Interactive effects of soil amendments (biochar and gypsum) and salinity on ammonia volatilization in coastal saline soil

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Abstract: Ammonia (NH_3) volatilization is a major route of nitrogen (N) loss from soil, especially in saline soil. Biochar and gypsum are two important soil amendments that are widely used in coastal saline farmland. However, little is known about the interactive effects of soil amendments and salinity on NH_3 volatilization. In this study, five soil salinity levels, three N sources (urea, monoammonium phosphate (MAP), and manure) and two soil amendments (biochar and gypsum, both applied at two rates) were selected to conduct incubation experiments. Nitrogen transformation experiments were conducted simultaneously with NH_3 volatilization experiments. The results showed that cumulative NH_3 volatilization increased with salinity due to the accumulation of ammonium, which resulted from the inhibition of nitrification by salinity, and also the effect of salinity on soil properties related to NH_3 volatilization. Among the tested N sources, the highest NH_3 volatilization was observed for urea, followed by MAP and manure, in soils with three different salinity levels. Biochar application increased NH_3 volatilization in saline soil, as salt ions constrained the NH_3/ NH_4^+ adsorption capacity of biochar, and the inhibition of nitrification by biochar was aggravated in saline soil. Overall, NH_3 volatilization increased with the biochar application rate in saline soil, whereas the effect of a low rate of biochar application on NH_3 volatilization was not significant. Gypsum decreased NH_3 volatilization in saline soil, whereas the contribution of different gypsum rates to NH_3 volatilization showed no difference. The conclusion could be drawn from the above results that low rates of biochar and gypsum may prevent or reduce NH_3 volatilization and nitrogen losses in coastal saline soil.

Keywords: Ammonia volatilization; Soil salinity; Biochar; Gypsum; Nitrogen sources; Interactive effects

1. Introduction

Nitrogen (N) is a vital dominant nutrient for crop growth that undergoes a series of transformations in soil, including ammonia (NH_3) volatilization, nitrification, denitrification and immobilization. During the various transformation processes, some nitrogen enters the atmosphere and water through runoff, leaching, NH_3 volatilization and nitrous oxide emissions, resulting in a reduction in the available nitrogen in farmland. Many investigations conducted in China have indicated that the recovery efficiency of N fertilizer is only 18%~30% (Wang et al., 2001; Peng et al., 2006, 2010) and is lower than the ideal N recovery efficiency (30%~50%) indicated by Dobermann (2005). In addition to the adverse impacts on crop productivity, the loss of nitrogen to the atmosphere and water will lead to atmospheric pollution and water eutrophication.

NH_3 volatilization is one of the major pathways of nitrogen loss in arable land (Rochette et al., 2013), and the proportion of NH_3 volatilization loss from applied nitrogen fertilizers ranges from 1~50% (Sommer et al., 2004). In some rice-wheat rotation systems in South China, NH_3 volatilization can even become the main route of nitrogen fertilizer loss (Liu et al., 2015). Beusen et al. (2008) investigated the NH_3 emissions from agricultural systems on a worldwide scale and found that 27-38 million tons of NH_3 are emitted into the atmosphere every year, which results in the loss of nitrogen in agro-ecological systems. On the other hand, NH_3 is a vital atmospheric contaminant involved in atmospheric processes such as the formation of fine particulate matter (PM2.5), which is the key facilitating factor in haze formation (Ho et al., 2016; Yang et al., 2011). Furthermore, the redeposition of NH_3 to the land surface is an important cause of soil acidification (Van Breemen et al., 1982) and the eutrophication of water ecosystems (Beusen et al., 2008).

NH_3 volatilization is affected by a series of factors, and the key influencing factor varies under different environmental conditions. In saline soil, soil salinity may become the main influencing factor. Soil salinization is a worldwide problem affecting approximately 10 million km^2 of land (Setia and Marschner, 2013). Some studies have indicated that NH_3 volatilization shows a positive correlation with salinity (Duan and Xiao, 2000). However, NH_3 volatilization is affected by related nitrogen transformation mechanisms such as urea hydrolysis and nitrification. Kumar and Wagenet (2007) reported that the amount of urea hydrolyzed was lower in saline soil than in non-saline soil. On the other hand, some studies have investigated the effect of salinity on nitrification. For example, Akhtar et al. (2012) indicated that the first and second steps of nitrification were both inhibited by salinity, and Reddy and Crohn (2014) reported that salinity had a negative effect on nitrification. Some studies have also indicated that microorganisms related to nitrogen transformation are inhibited by salinity (Yuan et al., 2007; Rietz and Haynes, 2003). These studies have indicated that urea hydrolysis and nitrification are both inhibited by salinity. However, urea hydrolysis and nitrification have adverse effects on the ammonium content in soil. The inhibition of nitrification will lead to the accumulation of ammonium and, consequently, the aggravation of NH_3 volatilization. In contrast, the inhibition of hydrolysis may reduce the NH_4^+-N concentration and thus reduce NH_3 volatilization relative to other nitrogen fertilizers which releases nitrogen directly without hydrolysis. Therefore, the effect of salinity on the NH_3 volatilization of urea may be different from that in other nitrogen fertilizers and needs to be further studied.

Biochar, an amendment pyrolyzed from organic material, has attracted much scientific and commercial attention in recent years regarding its function in sequestering carbon and the improvement of nutrient use efficiency (Mandal et al., 2016; Liu et al., 2013) due to its properties of C-richness, porosity, alkalinity and high adsorbability (Cao et al., 2011). Numerous studies involving field, pot and incubation experiments have been conducted to investigate the effects of biochar application on soil physical-chemical properties (Suliman et al., 2017), soil nutrient retention (Knowles et al., 2011; Bai et al., 2015), crop productivity and nutrient uptake (Zhang et al., 2012; Graber et al., 2010), greenhouse gas emission (Case et al., 2012; Nelissen et al., 2014), NH_3 volatilization (Mandal et al., 2016; Feng et al., 2017), and soil microbial activities (Lin et al., 2017; Bi et al., 2017). The results have indicated that biochar is beneficial to most of the aforementioned processes. However, the conclusions about the effect of biochar addition on NH_3 volatilization have been inconsistent. For example, Mandal et al. (2016) reported that 5% biochar addition significantly reduced NH_3 volatilization in non-saline soil. In contrast, Feng et al. (2017) found that low biochar treatment (0.5 wt%) did not significantly increase NH_3 volatilization, while higher biochar treatment (3 wt%) significantly increased NH_3 volatilization in non-saline paddy soils. Furthermore, Sun et al. (2017) found that biochar applied at higher rates (>2%) aggravated NH_3 volatilization in coastal saline soil. The effect of biochar addition on NH_3 volatilization depends on the interactions of several properties including adsorbability, pH and the impact on nitrification (Feng et al., 2017). However, the dominant property varies under different conditions. In saline soil, the NH_3 adsorption capacity of biochar may be affected by the higher salt ion content. Additionally, its effect on nitrification may be influenced by the inhibition of nitrification by salinity. Therefore, the effect of biochar on NH_3 volatilization in saline soil may be different from that in non-saline soil. However, few studies have compared the effect of biochar addition on NH_3 volatilization in saline and non-saline soils. Thus, the interactive effects of biochar addition and salinity on NH_3 volatilization warrant further study.

