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ORIGINAL ARTICLE

Effect of Soil Moisture on Ammonia Volatilization from Urea Applied Alfisol in the Dry Zone of Sri Lanka

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Abstract
Soil moisture is one of the major factors that determines volatilization of urea. In this study, we investigated the effect of soil moisture on urea volatilization from an Alfisol (Reddish Brown Earth soil). A bulk soil sample was collected from the research field of the Faculty of Agriculture, Rajarata University of Sri Lanka. A pot experiment was arranged under completely randomized design with four replicates per treatment. Soil moisture levels were maintained at 0 kPa (volumetric water content (VWC): 33%), 33 kPa (VWC: 16%), 44 kPa (VWC: 8%), and 54 kPa (VWC: 2%) as the treatments. A 50% overhead shade net was hung at 1.8 m aboveground covering the treatment pots. Urea was applied to each pot at a rate of 1,276.5 mg kg^{-1} and emitted NH_3 was collected using the enclosure method. Soil NO_3^--N, NH_4^+-N, pH, and EC were determined at six times at two-day intervals. The effect of soil moisture, time, and their interaction effect on NH_3 volatilization was analyzed using repeated measure *ANOVA* with *post-hoc* Tukey HSD test for mean comparison. The NH_3 volatilization significantly decreased with time ($p < 0.05$). Time and treatment interactions effect were significant for volatilized NH_3 and other soil parameters measured except for soil NO_3^--N ($p < 0.05$). A decreasing trend was observed for NH_3 volatilization at 0 kPa, 33 kPa, 44 kPa & 54 kPa metric suctions as 6.3 g m^{-2} day^{-1}, 4.9 g m^{-2} day^{-1}, 4.7 g m^{-2} day$^{-1,}$ and 0.065 g m^{-2} day^{-1} respectively. Soil NH_4^+-N and EC fluctuated significantly among the treatments. Maintaining the soil moisture at 33 kPa during urea application is recommended for achieving high fertilizer use efficiency.

Keywords: *Alfisols, Ammonia volatilization, N use efficiency, Urea*

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1. Introduction

Global climate change due to anthropogenic activities such as the emission of greenhouse gases in excessive quantities into the lower atmosphere cause many negative impacts on the natural environment such as sea-level rise, melting ice caps in Arctic and Sub Arctic regions and changes in weather patterns (Jungqvist et al. 2014). Erratic patterns of rainfall may lead to fluctuations in soil moisture affecting many biochemical processes such as rates of mineralization, dissolution of organic & inorganic compounds in soil, decomposition of soil organic matter, and nutrient assimilation by plants including those applied to the soil in the form of fertilizers (Jungqvist et al. 2014).

Urea, which accounts for around 50% of the global N fertilizer consumption (Dari et al. 2019), is considered to be the most cost-effective N source for dry zone paddy and other crops cultivated in Sri Lanka within the areas occupied mostly by Reddish Brown Earth (RBE) (Rhodustalf) soil belonging to Alfisols (Liyanage et *al*. 2014). Elliot and Fox (2014) indicate that up to 50% of the total nitrogen in fertilizer could be lost through NH_3 volatilization under favorable soil and weather conditions. Moreover, Adriano et al. (1971) and Hoff et al. (1981) report that the maximum volatilization occurs within 3–5 days of application, and the loss may range from 20–80% of the initially applied fertilizer amount suggesting substantial loss from agricultural soils. Soil applied urea either in granular or liquid form is hydrolyzed by the urease enzyme, producing ammonia and carbonic acids (Dari et al. 2019). The urea volatilization process reduces the //efficiency of nitrogen and other nutrients taken up by plants (Mandal et al. 2016). Therefore, this leads to reduce grower's economic return causing negative impacts on the natural environment like soil acidification and eutrophication (Dari et al. 2019).

