et al.*, 2011).

The CEC of the Clinoptilolite zeolite may have caused adsorption of the cations at the exchange sites of the Clinoptilolite zeolite. This process renders cations readily available for plant uptake (He *et al.*, 1999; Ahmed *et al.*, 2010). The higher Na (almost double the amount of K in

Table 4: Selected soil exchangeable cations ($cmol_c\ kg^{-1}$) at 33 days of incubation

Exchangeable cations	T1	T2	T3	T4	T5	T6
K^+	0.14^e (±0.003)	1.16^c (±0.106)	2.91^a (±0.029)	1.67^b (±0.008)	1.16^c (±0.010)	0.85^d (±0.014)
Cu^{2+}	0.030^{bc} (±0.005)	0.040^b (±0.003)	0.062^a (±0.003)	0.038^b (±0.000)	0.018^{cd} (±0.001)	0.012^d (±0.000)
Zn^{2+}	0.002^c (±0.0001)	0.012^b (±0.0010)	0.026^a (±0.0009)	0.002^c (±0.0002)	0.002^c (±0.0000)	0.001^c (±0.0001)

Note: Different alphabets within a row indicate significant difference between means using Tukey's HSD test at P≤0.05; ( ) values in parenthesis represent standard error of triplicates. T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite

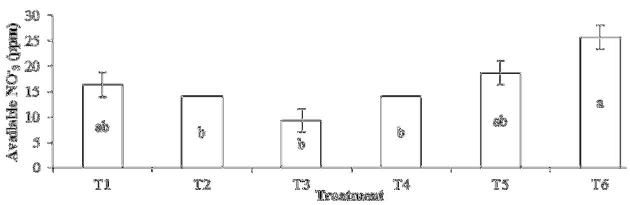

Fig. 5: Soil available NO_3^- of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

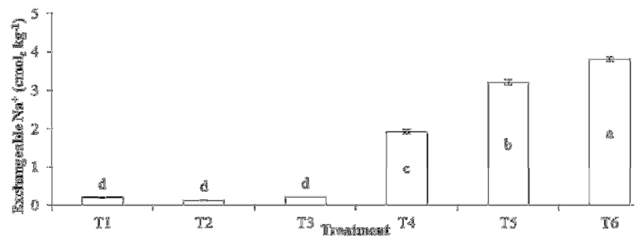

Fig. 7: Soil exchangeable Na^+ of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g zeolite, T5: soil + complete fertilization + 40 g zeolite, and T6: soil + complete fertilization + 60 g zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

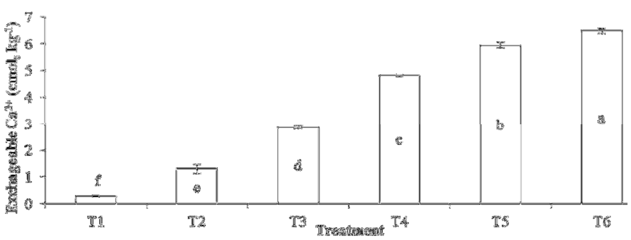

Fig 6: Soil exchangeable Ca^{2+} of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

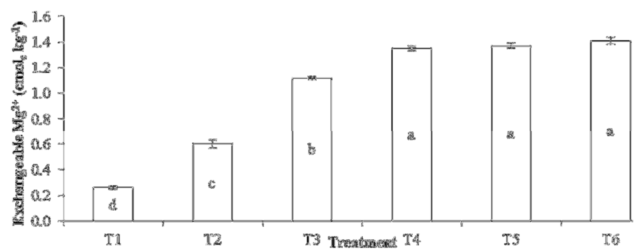

Fig. 8: Soil exchangeable Mg^{2+} of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at P ≤ 0.05. The error bars are the ± standard error of triplicates

Clinoptilolite zeolite) content compared with K in Clinoptilolite zeolite may have reduced K availability in the soil after 33 days of incubation *via* antagonism. The lower contents of Cu and Zn (bivalent cations) in the Clinoptilolite zeolite compared with Ca, Mg, Fe, and Mn may have caused lower availability of Cu and Zn in the soil. Increasing amount of Clinoptilolite zeolite reduced exchangeable Cu and Zn in the soil. This was because the Clinoptilolite zeolite has higher affinity for Cu and Zn than Fe and Mn (Erdem *et al.*, 2004; Iskander *et al.*, 2011).

Conclusion

Mixing an acid soil (Typic Paleudults) with Clinoptilolite zeolite under waterlogged condition reduced ammonia loss from urea and successfully improved ammonium and nitrate ions retention, soil pH, and selected exchangeable cations. Thus, Clinoptilolite zeolite could be used to amend waterlogged acid soils in rice fields to minimize urea-N loss and as well improve soil chemical properties but long term

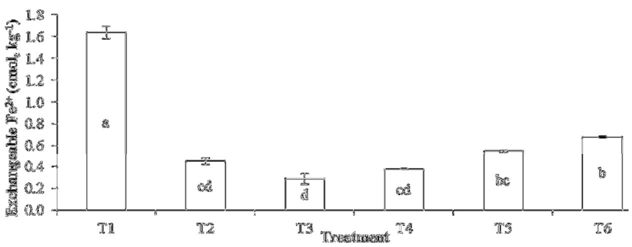

Fig. 9: Soil exchangeable Fe^{2+} of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at $P \leq 0.05$. The error bars are the ± standard error of triplicates

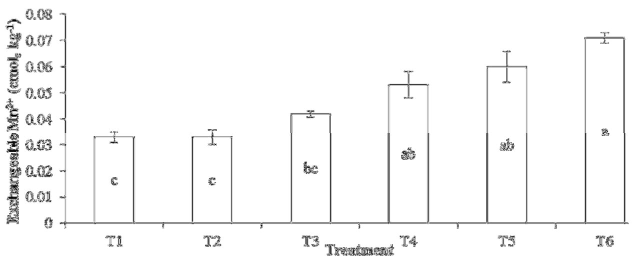

Fig. 10: Soil exchangeable Mn^{2+} of different treatments (T1: soil alone, T2: soil + 1.31 g urea, T3: soil + complete fertilization, T4: soil + complete fertilization + 20 g Clinoptilolite zeolite, T5: soil + complete fertilization + 40 g Clinoptilolite zeolite, and T6: soil + complete fertilization + 60 g Clinoptilolite zeolite) at 33 days of incubation. Different alphabets indicate significant difference between means using Tukey's HSD test at $P \leq 0.05$. The error bars are the ± standard error of triplicates

field evaluation is essential to consolidate the findings in this study. This aspect is being embarked on in our field experiments.

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