Gypsum, a byproduct of flue-gas desulfurization, is widely used as a saline-alkali soil amendment due to its low cost and high production (Stamford et al., 2015). Various studies have been conducted to explore the effect of gypsum addition on soil physical-chemical properties (Yu et al., 2003), crop yields (Hamza and Anderson, 2003; Caires et al., 2010), soil respiration (Wong et al., 2009) and so on. However, its effect on NH_3 volatilization in soils is poorly documented. Only Zia et al. (1995) has compared NH_3 volatilization in soil with or without gypsum amendment, and they found that gypsum application significantly reduced NH_3 volatilization loss. In addition, some researchers have investigated the effect of gypsum addition on NH_3 volatilization during the composting of livestock manure and biosolids (Mishra et al., 2013; Burt et al., 2017; Tubail et al., 2008).

Most researchers believe that the effect of gypsum addition on reducing NH_3 volatilization might be attributed to its lower pH (Zia et al., 1999). However, a recent study indicated that gypsum addition inhibited the abundance of nitrification functional genes (Li et al., 2016), thus inhibiting nitrification, which might lead to the accumulation of ammonium. In saline soil, the inhibitory effect of gypsum on nitrification may be aggravated by the inhibition of nitrification by salinity. The interactive effects of gypsum and salinity on NH_3 volatilization are still ambiguous and require further study.

The coastal saline soil region is one of the major saline soil regions in China and is distributed across 11 provinces in eastern China. In salinized farmland, soil salinity influences nitrogen transformation and NH_3 volatilization. Biochar and gypsum are two widely used amendments in saline soil. Their interactive effects with salinity on NH_3 volatilization are poorly studied in saline soil. Therefore, we selected five soil salinities, three nitrogen sources and two amendments (biochar and gypsum) (1) to investigate the influence of soil salinity on NH_3 volatilization, (2) to determine the NH_3 volatilization of different nitrogen sources, and (3) to assess the interactive effects of soil amendments (biochar and gypsum) and salinity on NH_3 volatilization in saline soil.

2. Materials and methods

2.1. Soil, nitrogen sources, biochar and gypsum

Soil samples were collected from the 0~10 cm soil layer in coastal saline farmland in eastern China (32°38'42.01"N, 120°54'8.04"E) in June 2018 after the wheat harvest. This farmland is located approximately 1 km from the Yellow Sea in the east. The soils exhibited five different salt contents and were collected from five sites in the same farmland. All the soils were typical saline alluvial soils (Fluvisols, FAO). We designated the soils NS (non-saline soil), LS (low-salinity soil), MS (moderately saline soil), HS (high-salinity soil) and SS (severely saline soil). Then, the soil samples were air dried and ground to pass through a 2 mm sieve prepared for the incubation experiment. Nitrogen sources including urea, monoammonium phosphate (MAP) and manure were collected from a local poultry farm. Biochar was derived from wheat straw under oxygen-limited conditions. The temperature was increased to 550°C at a rate of 5 °C min^{-1} and then maintained for 4 h. Gypsum was purchased from a local gypsum factory (Zhenhua gypsum Co., Ltd, Jiangsu, China).

The pH of the soils and amendments (1:5 w/v) was measured using a combined pH electrode (Mettler-Toledo Ltd., Shanghai, China); the electrical conductivity (EC) was measured using a conductivity electrode (Mettler-Toledo Ltd., Shanghai, China); the total organic carbon (TOC) content of the soils was measured using the potassium dichromate external heating method; the total N content was measured using the Kjeldahl method; the soil texture was measured using the hydrometer method; and the cation exchange capacity (CEC) was measured using the ammonium acetate extraction-flame photometry method (Lu, 2000). Proximate analysis of the biochar was performed by thermogravimetry using a muffle furnace (Liu et al., 2018). The properties of the soils and amendments are listed in Table 1.

2.2. Experimental treatments and management

Three incubation experiments were conducted in this study. For all experiments, 100 g of soil (on an oven-dried basis) was weighed and transferred to a 500 ml Mason jar. All jars were incubated in the dark at 25±1°C. During the incubation period, soil moisture was maintained at 60% of water-filled pore space (WFPS), which was calculated from the bulk density and the gravimetric moisture content (Yu et al., 2016). Before incubation, all jars were preincubated at 25°C in a constant-temperature incubator for three days to activate the soil microorganisms and ensure water diffusion uniformity. The first experiment was conducted to measure the effect of soil salinity on NH_3 volatilization. All five soils with urea as the nitrogen source were used to conduct a 65-day experiment. The second experiment was performed to measure the effect of nitrogen sources on NH_3 volatilization. Three soils (NS, LS and MS) were selected from the five soils included in experiment 1, and urea, MAP and manure were added to each soil for a 29-day experiment. The third experiment was conducted to measure the effect of biochar and gypsum on NH_3 volatilization. Two soils (NS and MS) were selected to conduct a 29-day experiment with urea as the nitrogen source. For all experiments, nitrogen sources were added at a rate of 200 mg N kg^{-1} soil. The urea and MAP were dissolved in deionized water and added to the soils, and manure was added as dry material and mixed with the soil thoroughly, as were biochar and gypsum. Biochar was added at rates of 1% and 2% (equivalent to 15 t ha^{-1} and 30 t ha^{-1}) because 15–30 t ha^{-1} of biochar is the range that is widely used (Taghizadeh-Toosi et al., 2012a, b). Gypsum was added at rates of 0.36 g kg^{-1} and 0.72 g kg^{-1} (equivalent to 5 t ha^{-1} and 10 t ha^{-1}, respectively). Each treatment included three replications.