Soil moisture and temperature are the major factors affecting NH_3 volatilization, of which, the effect of initial soil moisture content may have a direct impact (Jones et al. 2007). The hydrolysis of urea in the soil is an enzyme-mediated reaction that requires water (Mackenzie et al. 1991). The highest and the lowest NH_3 volatilization from the applied urea occur at the matric water potentials of -0.01 MPa and -1.5 MPa, respectively (Ferguson et al. 1986). There is an 8% increase in NH_3 volatilization from granular urea applied to soil for every 10% increment of initial soil moisture (Mackenzie et al. 1991). By contrast, dry soil with low relative humidity leads to reduce NH_3 volatilization losses from soil (Dari et al. 2019).

The reduction of N use efficiency due to ammonia volatilization from soil applied urea is commonly observed in tropical countries (Patra et al. 1996). However, NH_3 volatilization behavior from urea applied to Alfisols in Sri Lanka has not yet been studied in response to the changes in soil moisture. Among the direct and indirect methods developed to study ammonia volatilization from urea applied soils, high accuracy and precision are observed in direct methods such as enclosure method, venting method, wind tunnel method, and micrometeorological method (Yang et al. 2018). Most of these methods are developed and tested for studying urea volatilization in temperate soils (Lockyer 1984), whereas the applicability of these methods to the tropical soils such as those in Sri Lanka are not widely investigated. Therefore, this study was conducted, (1) to investigate the most appropriate NH_3 trapping method, and (2) to evaluate the effect of soil moisture on NH_3 volatilization. Furthermore, temporal variations of soil parameters like pH, EC, NH_4^+ and NO_3^- following the application of urea were also investigated.

2. Materials and Methods

Study Site and Sample Preparation

This study was conducted in the Research Field, Faculty of Agriculture, Rajarata University of Sri Lanka, which belongs to agroecological zone DL1b. The mean annual rainfall and temperature are 1000 - 1500 mm and 27°C respectively (Punyawardena et al. 2003).

A bulk sample of RBE soils from up to a depth of 0–30 cm was collected from the Research Field, Faculty of Agriculture, Rajarata University of Sri Lanka. The collected soil samples were air-dried and passed through a 2 mm sieve. Approximately, 9.4 kg of soil was packed uniformly in experimental plastic pots to obtain a uniform soil bulk density. The soil was saturated with water and was allowed to air dry naturally. During air drying, soil volumetric moisture content and soil matric suction were periodically measured at saturation, field capacity, half field capacity and air-dried soils using a time-domain reflectometer (TDR; Spectrum FieldScout TDR 350) and tensiometers (IRROMETER 212 Model SR) in triplicates. The TDR was calibrated for the selected Alfisol using the standard procedure mentioned in the user manual for Spectrum FieldScout TDR 350 (Paul 2017). The volumetric water contents and metric suctions were 33% and 0 kPa at saturation, 16% and 37 kPa at field capacity, 8% and 44 kPa at half field capacity, and 2% and 54 kPa at air-dried conditions. Moreover, the polynomial regression models were fitted to describe the relationship between volumetric moisture content and soil matric water potential, which were of the form; $y = -0.0003x^3 + 0.0211x^2 - 0.8121x + 31.429$, where y is the soil volumetric water content (%); x is the soil matric water potential (kPa).

This study was conducted without planting any crops in the pots. For comparison purposes, a 50% overhead shade net was hung at 1.8 m above the treated pots to simulate the shading effect from a typical crop canopy. According to the fertilizer recommendation provided by the Department of Agriculture, Sri Lanka for brinjal, prilled urea was incorporated into the uppermost layer (2–5 cm) of the treatment pots at a rate of 300 kg of N per ha, 325 kg of P per ha and 170 kg of K per ha. Thus, 1276.5 mg kg^{-1} of prilled urea were incorporated into each treatment pot. The soil of each treatment pot was packed to the bulk density of 1.2 Mg m^{-3}.

