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ABSTRACT

Ammonia (NH_3) volatilization is one of the major forms of nitrogen (N) losses from soil after N fertilization, especially in salt-affected soil, which leads to low N use efficiency. To evaluate the effect of biochar on NH_3 volatilization from salt-affected soil with two different N fertilizers (urea and ammonium sulfate (AS)), experiments were conducted with two salt-affected soils (electrical conductivity $EC_{1:5}$ of 1.0 and 5.0 ds m^{-1}, namely S1 and S2) and non-saline soil as control (S0, $EC_{1:5}$ < 0.3 ds m^{-1}). Biochar was applied to S1 and S2 at the dosage of 20 t ha^{-1}. Results showed that increasing soil salinity significantly promoted NH_3 volatilization by 38.7%–76.8% than control and AS treatments recorded higher NH_3 volatilization than urea in all salinity levels. The addition of biochar decreased NH_3 volatilization by 10.8%–20.9%. The proportion of cumulative NH_3 volatilization in the first week to the whole experimental period was significantly higher in S1, and biochar addition can reduce the percentages of gaseous N losses. This study unravels the immense capability of salt-affected soil to aggravate N losses in the form of NH_3 volatilization, and biochar can be used as a potential soil amendment in decreasing NH_3 volatilization in salt-affected soil.

Introduction

Nitrogen (N) fertilizer is the most widely used fertilizer worldwide and the primary N source to agroecosystems, and it is often used extensively to enhance crop production (Shan et al. 2015). However, excessive or unbalanced application of N fertilizers to soils leads to a large amount of N losses, especially in the form of gaseous ammonia (NH_3) emission (Bolan et al. 2004; Singh et al. 2010; Clough et al. 2013). Gaseous NH_3 losses from synthetic fertilizers contribute about 20% of the global NH_3 volatilization and up to 45% in Asia (Huo et al. 2015). These high losses of N through NH_3 volatilization pose a major challenge to the environment, since NH_3 has a negative impact on atmospheric quality (Battye et al. 2003; Muñoz et al. 2013). Furthermore, the deposition of NH_3 into terrestrial and aquatic ecosystems causes directly or indirectly soil acidification, N deposition, changes in biodiversity and perturbs ecosystems (Bouwman et al. 1997; Emmett 2007; Ellis et al. 2011).

Salt-affected soils are widely distributed in more than 100 countries on earth, accounting for approximately 23% of the total cultivated land area (Shahid et al. 2018). In salt-affected soil, N is

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generally less available, and NH_3 volatilization was considered much more serious in the salt-affected soils (Dendooven et al. 2010; Elgharably et al. 2010; Steele and Aitkenhead-Peterson 2013), which was attributed to decreased soil adsorption capacity on ammonium (NH_4^+) with an increase in salinity and inhibitory effect of soil salt on nitrification (Weston et al. 2010; Akhtar et al. 2012). Therefore, it is imperative to abate the N losses via NH_3 volatilization, improve the N retention in salt-affected soils and therefore increase the N utilization efficiency both from the sustainable production and environmental viewpoints.

In recent years, biochar has drawn an increasing attention due to its potential as an environmental-friendly soil amendment. Biochar is a carbon (C) rich product derived from the pyrolysis of organic material in the absence of oxygen at relatively low temperatures (< 700 °C) (Clough et al. 2013). The application of biochar to soils can alter the soil properties such as soil pH, water retention characteristics and cation exchange capacity (Lehmann 2007; Novak et al. 2009; Laird et al. 2010) and nutrient cycling (Anderson et al. 2011; Saifullah et al. 2018), alter the rates of the N transformation processes, thereby influencing the N dynamics in soil (Clough et al. 2013) and stimulate microbial immobilization of N and N retention into the soil (Zavalloni et al. 2011). When it comes to salt-affected soil, biochar was reported affected the dynamics of NH_3 oxidizers and nitrification process in coastal alkaline soil (Song et al. 2014) and reduced soil N leaching losses (Singh et al. 2010; Xu et al. 2016).

Although there have been numerous incubation and field studies on NH_3 volatilization from urea applied directly in salt-affected soil (Akhtar et al. 2012; Li et al. 2020), suggesting an increment of NH_3 volatilization with the increase of soil salinity, the effect of biochar application on the gaseous emissions of N in salt-affected soil is poorly documented. How biochar influences NH_3 volatilization in the presence of the interplaying factors such as various N sources and soil salinities and the associated mechanisms are not yet fully understood.

Assuming the addition of biochar to also have mitigation effect on NH_3 volatilization in salt-affected soil, biochar was introduced into soils maintained at different salinity levels with either urea or ammonium sulphate as a soil N source. Soil NH_3 volatilization and the concentrations of soil NH_4^+ were measured. The objectives of this research were to evaluate 1) the effect of biochar on NH_3 volatilization in soils of different salinity levels; 2) the difference of the biochar effect on NH_3 between different N sources. The results are expected to provide new insights for mitigating gaseous N losses based on nitrogen management and usage of biochar as an organic amendment on salt-affected soil.

Materials and methods

Experimental site and soil description

Field experiments were conducted in 2018 summer at the Kunshan Irrigation and Drainage Experiment Station in the Taihu Lake region, Jiangsu Province, China (31° 16′ 9″ N; 120° 58′ 27″ E). The study area has a subtropical monsoon climate with an average annual air temperature of 17.6 °C, a mean annual precipitation of 1,200.4 mm. During the experiment period, daily mean air temperature ranged from 22.0 °C–37.5 °C with an average of 29.1 °C. And daily mean wind speed was 0.65 m s^{-1} (Figure 1).