2.3. NH_3 volatilization measurement

For the measurement of NH_3 volatilization, a 25 ml glass beaker containing 10 ml of 0.1 M H_2SO_4 was placed in a Mason jar to absorb NH_3. Then, the NH_3 absorbed by H_2SO_4 was measured using the indigo blue colorimetry method (Lu, 2000). NH_3 volatilization was measured every day in the first week, then every two days in the second week, every three days in the third week, and every four days or once per week in the next few weeks. Cumulative NH_3 volatilization was calculated from the sum of the daily NH_3 volatilization measurements.

2.4. Soil N transformation

Nitrogen transformation experiments were conducted synchronously with the NH_3 volatilization experiments. We set up a control for each of the soils and then determined NH_4^+-N and nitrate NO_3^--N concentrations by calculating the difference between the soils with and without nitrogen addition.

NH_4^+-N and NO_3^--N were extracted using a 1 M potassium chloride solution at a ratio of 1:10 w/v in a 250 ml conical flask, and the flask was then subjected to shock using a 200 rpm end-over-end shaker for 1 h at 25°C. The extracted solution was filtered for the measurement of NH_4^+-N and NO_3^--N concentrations. NH_4^+-N was measured using the indigo blue colorimetry method, and NO_3^--N was measured using the ultraviolet dual wavelength method (Lu, 2000).

2.5. Statistical analysis

The means and standard deviations were calculated using Excel 2016. The statistical tests were conducted using SPSS 16.0. The figures were drawn using Excel 2016 and Origin 8.0.

3. Results

3.1. Effect of soil salinity on NH_3 volatilization

Different NH_3 volatilization patterns were observed in the soils with different salinities during the 65-day incubation experiment (Fig. 1a). The NH_3 volatilization rate, the length of the NH_3 volatilization period and cumulative NH_3 volatilization were all different between the treatments. Regarding the NH_3 volatilization rate, at the early stage, the NH_3 volatilization rate in the higher-salinity soils (HS and SS) was lower than that in the lower-salinity soils (NS, LS and MS), while in the later stage, the NH_3 volatilization rate in the higher-salinity soils (HS and SS) was greater than that in the lower-salinity soils (NS, LS and MS). NH_3 volatilization in NS, LS, MS, HS and SS reached the peak rate on the third day, fourth day, seventh day, thirteenth day and twenty-fifth day, respectively, and the length of the NH_3 volatilization period in NS, LS, MS, HS and SS was 6 days, 11 days, 13 days, 44 days and 65 days, respectively. The cumulative NH_3 volatilization increased with salinity, with cumulative amounts of 1.50 mg kg^{-1}, 4.16 mg kg^{-1}, 5.03 mg kg^{-1}, 27.71 mg kg^{-1} and 37.73 mg kg^{-1} being recorded in NS, LS, MS, HS and SS, respectively, and a significant difference existed between the treatments ($P<0.05$) (Fig. 1b). A correlation analysis was performed to evaluate the relationship between soil salinity and cumulative NH_3 volatilization, and the results showed that cumulative NH_3 volatilization was positively linearly correlated with soil salinity ($R^2 = 0.977$ at $P<0.05$) (Fig. 1c).

3.2. Effect of N sources on NH_3 volatilization

Different NH_3 volatilization patterns were observed in the soils treated with different N sources (Fig. 2).

The length of the NH_3 volatilization period and cumulative NH_3 volatilization differed under the different N sources in the three soils. The NH_3 volatilization period of all nitrogen sources increased with salinity, which confirmed the finding described in section 3.1 that salinity aggravated NH_3 volatilization. In all three soils (NS, LS and MS), the NH_3 volatilization rate of manure was always the lowest throughout the NH_3 volatilization process. The mean NH_3 volatilization rate of urea was higher than that of MAP. However, MAP exhibited a longer NH_3 volatilization period than urea, and the NH_3 volatilization rate of urea was higher than that of MAP in the early stage, while an opposite pattern appeared in the later stage. The cumulative NH_3 volatilization of different nitrogen sources displayed the order of urea>MAP>manure in the three saline soils, and the difference in cumulative NH_3 volatilization increased with salinity.

3.3. Effect of biochar and gypsum on NH_3 volatilization

Two biochar and gypsum application rates were selected to measure their effects on NH_3 volatilization in two soils (NS and MS), and low cumulative NH_3 volatilization was observed under all treatments in non-saline soil compared with moderately saline soil (Fig. 3). In non-saline soil, neither high (BCH) nor low biochar addition (BCL) significantly affected cumulative NH_3 volatilization compared with the control, and the cumulative NH_3 volatilization under BCL was slightly higher than that under BCH. Both high (SGH) and low gypsum addition (SGL) significantly decreased cumulative NH_3 volatilization compared with the control, and the cumulative NH_3 volatilization under SGL was lower than that under SGH. The difference between the high and low dosages of the amendments was not significant. In moderately saline soil, biochar addition increased the cumulative NH_3 volatilization compared with the control, with BCH significantly increasing the cumulative NH_3 volatilization. In contrast, gypsum addition decreased the cumulative NH_3 volatilization compared to the control; however, the difference was not significant under either high or low gypsum addition.

3.4. Effect of salinity on N transformation

The NO_3^--N and NH_4^+-N concentrations in soils with different salinities were measured in parallel with the NH_3 volatilization experiment (Fig. 4). Similar change patterns for both NO_3^--N and NH_4^+-N were observed in the lower-salinity soils (NS, LS and MS). In the first week, the NH_4^+-N concentration reached its peak, after which it decreased sharply in the second week due to nitrification, while the NO_3^--N concentration reached its peak in the second week. The NH_4^+-N concentrations among the three soils displayed the order of MS>LS>NS in the first week, which was consistent with the cumulative NH_3 volatilization (Fig. 1b) observed in NS, LS and MS.

The dynamics of the NO_3^--N and NH_4^+-N concentrations in the higher-salinity soils (HS and SS) were different from those in the above three soils. The higher-salinity soils exhibited longer nitrogen transformation periods. The NH_4^+-N concentration continuously increased in the first 3 weeks for HS and the first 4 or 5 weeks for SS. The NO_3^--N concentration continued to increase throughout the period. At the end of the incubation experiment, the NO_3^--N concentrations in HS and SS were significantly lower than those in the three lower-salinity soils.