Comparison of NH_3 Trapping Methods

Treatments of this study were urea-applied pots fitted either with the vented chamber setup or the enclosure setup. Each treatment was replicated four times. In the vented chamber method, NH_3 volatilized from soil was trapped in a mixture of phosphoric acid and glycerol-soaked into a sponge (Fig. 1a). Trapped NH_3 was extracted to 1M KCl solution and NH_4^+ -N concentration of the extractant was analyzed using the salicylate colorimetric method (Nelson 1983). In the enclosure method, NH_3 volatilized from urea applied soils was trapped using 2% boric acid (Fig. 1b). The NH_3 trapped by 2% boric acid was quantified by the titrimetric method using 0.2 M HCl. Volatilized NH_3 from urea applied soil was trapped four times in two days intervals for eight days starting from the time after urea application. The field capacity was maintained in each treatment pot using the TDR (Spectrum FieldScout TDR 350) and tensiometers (IRROMETER 212 Model SR). Metric suction was monitored using the tensiometers which were kept fixed to each pot throughout the experimental period. Soil volumetric moisture measurements were taken by temporally installing the TDR into the pot at the time of measurements by averaging three readings from each pot.

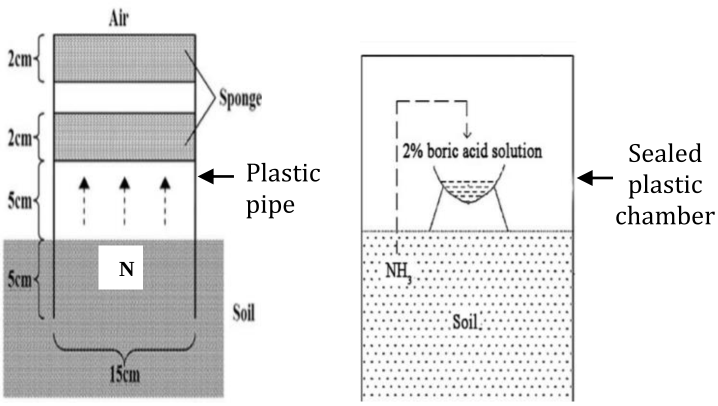


Figure 1: A diagram indicating the installation of (a) vented chamber and (b) enclosure setups to trap the volatilized NH_3 in experimental pots in the Research Field, Faculty of Agriculture Rajarata University of Sri Lanka.

Effect of Soil Moisture on Soil NH_3 Volatilization

A pot experiment was carried out to test the effect of soil moisture on soil NH_3 volatilization. The four treatments of the study were the metric suctions maintained at 0 kPa, 37 kPa, 44 kPa and 54 kPa by applying pre-determined amounts of water to each pot. The predetermined water amount to be added to each pot was quantified based on the soil metric suctions of each pot, measured at 12 hours intervals and the developed regression model describing the relationship between soil volumetric water content and soil matric suction.

Soil Analysis

Soil NO_3^--N, NH_4^+-N, pH, and EC were analyzed six times at two days intervals for 12 days starting from the time after urea application. Soil texture was measured in the bulk soil collected for the pot experiment at the beginning of the study. Soil pH and EC were measured in soil suspensions (Soil/Distilled water 1:5) using pH (HACH - Sension 156; Loveland CO) and EC (HACH - Sension 156; Loveland CO) meters, respectively. The salicylate colorimetric method proposed by Nelson (1983) was used to determine soil NO_3^--N and NH_4^+-N. Soil texture was determined by a simplified hydrometer method (Day 1965) and soil temperature fluctuations were measured using a soil thermometer.

Data Analysis

A pot experiment for investigating the best ammonia trapping method was arranged under completely randomized design (CRD) with two treatments and four replicates per treatment. The effect of soil moisture, time, and their interaction effect on NH_3 volatilization and other measured parameters were analyzed using repeated measure ANOVA with *post-hoc* Tukey HSD test for mean comparison using the SPSS software.

3. Results and Discussion

Comparison of NH_3 Trapping Efficiency

There was a marked difference in the efficacy of trapping volatilized ammonia between the two trapping methods evaluated. The amount of ammonia volatilized were significantly ($p < 0.05$) higher in the enclosure method in comparison to the vented chamber method throughout (Fig. 2) the eight days. The amount of ammonia volatilized was the highest ($p < 0.05$) two days after installation of the enclosure setup. Moreover, the NH_3 volatilization gradually decreased with time in the enclosure method.