Soil samples were collected from a deserted field of high salinity level, and the electric conductivity (EC) of the salt-affected soil (0–20 cm) is about 1.0 dS m^{-1} (EC$_{1:5}$, a 1:5 w/w soil/water ratio). The non-saline soil (control) was collected from a neighboring farmland. The average EC of control soil samples is less than 0.3 dS m^{-1}. Soil samples were air-dried and sieved to < 5 mm to remove sand and coarse root fragments, and then mixed thoroughly. The physicochemical properties of soils are listed in Table 1.

Experiment design

Three levels of salinity, namely S0 (control, <0.3 dS m^{-1}), S1 (1.0 dS m^{-1}) and S2 (5.0 dS m^{-1}), were set in this experiment, with salinity level S2 realized by adding sodium chloride to S1 soil samples. The soil samples were filled into the plots (length $\times$ width $\times$ depth = 1 m $\times$ 1 m $\times$ 0.5 m) at the density listed
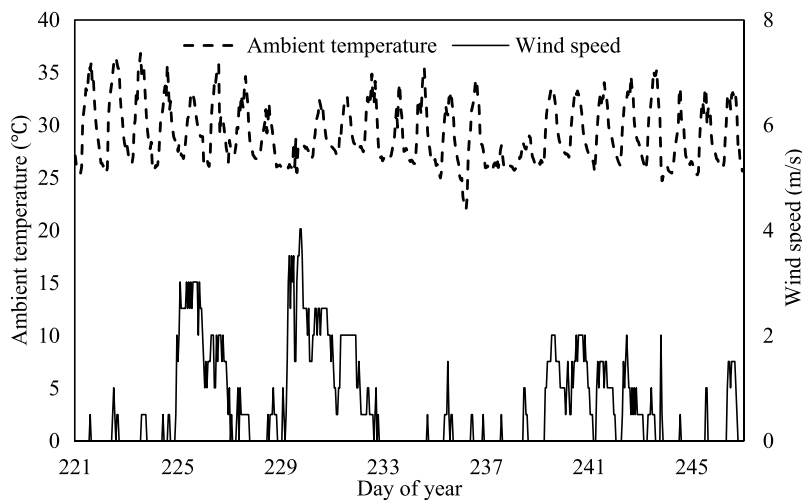
Figure 1. Hourly air temperature and wind speed during the experimental period.

in Table 1, and four acrylic panels welded together are placed around the plots to separate from the surrounding soil. The plots were set aside for more than 6 months to leave enough time for microorganisms to adapt to changing soil conditions. Three replicates were maintained for all treatments. The plots were displayed under an automatic movable rainout shelter. Two types of fertilizers, urea (U, total nitrogen contents (TN) = 46.4%) and ammonium sulfate (AS, TN = 21.1%), were used as the N sources to examine their effect on NH_3 volatilization, both applied at the amount of 120 kg N ha^{-1} in solutions together with the first irrigation, the water used for irrigation was from a river near the experiment site. Additionally, two salt-affected soils (S1 and S2) were applied with biochar to examine the effect of biochar (applied at the amount of 20 t ha^{-1}) on NH_3 volatilization from the salt-affected soil. The main properties of biochar (pyrolysis temperature of 600°C), which was supplied by the Zhejiang Biochar Engineering Technology Research Center, are shown in Table 2. Biochar was evenly spread in the fields manually and incorporated into soil (~ 20 cm) thoroughly using the shovel and hoe before the start of this experiment. A total of 10 treatment combinations (namely S0 + U, S1 + U, S1 + U+ BC, S2 + U, S2 + U+ BC, S0+ AS, S1 + AS, S1+ AS+BC, S2+ AS, S2+ AS+BC) were replicated three times. The experiment employed a randomized complete block design.

NH_3 volatilization measurement

NH_3 volatilization loss from each barrel was captured via the ventilation method using 25 cm high PVC chambers (20 cm in diameter), as described by Xu et al. (2012). The chambers were placed in

Table 1. Properties of salt-affected soil and non-saline soil.

Soil parameters	Non-saline soil	Salt-affected Soil	Signification level
Soil texture (Sand/Silt/Clay) (%)	23.1/62.3/14.6	23.5/64.2/12.3	n.s.
Bulk density (g cm^{-3})	1.34	1.36	n.s.
Initial EC (dS m^{-1})	0.25	1.04	**
pH	7.66	7.73	n.s.
Total C (g kg^{-1})	3.5	2.4	*
Total N (g kg^{-1})	0.4	0.2	*
NH_4^+–N (mg N kg^{-1})	4.6	3.8	n.s.
NO_3^-–N (mg N kg^{-1})	3.5	3.3	n.s.
NO_2^-–N (mg N kg^{-1})	0.3	0.3	n.s.

n.s., * and ** represent no significance, significant differences at $p < 0.05$ and $p < 0.01$, respectively.