3.5. Effect of N sources on N transformation

The NO_3^--N and NH_4^+-N concentrations of the soils treated with different N sources are shown in Fig. 5. Among the tested N sources, the NH_4^+-N and NO_3^--N concentrations of the soils with manure addition were always the lowest and were significantly lower than those of the soils with urea and MAP addition throughout the incubation experiment. The same pattern was found in all three soils. For urea and MAP, similar change patterns of NO_3^--N and NH_4^+-N concentrations were also found in all three soils. The NH_4^+-N concentration in the soils with MAP addition was always higher than that in the soils with urea addition during the incubation period. Additionally, the NH_4^+-N concentration in the soils with urea addition decreased more rapidly than that in the soils with MAP addition, and the NO_3^--N concentration in the soils with urea addition increased more rapidly than that in the soils with MAP addition.

3.6. Effect of biochar and gypsum on N transformation

The NO_3^--N and NH_4^+-N concentrations of the soils amended with biochar and gypsum are shown in Table 2 (non-saline soil) and Table 3 (moderately saline soil). Regarding biochar addition, in the non-saline soil, even when the NH_4^+-N concentration sharply decreased to a low level in the first week due to nitrification, the NO_3^--N concentration was lower than that in the control throughout the incubation experiment. In the moderately saline soil, nitrification was slower than in the non-saline soil. The NH_4^+-N concentration in the soils with biochar addition was significantly higher than that in the control in the first two weeks. The NO_3^--N concentration was lower than that in the control throughout the incubation experiment, and the NO_3^--N concentration in the soil with high biochar addition was lower than that in the soil with low biochar addition.

Under gypsum addition, in the non-saline soil, the NH_4^+-N concentration was low due to rapid nitrification, and the NO_3^--N concentration in the soil with gypsum addition was lower than that in the control in the first week. In the moderately saline soil, the NH_4^+-N concentration under gypsum addition was also significantly higher than that in the control in the first two weeks, and the NO_3^--N concentration was significantly lower than that in the control in the first two weeks.

3.7. Effect of biochar and gypsum on soil pH

The pH levels of the soils with biochar and gypsum addition after the incubation experiment are shown in Fig. 6. In the non-saline soil, high biochar addition (BCH) significantly reduced the soil pH. However, the difference in pH between the low biochar addition (BCL) and the control treatments was not significant, and the difference in pH between BCH and BCL was also not significant. In the moderately saline soil, the differences were similar to those in the non-saline soil, except that the pH under BCH was significantly lower than that under BCL. Regarding the gypsum treatments, both high (SGH) and low gypsum addition (SGL) significantly reduced the soil pH, and the pH decreased with the gypsum addition rate in the non-saline soil, as also in the moderately saline soil.

4. Discussion

4.1. Effect of soil salinity on NH_3 volatilization

NH_3 volatilization is one of the most important routes of nitrogen loss in farmland and causes large nitrogen losses around the world every year (Sommer et al., 2004). In recent years, NH_3 volatilization under different conditions has been widely studied. These studies have covered large scales and have examined factors such as soil reactions (Mandal et al., 2016), soil amendments (Martines et al., 2010; Chen et al., 2013), water and nitrogen management (Zhou et al., 2016), tillage management (Rochette et al., 2009), and biochemical inhibitors (Soares et al., 2012). However, few studies have focused on soil salinity, even though salinization is a common problem in agricultural land and 50% of all arable land is predicted to be affected by salinization by 2050 (Wang et al., 2003). Additionally, in some related nitrogen transformation studies, a salinity gradient has been achieved by adding salt, which does not reflect actual field conditions well. Therefore, we selected in situ soils with different salinities to conduct our experiments.

In our study, NH_3 volatilization was positively correlated with soil EC. However, other soil properties, including the soil pH, texture, organic matter content and CEC, might also have affected NH_3 volatilization because in situ soils were selected. For instance, Mandal et al. (2016) indicated that an increase in pH increased NH_3 volatilization. Fenn and Kissel (1976) found that NH_3 volatilization was negatively correlated with CEC. Reynolds and Wolf (1987) reported that NH_3 volatilization was negatively correlated with clay content and organic carbon. Therefore, we analyzed the correlations between cumulative NH_3 volatilization and these soil properties. In our study, the soil pH and clay content were not correlated with NH_3 volatilization because these properties were similar in all soils. The TOC content was negatively correlated with NH_3 volatilization (R^2=0.50, P<0.01). However, the difference in TOC might have resulted from the difference in soil salinity. Na^+ accumulation degrades the soil aggregate structure, which leads to a decrease in organic carbon (Guo et al., 2019). On the other hand, higher soil salinity decreases plant root biomass, which is an important source of soil carbon. CEC was also negatively correlated with NH_3 volatilization (R^2=0.57, P<0.01) in the present study. Previous studies have indicated that soil CEC is determined by the soil clay and organic matter contents and pH (Lu, 2000). However, in our study, the soil pH and clay content showed no correlation with CEC, while soil organic carbon showed a significant correlation with CEC (R^2=0.73, P<0.01), which indicated that soil CEC was also affected by soil salinity. These results confirmed that soil salinity was the dominant factor under our study conditions.

As shown in Fig. 1, NH_3 volatilization presented different change patterns between lower-salinity soils (NS, LS and MS) and higher-salinity soils (HS and SS). In the lower-salinity soils, NH_3 volatilization increased rapidly and reached a peak, then decreased dramatically over a short time (two weeks), which was consistent with other studies, such as that of Feng et al. (2017), who found that NH_3 volatilization occurred for a short time and was nearly complete within one week, as also indicated by Sun et al. (2013). This is because urea hydrolysis is a rapid process if there is no influence of inhibitory factors (Vlek and Carter, 1983). In our study, cumulative NH_3 volatilization in the lower-salinity soils accounted for 0.75 to 2.53% of the nitrogen applied in the incubation experiment. This result is similar to those reported by Zhou et al. (2016), who found that 3.2 to 3.8% of nitrogen was lost via NH_3 volatilization. Similar to the urea application method with drip fertigation employed by these researchers, we added urea in solution form. When the urea solution was added to the soils, it infiltrated into the soils quickly and reached the deeper layer of the soils, consequently minimizing NH_3 volatilization (Haynes, 1985).