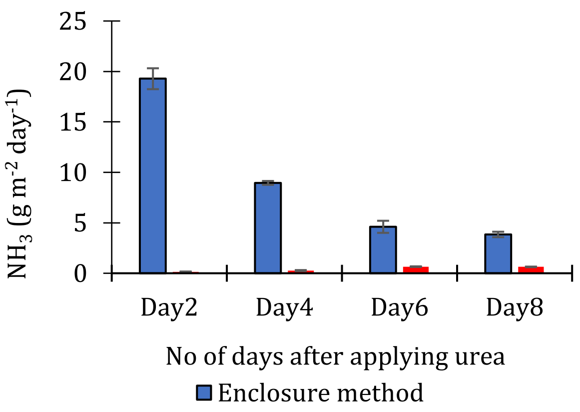


Figure 2: Temporal variation of trapped NH_3 from the urea applied Alfisols, using enclosure and vented chamber methods

According to Shangguan et al. (2012), the enclosure method in comparison to other methods efficiently trap NH_3 volatilized from wheat cultivating soil in winter under ridge and furrow land preparation. Moreover, the vented chamber method is not suitable to investigate NH_3 volatilization from fields having high wind velocity (Yang et al. 2018). Xu et al. (2011) show that the amount of NH_3 trapped by the vented chamber method range from 0.54×10^{-4} to 36.09×10^{-4} kg m^{-2}, indicating that the method was not sensitive to low concentrations of NH_3 gas. The research field also experienced high wind velocity (17.4 km per hour) during the study period. Therefore, the enclosure method was used for measuring volatilized NH_3.

Temporal Variation of NH_3 Volatilization

The soil moisture and the time after urea application appeared to be the most important factors controlling ammonia volatilization. The interaction effect of these two factors on NH_3 volatilization was ($p < 0.05$) significant (Fig. 3). We compared the changes in NH_3 volatilization within a soil moisture treatment. A significant reduction ($p < 0.05$) in NH_3 volatilization was observed at 37 kPa (from 13.69 to 3.67 g m^{-2} day^{-1}) and 44 kPa treatments (from 13.20 to 4.10 g m^{-2} day^{-1}) from the end of two days to end of six days. In contrast, the reduction of NH_3 volatilization in 0 kPa treatment was not ($p > 0.05$) significant from the end of two days to the end of four days and but was significant ($p < 0.05$) from four to six days after urea application (Fig. 3).

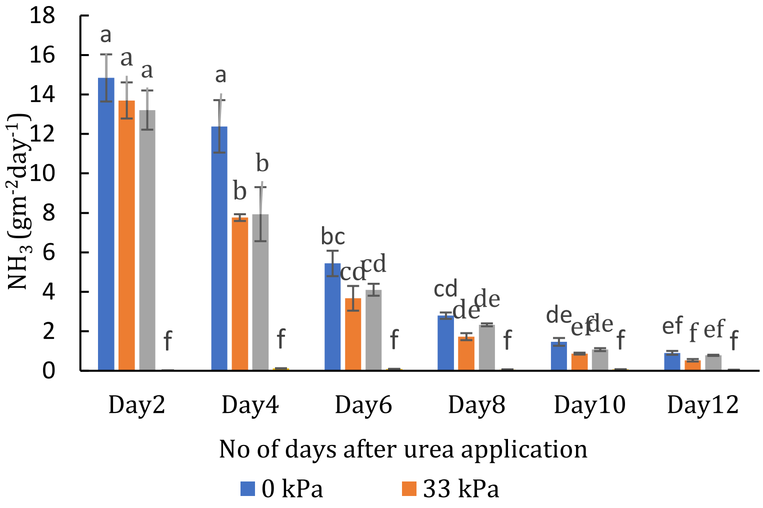
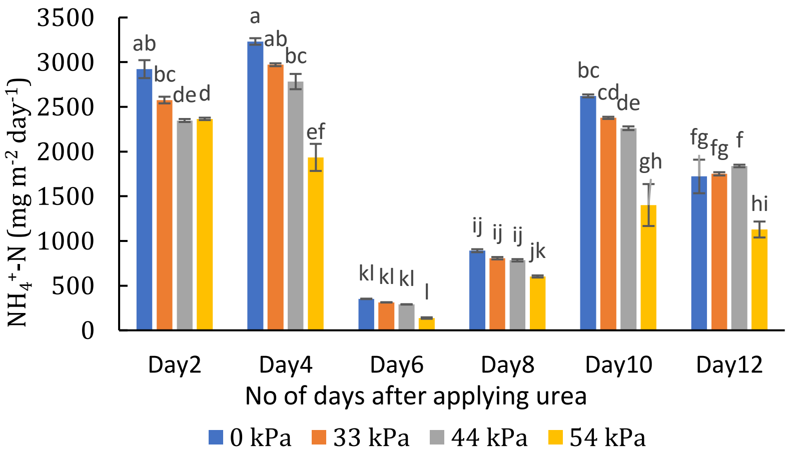