Table 2. Main properties of the biochar used in the experiment.

biochar	pH	C content %	Total N %	Total P %	Total K %	CEC cmol kg^{-1}	Special surface area m^2 g^{-1}	Total pore volume cm^3 g^{-1}
Rice straw biochar	10.1	42.6	0.75	0.15	1.06	44.8	81.9	0.08

the central part of each plot, using two sponges (moistened with a 25 mL phosphoglycerol solution in advance) as absorbents. The sponge inside each chamber was to absorb NH_3 volatilized from soil, and the top one was for isolating the effect of NH_3 from the ambient air. The lower sponge samples were collected daily at 10:00 am throughout the whole experiment. Ammonia collected in the phosphoglycerol-moistened sponges inside the chambers was immediately extracted with 300 mL of 1 M KCl solution after 1 h of oscillation, and the extracts were analyzed using an ultraviolet–visible spectrophotometer (Rayleigh UV1800). The AV rate was calculated using Eq. (1)

$$R_{AV} = \frac{M}{A \cdot D} \times 10^{-2}$$ (1)

where R_{AV} is the ammonia volatilization rate (kg N ha^{-1} d^{-1}), M is the amount of ammonia N collected by the PVC collector (mg), A is the cross-sectional area of the PVC collector (m^2), and D is the interval for ammonia volatilization sample collection (d).

Soil characteristics measurement

As the NH_3 volatilization experiment goes, pH, EC and soil moisture content of 0–10 cm soil were measured at five-day intervals through the whole experiment for all the treatments. The gravimetric soil moisture content was determined by oven drying method. The soil pH and EC were measured using a pH meter (Mettler Toledo, Zurich, Switzerland) and a conductivity meter (Spectrum EC450, Aurora, USA) with 1:5 w/w soil/water extracts. NH_4^+ concentrations were measured by extracting the soil samples (dry soil weight = 10 g) with 1 M KCl solution at 220 rpm using an end-over-end shaker for 1 h at 25 °C. After 5 h of quiescence at 4 °C, the supernatant was analyzed for NH_4^+-N concentrations using an ultraviolet–visible spectrophotometer (Rayleigh UV1800).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) and UNIANOVA by the Least significant difference (LSD) test using IBM Statistics 24 and a $p < 0.05$ was considered as statistically significant. The variability of the data was expressed as the standard deviation. Regression analysis was conducted to determine the relationship between NH_3 fluxes and NH_4^+ concentrations.

Results

Soil characteristics

During the experimental period, soil pH ranged between 7.61 and 8.35, but no significant difference was observed between treatments with biochar applied and without biochar, consistent with the finding by Chen et al. (2013) that biochar addition had no remarkable effect on the medium pH (7 or 8) treatment.

Meanwhile, the EC of non-saline soil remained very low during the whole experiment (< 0.3 dS m^{-1}), while that of salt-affected soil increased gradually along with time as soil water content decreased, and gained an increment between 0.3 and 0.5 ds m^{-1} compared to the initial EC. However, this increment was not statistically significant (Figure 2).
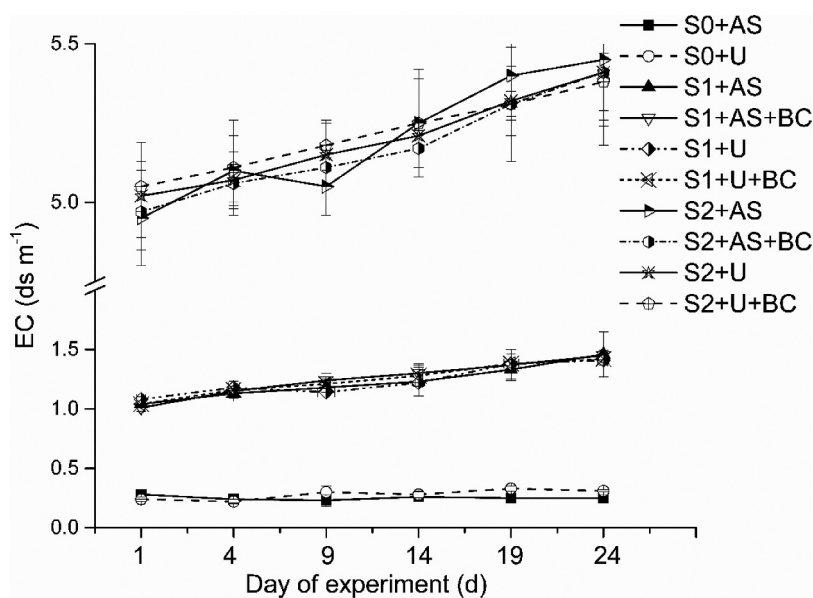
Figure 2. Variations of EC for all treatments along with time. Error bars represent the standard deviation for three replicates.

Cumulative NH₃ volatilization

The results (Figure 3) showed that the gaseous loss of NH_3 rose with increasing soil salinity levels, irrespective of N sources. At the first 7 d of experiment, for the AS treatment, cumulative NH_3 volatilization of S1 and S2 salinity level exceeded the control (S0) by 34.1% and 31.6%, respectively. When it comes to urea, the NH_3 volatilization of S2 salinity level was 6.1% lower than S0, compared to an exceedance of 57.2% in S1. After 24 d of experiment, the cumulative NH_3 volatilization of S1 was increased by 56.9% and 38.7% than S0; for S2 treatment by 66.3% and 76.8%, following the order of urea and AS.

The AS-treated soils recorded higher amount of NH_3 volatilization than urea-treated soils, and followed the order of S2 (20.2 kg N ha^{-1}) > S1 (15.9 kg N ha^{-1}) > S0 (11.4 kg N ha^{-1}), which also implied that soil salinity has a significant effect on NH_3 volatilization. The cumulative NH_3 volatilization did not vary significantly between two different nitrogen managements at S0 and S1, but was significantly lower at S2 salinity level with urea application. It indicated that higher salinity might have an inhibiting effect on the hydrolysis of urea, leading to less NH_3 volatilization after urea application from intensely salt-affected soils.

NH₃ volatilization rate

NH_3 volatilization rates varied among different treatments (Figure 4), due to the effect of N sources, salinity levels and the addition of biochar.