In the higher-salinity soils (HS and SS), the NH_3 volatilization pattern was different from the conventional short-duration NH_3 volatilization pattern found in most previous studies. The NH_3 volatilization period was significantly longer than that in lower-salinity soils. The peak of NH_3 volatilization was delayed due to the inhibition of urea hydrolysis by soil salinity (Kumar et al., 1988). When NH_3 volatilization reached its peak, it was maintained for a longer time than in the lower-salinity soils and then decreased slowly until NH_3 volatilization was complete (Fig. 1a). NH_3 volatilization is directly determined by the ammonium concentration in soil (Bosch-Serra et al. 2014). Ammonium is the intermediate product of N transformation, which connects urea hydrolysis and nitrification. We determined the NH_4^+-N and NO_3^--N concentrations in the soils (Fig. 4) and found that the NH_4^+-N concentration was still high from the third to eighth week relative to that in the lower-salinity soils, which contained no NH_4^+-N at the end of the second week. Additionally, the NO_3^--N concentration was always low in the first 5 weeks (Fig. 4). The results proved that nitrification was significantly inhibited by soil salinity, as indicated by Ye et al. (2009). Similar results were found in the lower-salinity soils; the measured NH_4^+-N and NO_3^--N concentrations demonstrated that nitrification was inhibited by soil salinity, as the NH_4^+-N concentration increased with the increase in soil salinity, while the NO_3^--N concentration was inversely related to soil salinity in the first week (Fig. 4). Overall, we may conclude that soil salinity aggravates NH_3 volatilization by inhibiting nitrification and affecting soil properties related to NH_3 volatilization.

4.2. Effect of N sources on NH_3 volatilization

In coastal saline farmland, manure is widely used as a soil amendment; MAP is usually selected as the basic fertilizer; and urea is usually used as an additional fertilizer. In our study, the cumulative NH_3 volatilization was highest for urea, which was consistent with the findings of Mandal et al. (2016), who inferred that urea hydrolysis increased the soil pH and thereby aggravated NH_3 volatilization. The NH_4^+-N concentration in urea-treated soil was always lower than that in MAP-treated soil (Fig. 5), although urea-treated soil still showed the highest cumulative NH_3 volatilization, which may confirm the existence of inference. Some differences also existed. The difference in cumulative NH_3 volatilization between MAP-treated soil and manure-treated soil was inconsistent in the study by Mandal et al. (2016). We found that the cumulative NH_3 volatilization in manure-treated soil was always lower than that in MAP-treated soil. The nitrogen in manure is mainly organic nitrogen and is released slowly by mineralization. The released NH_4^+-N will be nitrated to NO_3^--N quickly and thus result in a low NH_4^+-N concentration, which can be indicated by the NO_3^--N and NH_4^+-N concentrations in Fig. 5.

4.3. Interactive effect of salinity and biochar on NH_3 volatilization

Biochar is one of the most popular soil amendments used for soil improvement and nutrient utilization. Recently, biochar has also been widely used in saline soil to alleviate the negative effect of salinity on soil properties and plant growth (Thomas et al., 2013). However, its effect shows high dependence on the experimental conditions and its own agronomic properties (Liu et al., 2013; Cely et al., 2015). With respect to the effect of biochar on NH_3 volatilization, the results are also inconsistent under different experimental conditions. In our study, two soils (NS and MS) and two biochar application rates were selected to measure their interactive effect on NH_3 volatilization.

In the non-saline soil, the difference in cumulative NH_3 volatilization between biochar-amended soils and the control was not significant, regardless of whether the biochar was applied at a high level (2%) or a low level (1%) (Fig. 3). These findings were partially consistent with those of Feng et al. (2017), who found that the difference in NH_3 volatilization between the control and treatment at a 0.5% biochar application rate was not significant; however, NH_3 volatilization was significantly greater than in the control under a biochar application rate of 3% in paddy soil. Chen et al. (2013) indicated that biochar affected NH_3 volatilization via two properties. The first is the adsorption capacity of biochar, which is determined by the biochar BET surface and CEC, between which the BET surface is the dominant factor related to the adsorption of NH_3 (Taghizadeh-Toosi et al., 2012b). The second property is the pH of biochar, which might affect the soil pH. Therefore, it is likely that the effects of the two properties were nearly balanced when biochar was applied at a 0.5% rate and that pH increases played a major role when biochar was applied at a 3% rate (Subedi et al., 2015; Sun et al., 2016). Mandal et al. (2016) found that NH_3 volatilization was alleviated under biochar application, which was in agreement with the findings of Malinska et al. (2014), who indicated that high-pH biochar reduced NH_3 volatilization, which could be attributed to its high sorption capacity. Interestingly, we obtained a finding that differed from those of these previous studies: soil pH did not increase with biochar addition and was even lower than in the control (Fig. 6), which was similar to the results of Cely et al. (2014), who found that the addition of biochar with different pH levels did not change the soil pH significantly, regardless of whether the biochar pH was higher than or close to the soil pH. Yang (2015) also reported that alkaline biochar could reduce the pH of soda-saline soil to some extent. Feng et al. (2017) indicated that the effect of biochar addition on nitrification also affected NH_3 volatilization and that the inhibition of nitrification by biochar resulted in the accumulation of ammonium. Biochar addition also increased soil EC (Fig. S1), as also reported by Cely et al. (2014), which would exacerbate the inhibition of nitrification. In our study, pH was not the driving factor, and the effects of the adsorption capacity and nitrification inhibition were nearly balanced. Therefore, the effect of biochar on NH_3 volatilization was not significant in non-saline soil.

In moderately saline soil, the cumulative NH_3 volatilization in high-biochar-treated soil was significantly greater than that in the control, while the cumulative NH_3 volatilization in low-biochar-treated soil was slightly higher than that in the control, although the difference was not significant. This result was in agreement with those reported by Sun et al. (2017), who conducted an experiment in coastal saline soil and found that the difference in NH_3 volatilization between the control and treatment at a 0.5% or 1% biochar application rate was not significant; however, NH_3 volatilization was significantly greater than in the control when the biochar application rate was greater than 2%. Similar to non-saline soil, biochar addition did not increase the soil pH