Figure 3: The interaction effects between soil moisture and time on NH_3 volatilization in urea-applied Reddish-Brown Earth soil (Alfisol) in Anuradhapura, Sri Lanka. The bars with different letters are significantly different (p< 0.05).

The NH_3 volatilization is particularly high for six days following fertilizer broadcasting and then sharply drop to relatively low levels (Yao et al. 2018). Moreover, Jones et al. (2007) report that significant NH_3 volatilization from applied urea typically occurs during two to three days after application. Gradual reduction of volatilized NH_3 occur with reduction of urea in soil, due to the loss of N via immobilization, nitrification, plant uptake, and fix in clay and organic matter (Dari et al. 2019).

Temporal Variation of Soil Extractable NH_4^+-N

According to the analysis, the interaction effect of time and soil moisture on soil NH_4^+-N was significant (*p< 0.05*) (Figure 4). A significant (*p< 0.05*) reduction of soil NH_4^+-N (from 2,365.7 mg kg^{-1} to 137.2 mg kg^{-1}) was observed at 0 kPa from the end of two days to six days. In contrast, increase from 2922, 2576, 2347 mg kg^{-1} at the end of two days to 3231, 2971, 2783 mg kg^{-1} at the end of four days and a significant decrease (from 3231, 2971, 2783 mg kg^{-1} to 351, 312, 289 mg kg^{-1}) from the end of four days to end of six days in soil NH_4^+-N were observed for all other treatments. The soil NH_4^+-N of all the treatments gradually increased from 890,806,783 mg kg^{-1} at eight days to 2622, 2377, 2260 mg kg^{-1} at the end of 10 days and decreased from 2622, 2377, 2260 mg kg^{-1} at the end of 10 days to 1721, 1750, 1838 mg kg^{-1} at the end of 12 days (Fig. 4).



Ammonium nitrogen concentration in soil increased up to four days with the hydrolysis of urea, drastically reduce in six days with nitrification, immobilization losses and gradually the concentration increased up to 10 days with accelerating the reverse reaction of the redox reactions of nitrification by denitrifying bacteria and fixing in to clay and organic matter (Dari et al. 2019). The reverse reactions of the redox (denitrifications) reactions were mentioned in Fig. 5. Denitrification is promoted in high soil pH and abundant water. When increasing the concentration of NH_3 by such processes, the NH_3

loss activates again reducing overall retention in the soil.

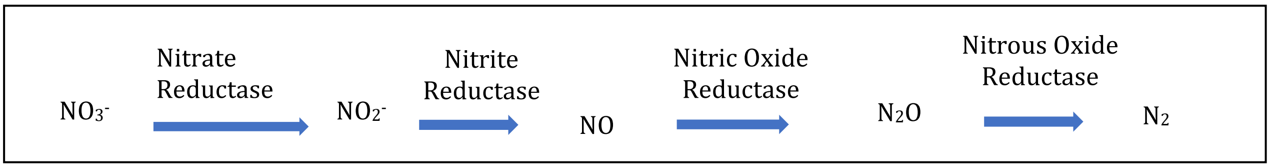


Figure 5: Denitrification processes catalyzed by four different enzymes

Ammonium Nitrogen concentration in soil increased sharply after urea fertilization and reached peak values within 1–3 days, then declined rapidly after 4–9 days. Similar to daily NH_3 volatilization, the daily NH_4^+-N content exhibits the same pattern (Yao et al. 2018).