For the soils treated with AS, NH_3 volatilization rate immediately reached a maximum of 4.2, 4.0, 3.9 and 3.8 kg N ha^{-1} d^{-1} at the first day of the experiment, following the order of S1, S1+ BC, S2 and S2+ BC, then had a sharp drop in the next few days. NH_3 volatilization rates did not vary significantly between four different treatments at the beginning of the experiment, while during the later period of the experiment, the NH_3 volatilization rate was significantly reduced by 1.9%–72.0% for the addition of biochar, and NH_3 volatilization rate of S2 gradually exceeded that of S1. Therefore, the cumulative NH_3 volatilization losses within 24 d followed the sequence of S2+ AS (20.2 kg N ha^{-1}) > S2+ AS+BC (18.1 kg N ha^{-1}) > S1+ AS (15.9 kg N ha^{-1}) > S1+ AS+BC (13.8 kg N ha^{-1}).
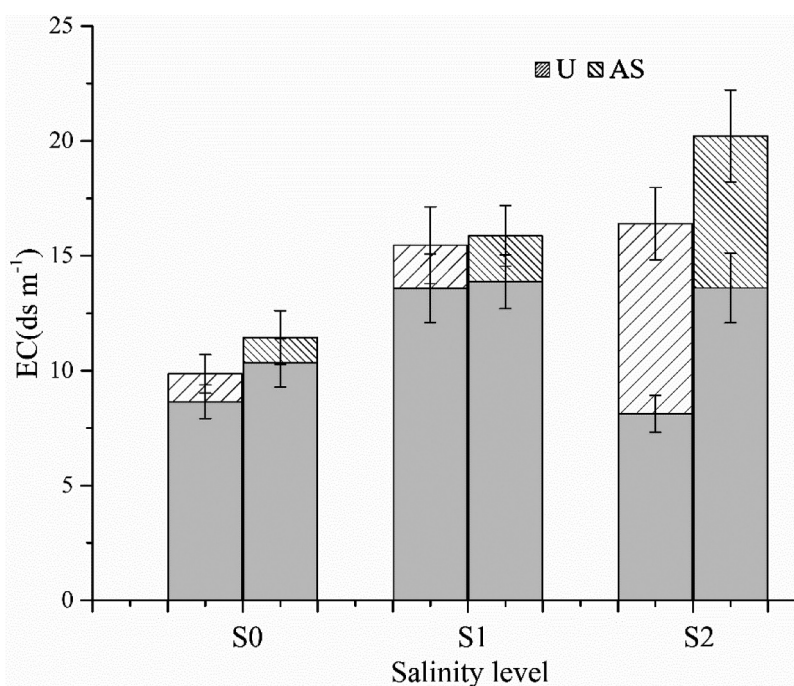
Figure 3. The cumulative NH_3 volatilization as affected by different N sources. The light grey parts represent cumulative NH_3 volatilization in the first week of each treatment irrespectively. Error bars represent the standard deviation for three replications.

Different from AS, it takes time for urea to hydrolyze to be utilized, so NH_3 volatilization rate of soils treated with urea was significantly lower than soils with AS at the beginning of the experiment, regardless of salinity level. For the S1 salinity level, NH_3 volatilization rate reached a maximum around 3.5 kg N ha^{-1} d^{-1} at the second day, which is almost 7 times the peak of S2 salinity level at the same day, and then rapidly dropped to 0.5 (S1 + U) and 0.4 (S1 + U+ BC) kg N ha^{-1} d^{-1} at the seventh day. For the S2 salinity level. NH_3 volatilization rate of S2 + U and S2 + U+ BC reached the peak of 1.5 and 1.3 kg N ha^{-1} d^{-1} at the fourth or fifth day after the N application, respectively, then dropped gradually in the following days. After 7 days of the experiment, NH_3 volatilization rate of S2 remained higher than S1 for the rest of the experiment. During the whole experiment, biochar addition results in a decrease of NH_3 volatilization rate compared to treatments without biochar, and cumulative NH_3 volatilization losses were reduced by 17.8%–20.9%. At the end of experiment, cumulative NH_3 volatilization losses of soils with urea were S2 + U (16.4 kg N ha^{-1}) > S1 + U (15.5 kg N ha^{-1}) > S2 + U+ BC (13.5 kg N ha^{-1}) > S1 + U+ BC (12.2 kg N ha^{-1}).