(Fig. 6), while biochar addition significantly increased soil EC in moderately saline soil (Fig. S1). Nitrification was also measured in the moderately saline soil. In contrast to the rapid nitrification process observed in non-saline soil, the NH_4^+-N concentration in biochar-amended soils was higher than that in the control in the first two weeks, and the NO_3^--N concentration in biochar-amended soils was lower than that in the control throughout the incubation period (Table 3). The results proved that nitrification was inhibited in soils subjected to biochar addition, which is consistent with Feng et al. (2017). Ameloot et al. (2014) showed that biochar addition restricted soil microbial activity, and Wang et al. (2015) found that biochar addition reduced the abundance of ammonia-oxidizing bacteria and thereby inhibited nitrification. The inhibitory effect of biochar addition on nitrification may have become stronger due to the interactive effect of biochar and salinity in moderately saline soil. With respect to the adsorption capacity, the salt ion concentration in moderately saline soil was significantly higher than that in non-saline soil, and the adsorption of salt ions decreases the NH_3/NH_4^+ adsorption capacity. Therefore, nitrification inhibition played an important role between the effects of the adsorption capacity and nitrification inhibition in moderately saline soil, and biochar addition therefore aggravated NH_3 volatilization in moderately saline soil. Regarding the difference in NH_3 volatilization between BCH and BCL, it was likely that nitrification inhibition was significantly increased with higher biochar addition; however, the rate of the increase in the adsorption capacity was lower than that for nitrification inhibition. Overall, NH_3 volatilization increased with the biochar application rate in moderately saline soil, whereas a low rate could prevent the increase in NH_3 volatilization, so biochar application at a low rate is suggested.

4.4. Interactive effect of salinity and gypsum on NH_3 volatilization

Gypsum is a traditional amendment used for the amelioration of saline soil. In our study, we selected two application rates for the two soils. The cumulative NH_3 volatilization in soils treated with gypsum was significantly lower than that in the control in non-saline soil. A similar result was found in moderately saline soil, although the difference was not significant (Fig. 3). This result was consistent with those of Zia et al. (1999), who demonstrated that gypsum addition could reduce NH_3 volatilization due to the effect of decreasing pH. A similar result was indicated by Burt et al. (2017) in composting. The pH mainly exerts its effect by influencing the equilibrium of NH_4^+ and NH_3. A decreased pH reduces the transformation of NH_4^+ to NH_3 and thus reduces NH_3 volatilization. In our study, the pH in soils amended with gypsum was significantly lower than that in the control (Fig. 6), which was in agreement with this previous study. We also found that the pH decreased more significantly with more gypsum addition.

Nitrification is another important process influencing NH_3 volatilization that is affected by gypsum. In our study, gypsum addition significantly increased soil EC (Fig. S1), which was confirmed by Burt et al. (2017) and Tubail et al. (2008), who attributed this effect to the increase in sulfate. An increase in the soil salt content will aggravate the inhibition of nitrification. Ponette et al. (1996) found that nitrification was depressed by gypsum application, and Li et al. (2016) reported that the copy number of nitrification functional genes was significantly decreased by gypsum addition. The lower NO_3^--N and higher NH_4^+-N concentrations found in soils with gypsum addition (Table 2 and Table 3) also indicated that nitrification was inhibited in our study. Furthermore, the inhibition was more significant under higher gypsum addition.

Overall, gypsum influenced both pH and nitrification, and its effect on NH_3 volatilization depended on the interaction between the decreasing pH and the inhibition of nitrification. Which of these factors is dominant in such situations will sometimes lead to different results. In the non-saline soil, the cumulative NH_3 volatilization in the soil with added gypsum was significantly lower than that in the control, and we might conclude that the effect of decreasing pH was dominant because nitrification occurred for a short duration (one week). In the moderately saline soil, the cumulative NH_3 volatilization in the soil with added gypsum was also lower than that in the control, although the difference was not significant (P=0.54 for both SGH and SGL relative to the control). This might have occurred because the NH_3 volatilization period grew longer due to the inhibition of nitrification by salinity; the inhibitory effect of gypsum addition on nitrification may have become stronger due to their interactive effect; and the effect of decreasing pH on NH_3 volatilization was alleviated compared with that in non-saline soil. Therefore, the difference between the soil with gypsum addition and the control was not significant in moderately saline soil. We also found that the difference in NH_3 volatilization between SGH and SGL was not significant; it was likely that because gypsum affected both the decrease in pH and the inhibition of nitrification, even though more gypsum addition could decrease the soil pH more significantly, its inhibitory effect on nitrification was also significantly increased. Thus, the two effects were still nearly balanced regardless of whether gypsum was added at a high or low rate. Overall, gypsum decreased NH_3 volatilization, although the contribution of different gypsum rates to NH_3 volatilization showed no difference, so gypsum application at a low rate is suggested.

5. Conclusions

The results clearly indicated that soil salinity significantly exacerbated cumulative NH_3 volatilization and even changed the NH_3 volatilization pattern when soil salinity exceeded a certain threshold. These effects were mainly ascribed to the accumulation of ammonium, which resulted from the inhibition of nitrification by salinity, and also the effect of salinity on soil properties related to NH_3 volatilization. Among the tested N sources, urea showed the highest cumulative NH_3 volatilization, followed by MAP and then manure in soils with three different salinity levels. The reason for these results lies in the fact that urea hydrolysis increases soil pH. Biochar addition had no significant influence on NH_3 volatilization in non-saline soil because the adsorption capacity and nitrification inhibition were in balance. Biochar application increased NH_3 volatilization in moderately saline soil because salt ions decreased the NH_3/NH_4^+ adsorption capacity of biochar, and the interactive effect of biochar and salinity exacerbated the inhibition of nitrification. Overall, NH_3 volatilization increased with the biochar application rate in saline soil, and a low biochar application rate could prevent the increase of NH_3 volatilization, so biochar addition at a low rate is suggested. Gypsum application significantly decreased NH_3 volatilization in non-saline soil by decreasing the soil pH. However, the differences were not significant in moderately saline soil due to the interactive effect of gypsum and salinity aggravating the inhibition of nitrification. Overall, gypsum decreased NH_3 volatilization in saline soil, whereas the contribution of different gypsum rates to NH_3 volatilization showed no difference. A conclusion could be drawn from the above results that low rates of biochar and gypsum application should be suggested to prevent or reduce NH_3 volatilization and nitrogen losses in coastal saline soil.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

Akhtar, M., Hussain, F., Ashraf, M.Y., Qureshi, T.M., Akhter, J., Awan, A.R., 2012. Influence of salinity on nitrogen transformations in soil. Commun. Soil Sci. Plant Anal. 43, 1674-1683.