Temporal Variation of Soil Extractable NO_3^--N

Our results showed that extractable NO_3^--N of the studied soil was significantly influenced by time and soil moisture. A significant reduction (p< 0.05) of average extractable NO_3^--N in the studied soil was observed from 1332.9 mg kg^{-1} at the end of four days to 208.6 mg kg^{-1} at the end of six days due to rapid conversion of NO_3^--N to NH_4^+-N. From the six days onwards, the average extractable NO_3^--N in the studied soil did not fluctuate significantly (p< 0.05*)* (Fig. 6a). Lower levels of soil NO_3^--N were observed at (415.1 mg kg^{-1}) 0 kPa and (181.1 mg kg^{-1}) 54 kPa metric suctions. Anoxygenic condition at 0 kPa and lower moisture condition at 54 kPa have shifted the relevant dynamic reaction to reduce soil NO_3^--N. High levels of soil NO_3^--N were observed at (520 mg kg^{-1}) 37 kPa and (520.0 mg kg^{-1}) 44 kPa metric suctions (Fig. 6b).

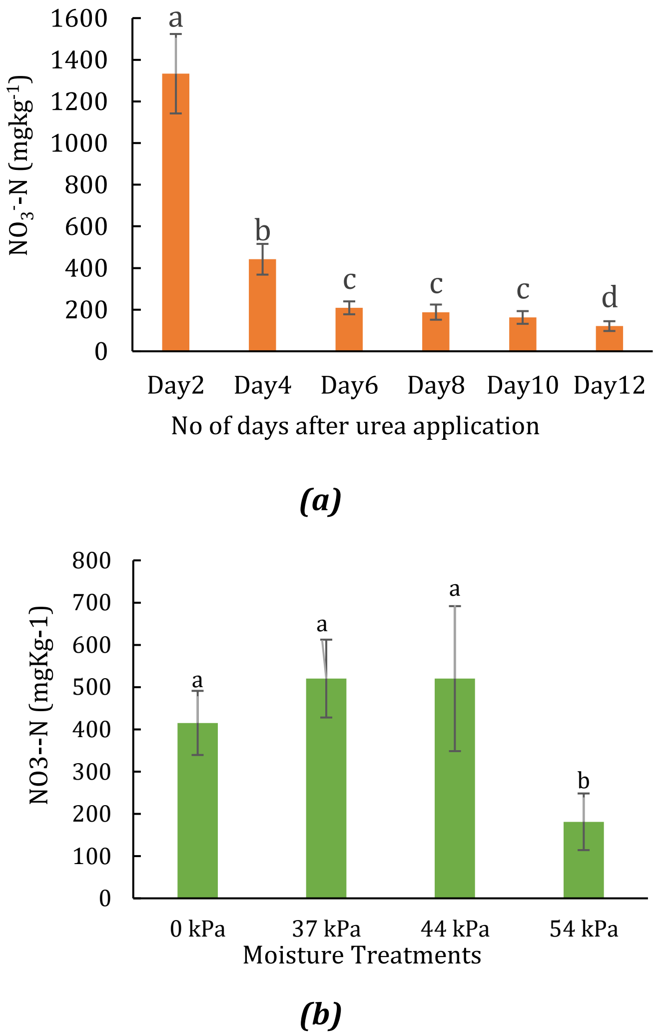


***Figure 6:** Main effect of time (a) and main effect of treatment (b) with soil NO_3^--N concentrations in urea-applied Reddish-Brown Earth soil (Alfisol) in*

Anuradhapura, Sri Lanka. The bars with different letters are significantly different ($p< 0.05$).

Temporal Variation of Soil pH

Repeated measure ANOVA revealed that time and treatment interaction effect on soil pH was significant ($p< 0.05$). However, all the treatments did not follow the same pattern of pH fluctuation over the studied period (Fig. 7).