All the treatments recorded high NH_3 volatilization rates during the first week of the experiment (Table 3). For the S1 salinity level, NH_3 volatilization losses of U, U+ BC, AS and AS+BC in the first week took up 87.9%, 91.2%, 87.4% and 90.2% of 24-day cumulative NH_3 volatilization, respectively, whereas they merely accounted for 49.5%–72.3% at the S2 salinity level. Table 3 also revealed that NH_3 volatilization losses of soils with AS were almost the same between two salinity levels, but were significantly lower at S2 salinity level when it comes to urea. This again confirmed that high salinity has an inhibiting effect on NH_3 volatilization. Due to the addition of biochar, cumulative NH_3 volatilization of soils treated with urea was reduced by 20.9% and 17.8% at S1 and S2 salinity level, respectively. Similarly, in the case of soils with AS, cumulative NH_3 volatilization was reduced by 13.2% and 10.8% at S1 and S2 level. It is noticeable that this reduction effect of biochar addition on NH_3 volatilization was more prominent in treatments with urea than AS, and it requires further study to gain a better understanding.
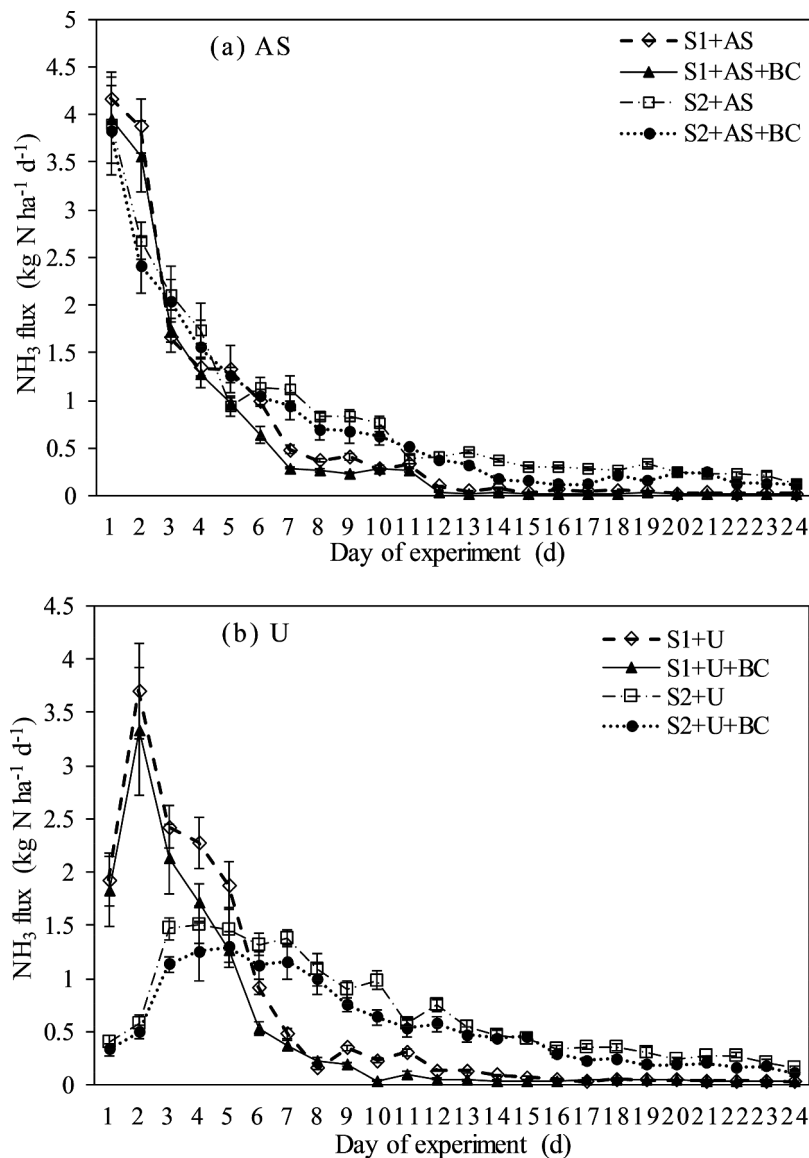
Figure 4. NH$_3$ volatilization rates of different treatments throughout the experimental period. Error bars represent the standard deviation for three replications.

Multifactor analysis of variance (Table 4) suggested that the main effect of biochar addition, salinity level and N fertilizer on cumulative NH$_3$ volatilization all reached the significant level (p < 0.05). However, the interaction was not statistically significant except for the interaction of salinity level and N fertilizer, which then reminds us that better N fertilizer management is required in the salt-affected soil.

Soil ammonium dynamics

Due to the addition of AS, soil ammonium concentrations immediately reached a maximum about 200 mg N kg^{-1} and gradually declined as time went by. The concentrations of NH$_4^+$ were about the

Table 3. Cumulative NH_3 volatilization from different treatments with two nitrogen managements.

salinity level	treatment	24 days cumulative NH_3 (kg N ha^{-1})	percentages to seasonal inputs (%)	1st week cumulative NH_3 (kg N ha^{-1})	Percentages to 24 days cumulative NH_3 (%)
S1	U	15.5b	12.9	13.6a	87.9
	U+ BC	12.2 c	10.2	11.2b	91.2
	AS	15.9b	13.2	13.8a	87.4
	AS+BC	13.8bc	11.5	12.4ab	90.2
S2	U	16.4b	13.7	8.1b	49.5
	U+ BC	13.5 c	11.2	6.8 c	50.4
	AS	20.2a	16.9	13.6a	67.3
	AS+BC	18.1ab	15.1	13.1ab	72.3

In the same volume with the same N source, data followed by the same letter are not significantly different ($p < 0.05$) by Least Significant Difference (LSD) test.

same among all the treatments with AS in the first few days, but were significantly lower in S1 salinity level in the later stage (Figure 5). This also corresponds with the pattern of NH_3 volatilization in soils treated with AS.

As for soils with urea, urea has to undergo a process of hydrolysis to release NH_4^+ into the soil, so the NH_4^+ concentrations of urea-treated soils had an increase at first, and then gradually went down (Figure 5). Just like the NH_3 volatilization of soils with urea, the changing process of NH_4^+ concentrations at S2 salinity level was lagged and inhibited by the higher salinity; therefore, the peak of NH_4^+ concentrations was lower and later at S2 salinity level. Similar to AS-treated soils, NH_4^+ concentrations at S2 salinity level were significantly higher at the end.

For all treatments, NH_4^+ concentrations of biochar-enriched soils did not vary markedly from those without biochar at the beginning of the experiment, but biochar-enriched soils gradually exceeded no-biochar soils in later, resulting in an average 42.5% (S1 level) and 13.5% (S2 level) increase of NH_4^+ concentrations eventually, though this increase was not statistically significant in S2 level.