Ameloot, N., Sleutel, S., Case, S.D.C., Alberti, G., McNamara, N.P., Zavalloni, C., Vervisch, B., delle Vedove, G., De Neve, S., 2014. C mineralization and microbial activity in four biochar field experiments several years after incorporation. Soil Biol. Biochem. 78, 195-203.

Bai, S.H., Reverchon, F., Xu, C.-Y., Xu, Z., Blumfield, T.J., Zhao, H., Van Zwieten, L., Wallace, H.M., 2015. Wood biochar increases nitrogen retention in field settings mainly through abiotic processes. Soil Biol. Biochem. 90, 232-240.

Beusen, A.H.W., Bouwman, A.F., Heuberger, P.S.C., Van Drecht, G., Van Der Hoek, K.W., 2008. Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems. Atmos. Environ. 42, 6067–6077.

Bi, Q.F., Chen, Q.H., Yang, X.R., Li, H., Zheng, B.X., Zhou, W.W., Liu, X.X., Dai, P.B., Li, K.J., Lin, X.Y., 2017. Effects of combined application of nitrogen fertilizer and biochar on the nitrification and ammonia oxidizers in an intensive vegetable soil. AMB Express 7, 198.

Bosch-Serra, A.D., Yaguee, M.R., Teira-Esmatges, M.R., 2014. Ammonia emissions from different fertilizing strategies in Mediterranean rainfed winter cereals. Atmos. Environ. 84, 204-212.

Burt, C.D., Cabrera, M.L., Rothrock, M.J., Jr., Kissel, D.E., 2017. Flue-gas desulfurization gypsum effects on urea-degrading bacteria and ammonia volatilization from broiler litter. Poult. Sci. 96, 2676-2683.

Caires, E.F., Joris, H.A.W., Churka, S., 2011. Long-term effects of lime and gypsum additions on no-till corn and soybean yield and soil chemical properties in southern Brazil. Soil Use Manage. 27, 45-53.

Cao, X., Ma, L., Liang, Y., Gao, B., Harris, W., 2011. Simultaneous immobilization of lead and atrazine in contaminated soils using dairy-manure biochar. Environ. Sci. Technol. 45, 4884-4889.

Case, S.D.C., McNamara, N.P., Reay, D.S., Whitaker, J., 2012. The effect of biochar addition on N_2O and CO_2 emissions from a sandy loam soil - The role of soil aeration. Soil Biol. Biochem. 51, 125-134.

Cely, P., Gascó, G., Paz-Ferreiro, J., Méndez, A., 2015. Agronomic properties of biochars from different manure wastes. J. Anal. Appl. Pyrolysis 111, 173-182.

Cely, P., Tarquis, A.M., Paz-Ferreiro, J., Méndez, A., Gascó, G., 2014. Factors driving the carbon mineralization priming effect in a sandy loam soil amended with different types of biochar. Solid Earth 5, 585-594.

Chen, C.R., Phillips, I.R., Condron, L.M., Goloran, J., Xu, Z.H., Chan, K.Y., 2013. Impacts of greenwaste biochar on ammonia volatilisation from bauxite processing residue sand. Plant Soil 367, 301-312.

Dobermann, A., 2005. Nitrogen use efficiency-state of the art. Paper of the IFA International Workshop on Enhanced-Efficiency Fertilizers. Frankfurt, Germany.

Duan, Z.H., Xiao, H.L., 2000. Effects of soil properties on ammonia volatilization. Soil Sci. Plant Nutr. 46, 845-852.

Feng, Y., Sun, H., Xue, L., Liu, Y., Gao, Q., Lu, K., Yang, L., 2017. Biochar applied at an appropriate rate can avoid increasing NH_3 volatilization dramatically in rice paddy soil. Chemosphere 168, 1277-1284.

Fenn, L.B., Kissel, D.E., 1976. The Influence of Cation Exchange Capacity and Depth of Incorporation on Ammonia Volatilization from Ammonium Compounds Applied to Calcareous Soils1. Soil Sci. Soc. Am. J. 40, 394-398.

Graber, E.R., Harel, Y.M., Kolton, M., Cytryn, E., Silber, A., David, D.R., Tsechansky, L., Borenshtein, M., Elad, Y., 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. Plant Soil 337, 481-496.

Guo, Z., Zhang, J., Fan, J., Yang, X., Yi, Y., Han, X., Wang, D., Zhu, P., Peng, X., 2019. Does animal manure application improve soil aggregation? Insights from nine long-term fertilization experiments. Sci. Total Environ. 660, 1029-1037.

Hamza, M.A., Anderson, W.K., 2003. Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. Aust. J. Agric. Res. 54, 273-282.

Haynes, R.J., 1985. Principles of fertilizer use for trickle irrigated crops. Fert. Res., 6, 235–255.

Ho, K.F., Ho, S.S.H., Huang, R.J., Chuang, H.C., Cao, J.J., Han, Y., Lui, K.H., Ning, Z., Chuang, K.J., Cheng, T.J., Lee, S.C., Hu, D., Wang, B., Zhang, R., 2016. Chemical composition and bioreactivity of PM2.5 during 2013 haze events in China. Atmos. Environ. 126, 162–170.

Knowles, O.A., Robinson, B.H., Contangelo, A., Clucas, L., 2011. Biochar for the mitigation of nitrate leaching from soil amended with biosolids. Sci. Total Environ. 409, 3206–3210.

Kumar, V., Wagenet, R.J., 1985. Salt effects on urea hydrolysis and nitrification during leaching through laboratory soil columns. Plant Soil 85, 219–227.

Kumar, V., Yadav, D.S., Singh, M., 1988. Effects of urea rates, farmyard manure, CaCO3, salinity and alkalinity levels on urea hydrolysis and nitrification in soils. Aust. J. Soil Res. 26, 367-374.

Li, Q., Guo, X., Lu, Y., Shan, G., Huang, J., 2016. Impacts of adding FGDG on the abundance of nitrification and denitrification functional genes during dairy manure and sugarcane pressmud co-composting. Waste Manage. 56, 63-70.

Lin, Y., Ding, W., Liu, D., He, T., Yoo, G., Yuan, J., Chen, Z., Fan, J., 2017. Wheat straw-derived biochar amendment stimulated N_2O emissions from rice paddy soils by regulating the amoA genes of ammonia-oxidizing bacteria. Soil Biol. Biochem. 113, 89-98.