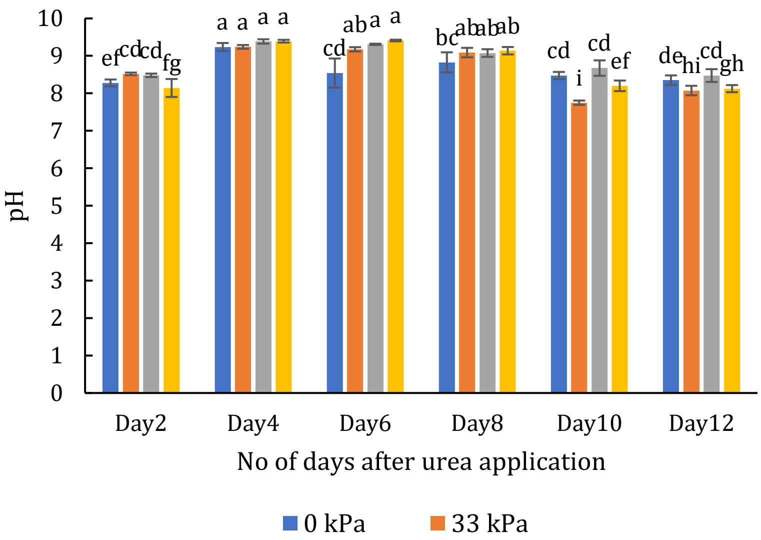
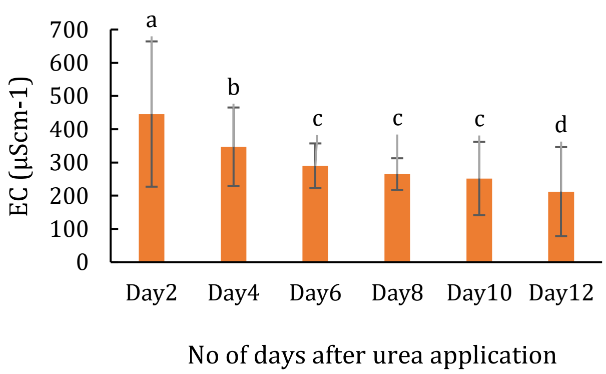


Figure 7: The interaction effects between soil moisture and time on pH in urea-applied reddish brown earth soil (Alfisol) in Anuradhapura, Sri Lanka. The bars with different letters are significantly different ($p< 0.05$).

Among soil factors, pH was considered to be the most important factor in regulating N losses through NH_3 volatilization. When pH was as high as 9.3, the electrical conductivity may not affect on NH_3 volatilization (Patra et al. 1996). Alkaline soils (pH > 7.0) were more susceptible to NH_3 volatilization, while neutral to acidic soils (pH 5.0–7.0) minimize NH_3 volatilization losses. During hydrolysis, the initial soil pH increases surrounding the fertilizer. The ratio of $NH_4^+$to NH_3 was largely dependent on pH thus high pH promote the loss from NH_3 volatilization. Soil application of urea results in elevated pH conditions at the site of fertilizer contact even in neutral to acidic soils, increasing NH_3 volatilization risk. The buffering capacity of soil affects the amount of NH_3 loss affecting on the NH_3 to NH_4^+ ratio (Dari et al. 2019). Our soil remained alkaline irrespective of the soil moisture availability, thus the risk of NH_3 volatilization could be high.

Temporal Variation of Soil Electrical Conductivity

The initial EC of the studied Alfisols was 0.03 dS m^{-1}. According to EC classification, soil can be classified as non-saline soil. However, EC level has increased by 10-folds after urea application. With volatilization of NH_3, electrolytes in soil solution decrease (Fig. 8a). This caused to reduce soil EC significantly ($p< 0.05$) during the studied period. Soil EC showed a positive correlation with soil moisture. High EC was observed at the metric suction of 0 kPa (0.40 dS m^{-1}) due to the high solubility of urea. The moderate EC values were observed at (0.31 dS m^{-1}) 33 kPa and (0.33 dS m^{-1}) 44 kPa metric suctions while the lowest soil EC values were observed in (0.17 dS m^{-1}) 54 kPa metric suctions (Fig. 8b).