Relationship between NH_4^+ and NH_3 volatilization

Correlation analysis shows that soil NH_4^+ concentration had obviously positive correlation with corresponding NH_3 volatilization rate, and NH_3 volatilization rates of all treatments increased exponentially with NH_4^+ concentrations (Figure 6). It should be noted that this result is based on the fact that the application amount of N fertilizer is 120 kg N ha^{-1}; hence, there is a limit to the concentrations of NH_4^+ in soil.

For the S1 salinity level, both N sources showed a significant correlation between soil NH_4^+ concentration and NH_3 flux. However, the matching degree is relatively lower for the S2 + U and

Table 4. Multivariate ANOVA of cumulative NH_3 volatilization.

Treatment	F	P	significant level
Biochar	12.509	0.003	**
salinity level	13.745	0.002	**
N fertilizer	12.509	0.003	**
Biochar×salinity level	0.008	0.930	n.s.
Biochar×N fertilizer	0.430	0.521	n.s.
salinity level×N fertilizer	4.924	0.041	*
Biochar×salinity level×N fertilizer	0.013	0.909	n.s.

n.s., * and ** represent no significance, significant differences at $p < 0.05$ and $p < 0.01$, respectively.

S2 + U+ BC among treatments (Figure 6), the reason might be that high salinity has a notable inhibiting effect on the hydrolysis of urea (Tripathi et al. 2007; Pan et al. 2013).

For the AS treatment, the difference between S1 and S2 salinity levels is not as significant as it was in urea treatment. As for the urea treatment, soil N is more likely to escape in the form of NH_3 from S1 salinity level at high concentrations of NH_4^+ and it is more from S2 at lower concentrations. The correlation line also implies that biochar addition may reduce the rate of NH_3 volatilization from soil at the same ammonium level.

Discussion

Effect of nitrogen sources and salinity levels on NH_3 volatilization

NH_3 volatilization from salt-affected soils accounts for a large proportion of the N input, took up 10.2%–16.9% of the total N inputs. And cumulative NH_3 volatilization losses from salt-affected soil were significantly higher than that from non-saline soils (Figure 3) either fertilized with urea or ammonium sulfate, consistent with the study of Akhtar et al. (2012) and Omar and Ismail (1999) who found that greater salinity resulted in higher NH_3 volatilization than non-saline soil.

Some researchers attributed the high NH_3 volatilization form of salt-affected soils to the high initial pH value (Vega-Jarquin et al. 2003; Dendooven et al. 2010); however, in the current study, pH values showed no remarkable differences among treatments. Weston et al. (2010) and Rysgaard et al. (1999) found that soil adsorption capacity on NH_4^+ declined with an increase in salinity, potentially contributing to increased NH_3 fluxes from salt-affected soil. Apart from the decrease of NH_4^+ adsorption capacity in salt-affected soils, the inhibiting effect of soil salinity on the nitrogen nitrification also has been found to be a significant factor in the process of N transformation (Rasul et al. 2006; Akhtar et al. 2012). Irshad et al. (2005) and Omar and Ismail (1999) have documented a retardation of nitrification with increasing salinity and significant greater accumulation of NH_4^+ in salt-affected soil than in non-saline soil. After the period with rapid NH_3 volatilization, the inhibiting effect of high salinity on nitrification began to take over and caused remarkably greater NH_4^+ accumulation in S2 regardless of the types of N fertilizer (Figure 5); therefore, the concentration of NH_3 volatilization in S2 had an increase of 6.0% and 27.5% than that of S1 in urea and AS treatment, respectively, given that NH_4^+ accumulation with increased salinity caused more N losses at the form of NH_3 volatilization (Akhtar et al. 2012).

Furthermore, both cumulative NH_3 volatilization and daily NH_3 volatilization rates varied between two N sources, it was observed that ammonium sulfate led to a greater loss of NH_3 volatilization than urea (Gandhi and Paliwal 1976). When applied into soil, AS supplied more NH_4^+ directly into the soil solution, and immediately released considerable NH_3 after application. Unlike AS, the transformation process of urea in soil is much more complicated. Being an organic nitrogenous fertilizer, the urea applied to soil is first transformed to NH_4^+ in a natural process under the activity of urease enzyme, which takes about one to several days depending on soil characteristics or temperature (De Datta 1987). Enzyme urease plays an important role in such process as it can catalyze the hydrolysis of urea and the subsequent release of NH_4^+ ions into the soil (Kumar et al. 1988). Cookson and Lepiece (1996) found that several soil properties have a significant effect on urease activity in non-saline soils, but soil salinity is the only significant factor that matters when it comes to salt-affected soils. Moreover, urease activity generally decreased with increasing salinity (Alrashidi and Aljabri 1990; Cookson 1999), becoming very low at EC values more than 12.0 ds m^{-1} (Cookson 1999), hence it can be expected that the rate of urea hydrolysis (Tripathi et al. 2007; Pan et al. 2013) and the concentration of NH_3 volatilization decreases at greater salinity level. For the urea treatment, due to the retarded hydrolysis of urea at the beginning, less amount of NH_4^+ was released
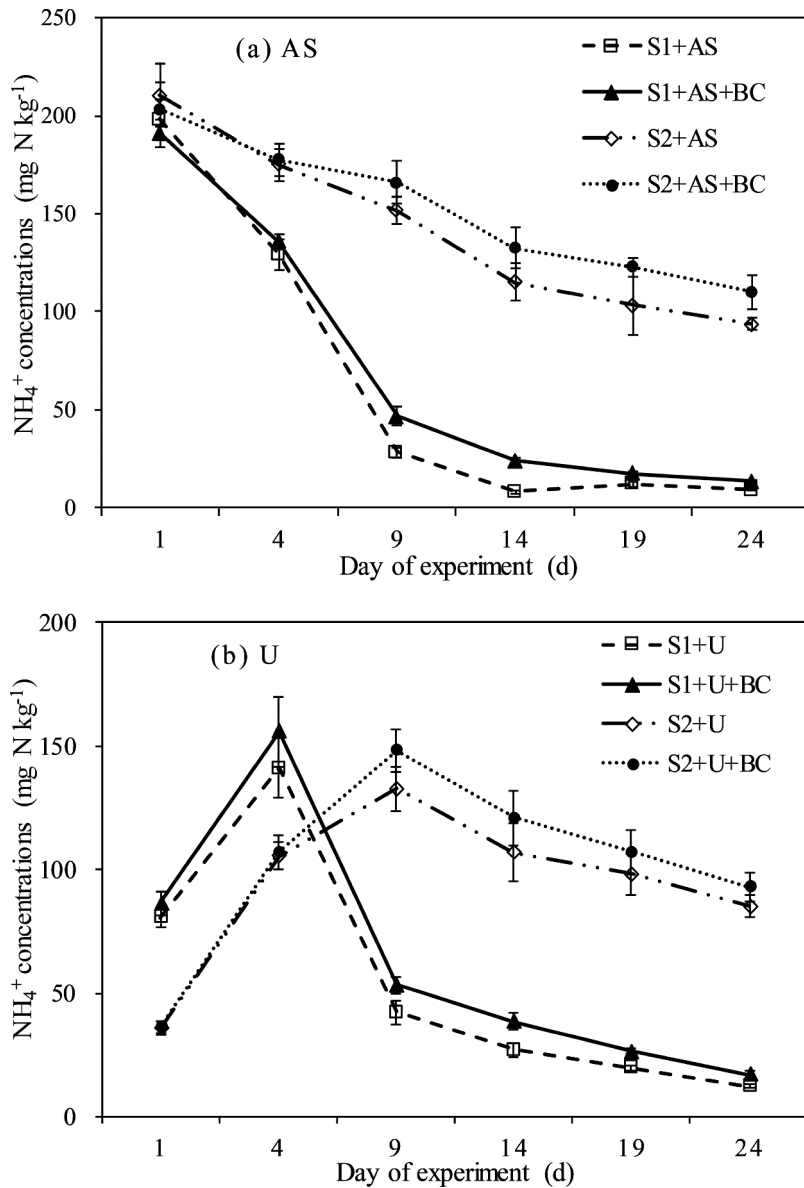
Figure 5. The variance of NH_4^+ concentrations of different treatments with time. Error bars represent the standard deviation for three replications.

into the soil of higher salinity level (Figure 5), the accumulation and consumption of NH_4^+ were delayed at the highest salinity level (S2), which could be another explanation of less NH_3 volatilization in S2 than S1 at the first few days of the experiment.

Effect of biochar on NH_3 volatilization

It has been well recognized that biochar can be used as an efficient soil amendment for its adsorption properties and N immobilization abilities in soils (Ding et al. 2010; Singh et al. 2010; Yao et al. 2012). Biochar has been reported to enhance N retention in many studies (Singh et al. 2010;
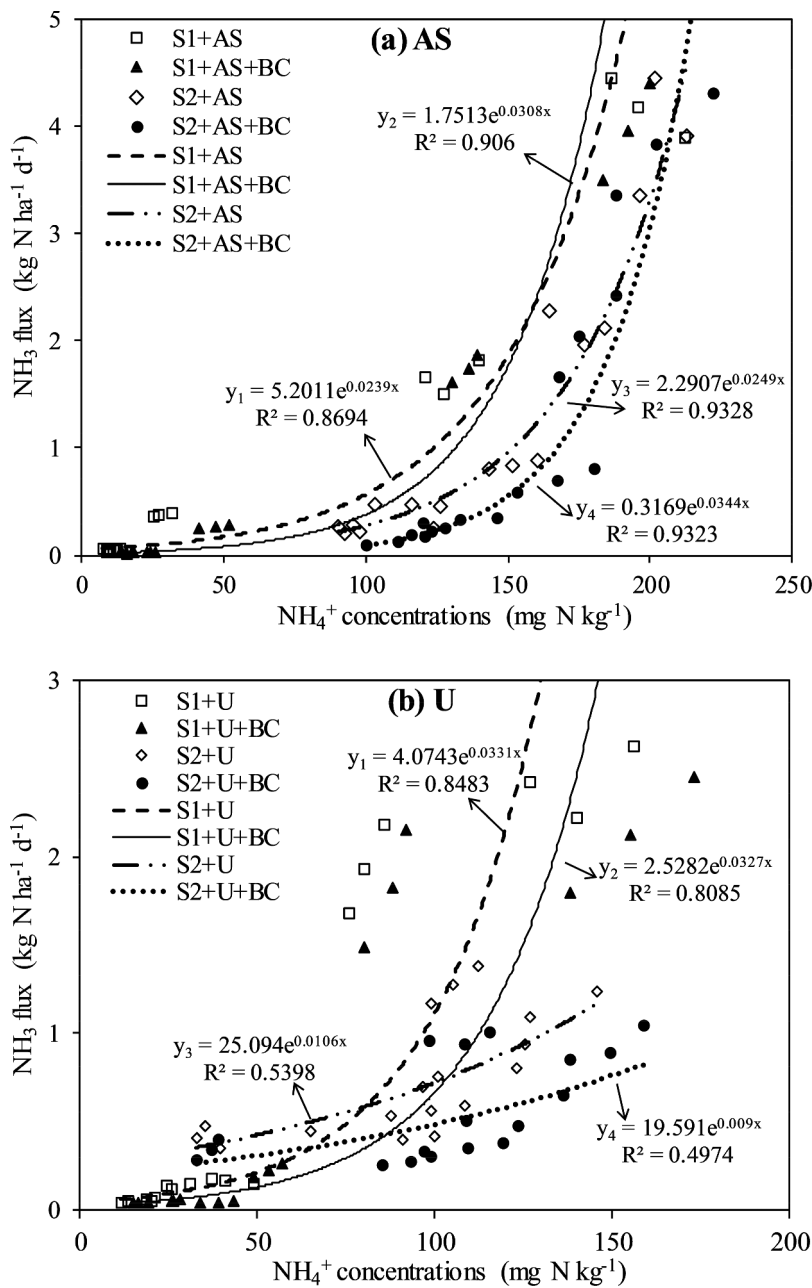
Figure 6. Single-factor linear regression analysis for NH$_3$ flux versus NH$_4^+$-N concentration of different treatments.