(a)

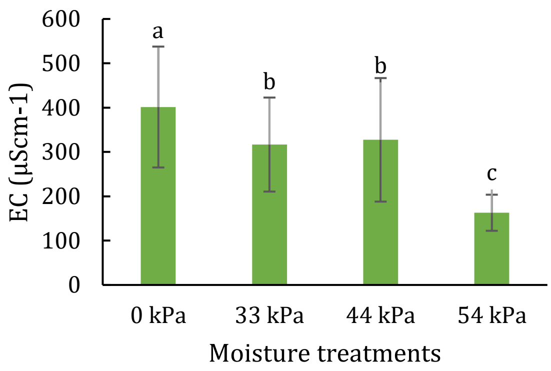


Figure 8: Main effect of time (a) Main effect of treatment (b) with EC in reddish brown earth soil (Alfisol) in Anuradhapura, Sri Lanka. The bars with different letters are significantly different ($p < 0.05$).

Hydrolysis of urea is a water-mediated enzymatic reaction. In fact, urea is hydrolyzed and converted into ammonium carbonate by the naturally occurring urease enzyme in soil (Dari et al. 2019). Therefore, ammonia volatilization efficiently occurs in urea applied soil with high moisture. Ammonium carbonate generated from hydrolysis of urea reacts with H^+ to form ammonium, carbon dioxide and water. The released ammonium is volatilized in the form of ammonia under higher soil pH (Dari et al. 2019). This emphasizes the high impact of soil pH on ammonia volatilization. Furthermore, Dari et al. (2019) and Ernst and Massey (1960) report that alkaline soils (pH > 7) are more susceptible for ammonia volatilization. Soil pH of the studied soil were above 8 over the studied period indicating high tendency to volatilize ammonia from the studied Alfisols. Supporting to these observations, Overrein and Moe (1967) further show soil with heavy surface application of urea significantly increased soil pH. Conversion of soil ammonium N to nitrate N is basically controlled by the nitrification. Nitrification is a process governed by nitrifiers (e.g., *Nitrosomonas* and *Nitrobacter*), a special group of soil microbes (Robertson and Groffman 2015). According to Sahrawat (2008), soil matrix, concentration of soil ammonium, water status, aeration, temperature, and pH are the main factors governing nitrification. In our experiment, application of urea increases soil ammonium concentration drastically. This might be a precursor for converting ammonium to nitrate at the beginning of the study period. This results in high nitrate concentration at the beginning of the study. However, soil nitrate concentration keeps decreasing due to denitrification followed by removal of N from the soil with time. Nitrification was limited to both 0 kPa and 54 kPa metric suctions. This implies that moisture levels of these treatments were not suitable to maintain nitrification at an optimum rate. Electrical conductivity is an indirect measurement of ions concentrations in soil solution (Tan 2011). In this study, continuous reduction of soil nitrate and ammonium might be the reason for decreasing trend of EC over time. Therefore, soil moisture has played an important role in increasing soil EC by facilitating the process of urea hydrolysis.

4. Conclusions

Our study demonstrated how NH_3 volatilization changes under different soil moisture conditions in urea-applied Reddish Brown Earth (Alfisol) in the dry zone of Sri Lanka. The highest and the lowest NH_3 volatilization losses were observed at 0 kPa (saturated conditions) and 54 kPa (air-dried conditions) metric suction indicating the significant impact of soil moisture on the ammonia volatilization in the selected Alfisols.

In addition, ammonia volatilization loss from urea and other ammonia forming fertilizers were controlled by many other soil properties such as pH, soil texture and temperature. High nitrification was observed at 33 kPa and 44 kPa metric suctions leading to greater NO_3^-- N losses via leaching. Out of two ammonia trapping methods, the enclosure method was the most reliable technique to trap NH_3 volatilized from the studied soil. We suggest evaluating the urea volatilization under various integrated nutrient management systems of crops and these results provide important insights into the nitrogen fertilizer management in agricultural fields in the dry zone of Sri Lanka. The reliability of the results can be enhanced by conducting field experiments instead of pot experiments. Remedial actions should be taken for mitigating the significant N losses as NH_3 volatilization from the studied soil.

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Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

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