Zheng et al. 2013; Liang et al. 2014; Yoo et al. 2014). In this study, the application of biochar significantly reduces the cumulative NH$_3$ volatilization by 17.0% and 13.8% with S1 and S2 salinity level in average (Figure 4). The results were consistent with the findings of Mandal et al. (2016), in which biochar reduced 40.8%–77.1% and 56.7%–70.5% of accumulative NH$_3$ volatilization with poultry manure and urea treatment, respectively, compared to no-biochar treatment. Besides, the addition of biochar increased the concentration of NH$_4^+$ (Figure 5), and the correlation line also

implies that biochar addition may reduce the rate of NH_3 volatilization from soil at the same ammonium level (in the mixture of soil and biochar), irrespective of soil salinity levels (Figure 6).

Though Schomberg et al. (2012) reported that the application of biochar, mostly alkaline, remarkably promoted NH_3 volatilization compared to the control. Soil pH rose as biochar was added into the soil, and then the ammonification process accelerated, therefore the NH_3 volatilization increased in the presence of biochar. While in this study, the slight change in soil pH (not shown) after biochar application did not show any remarkable influence on NH_3 volatilization. Chen et al. (2013) reported that the interactions of changes in soil pH and adsorption capacity induced by biochar addition affect the availability and dynamics of NH_3 in soil, thereby NH_3 volatilization. In low pH treatment (pH = 5), increasing pH rather than adsorption capacity resulting from biochar addition accelerated greater NH_3 volatilization, leading to lower availability of NH_3 for adsorption, whereas increasing adsorption capacity played a dominant role in reducing NH_3 volatilization for soil with medium pH (7 or 8). Therefore, the biochar-induced decrease in NH_3 volatilization can be explained on its high adsorption capacity of NH_3 due to its high surface area and surface functional groups (Joseph et al. 2010; Taghizadeh-Toosi et al. 2012; Clough et al. 2013). The lower NH_3 volatilization rates and higher NH_4^+ concentrations in the later-stage of the experiment in biochar treatments, mainly attributed to the strong NH_4^+ adsorption and N retention capacity of biochar (Zheng et al. 2013; Liang et al. 2014), even in salt-affected soil (Sun et al. 2017). Furthermore, as an alkaline gas, the acidic surface groups on biochar can protonate NH_3 into NH_4^+ ions (Eq. (2)), thus promoting their adsorption onto the cation exchange sites of biochar (Bandosz 2006); therefore, higher concentrations of NH_4^+ were observed in biochar treatments.

$$NH_3 \; + \; H^+ \; \rightarrow NH_4^+ \qquad (2)$$

In addition, cumulative NH_3 volatilization was reduced by 20.9% and 13.2% in S1 salinity level, respectively, following the application of urea and AS, whereas NH_3 was reduced by 17.8% and 10.8% in S2 salinity level after biochar addition in the current study (Table 3), in line with the speculation of Sun et al. 2017 that the competition of other ions for the acid cites on biochar surface may decrease its adsorption capacity of NH_3/NH_4^+ with increasing salinity based on their findings. With the overall influences of biochar application on NH_3 volatilization and N retention in salt-affected soil, the long-term comprehensive effects of biochar amendment on salt-affected soils should be further evaluated in the future.

Conclusion

The results demonstrated that greater salinity levels contributed to greater N losses as the form of NH_3 volatilization. The ammonium sulfate treated soils recorded higher amount of NH_3 volatilization than that of soils treated with urea, and NH_3 volatilization of soils with urea did not vary significantly between S1 and S2 due to the inhibiting effect of great salinity on the hydrolysis of urea. The process of NH_3 volatilization in urea-treated soils was lagged because of the inhibition on urea hydrolysis by high salinity. Biochar can be applied as amendment in salt-affected soil. The addition of biochar resulted in the decrease of NH_3 volatilization in both N application; thus, it led to the accumulation of soil ammonium. Nevertheless, further investigations are still required to make a comprehensive consideration of the effects of biochar on NH_3 volatilization and nitrogen transformation. And soil microbial study needs to be addressed on for better understanding the availability of biochar adsorbed NH_3 or NH_4^+.

Disclosure statement

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