Liu, J., Yang, F., Niu, W., Liu, Z., Niu, Z., 2018. Prediction of Calorific Value of Straw Biochar Based on Industrial Analysis Index. J. Agric. Sci. Technol. 20, 142-148. (In Chinese)

Liu, T.Q., Fan, D.J., Zhang, X.X., Chen, J., Li, C.F., Cao, C.G., 2015. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. Field Crops Res. 184, 80-90.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., Paz-Ferreiro, J., 2013. Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. Plant Soil 373, 583-594.

Lu, R.K., 2000. Soil argrochemistry analysis protocoes. China Agriculture Science Press, Beijing. (In Chinese)

Malinska, K., Zabochnicka-Swiatek, M., Dach, J., 2014. Effects of biochar amendment on ammonia emission during composting of sewage sludge. Ecol. Eng. 71, 474-478.

Mandal, S., Thangarajan, R., Bolan, N.S., Sarkar, B., Khan, N., Ok, Y.S., Naidu, R., 2016. Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere 142, 120-127.

Martines, A.M., Nogueira, M.A., Santos, C.A., Nakatani, A.S., Andrade, C.A., Coscione, A.R., Cantarella, H., Sousa, J.P., Cardoso, E.J.B.N., 2010. Ammonia volatilization in soil treated with tannery sludge. Bioresour. Technol. 101, 4690-4696.

Mishra, A., Cabrera, M.L., Kissel, D.E., Rema, J.A., 2013. Gypsum effect on nitrogen mineralization and ammonia volatilization from broiler litter. Soil Sci. Soc. Am. J. 77, 2045-2049.

Nelissen, V., Saha, B.K., Ruysschaert, G., Boeckx, P., 2014. Effect of different biochar and fertilizer types on N_2O and NO emissions. Soil Biol. Biochem. 70, 244-255.

Peng, S., Buresh, R.J., Huang, J., Zhong, X., Zou, Y., Yang, J., Wang, G., Liu, Y., Hu, R., Tang, Q., Cui, K., Zhang, F., Dobermann, A., 2010. Improving nitrogen fertilization in rice by sitespecific N management. A review. Agron. Sustain. Dev. 30, 649–656.

Peng, S.B., Buresh, R.J., Huang, J.L., Yang, J.C., Zou, Y.B., Zhong, X.H., Wang, G.H., Zhang, F.S., 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crops Res. 96, 37-47.

Ponette, Q., Belkacem, S., Nys, C., 1996. Ion dynamics in acid forest soils as affected by addition of Ca fertilizers. Geoderma 71, 53-76.

Reddy, N., Crohn, D.M., 2014. Effects of soil salinity and carbon availability from organic amendments on nitrous oxide emissions. Geoderma 235, 363-371.

Reynolds, C.M., Wolf, D.C., 1987. Influence of urease activity and soil properties on ammonia volatilization from urea. Soil Sci. 143, 418-425.

Rietz, D.N., Haynes, R.J., 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. Soil Biol. Biochem. 35, 845-854.

Rochette, P., Angers, D.A., Chantigny, M.H., Gasser, M.O., MacDonald, J.D., Pelster, D.E., Bertrand, N., 2013. Ammonia volatilization and nitrogen retention: how deep to incorporate urea? J. Environ. Qual. 42, 1635-1642.

Rochette, P., Angers, D.A., Chantigny, M.H., MacDonald, J.D., Gasser, M.O., Bertrand, N., 2009. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. Nutr. Cycling Agroecosyst. 84, 71-80.

Setia, R., Marschner, P., 2013. Carbon mineralization in saline soils as affected by residue composition and water potential. Biol. Fertil. Soils 49, 71–77.

Sommer, S.G., Schjoerring, J.K., Denmead, O.T., 2004. Ammonia emission from mineral fertilizers and fertilized crops. Adv. Agron. 82, 557-622.

Stamford, N.P., Figueiredo, M.V.S., da Silva Junior, S., Freitas, A.D.S., Santos, C.E.R.S., Lira Junior, M.A., 2015. Effect of gypsum and sulfur with acidithiobacillus on soil salinity alleviation and on cowpea biomass and nutrient status as affected by PK rock biofertilizer. Sci. Hortic. 192, 287-292.

Subedi, R., Kammann, C., Pelissetti, S., Taupe, N., Bertora, C., Monaco, S., Grignani, C., 2015. Does soil amended with biochar and hydrochar reduce ammonia emissions following the application of pig slurry? Eur. J. Soil Sci. 66, 1044-1053.

Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.M., Dallmeyer, I., Garcia-Perez, M., 2017. The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. Sci. Total Environ. 574, 139-147.

Sun, H., Lu, H., Chu, L., Shao, H., Shi, W., 2017. Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH_3 volatilization in a coastal saline soil. Sci. Total Environ. 575, 820-825.

Sun, H., Zhang, H., Min, J., Feng, Y., Shi, W., 2016. Controlled-release fertilizer, floating duckweed, and biochar affect ammonia volatilization and nitrous oxide emission from rice paddy fields irrigated with nitrogen-rich wastewater. Paddy Water Environ. 14, 105-111.

Sun, H., Zhang, H., Wu, J., Jiang, P., Shi, W., 2013. Laboratory lysimeter analysis of NH_3 and N_2O emissions and leaching losses of nitrogen in a rice-wheat rotation system irrigated with nitrogen-rich wastewater. Soil Sci. 178, 316-323.

Taghizadeh-Toosi, A., Clough, T.J., Sherlock, R.R., Condron, L.M., 2012a. Biochar adsorbed ammonia is bioavailable. Plant Soil 350, 57–69.

Taghizadeh-Toosi, A., Clough, T.J., Sherlock, R.R., Condron, L.M., 2012b. A wood based low-temperature biochar captures NH_3–N generated from ruminant urine-N, retaining its bioavailability. Plant Soil 353, 73–84.

Thomas, S.C., Frye, S., Gale, N., Garmon, M., Launchbury, R., Machado, N., Melamed, S., Murray, J., Petroff, A., Winsborough, C., 2013. Biochar mitigates negative effects of salt additions on two herbaceous plant species. J. Environ. Manage. 129, 62-68.

Tubail, K., Chen, L., Michel, F.C., Jr., Keener, H.M., Rigot, J.F., Klingman, M., Kost, D., Dick, W.A., 2008. Gypsum additions reduce ammonia nitrogen losses during composting of dairy manure and biosolids. Compost Sci. Util. 16, 285-293.

Van Breemen, N., Burrough, P.A., Velthorst, E.J., van Dobben, H.F., de Wit, T., Ridder, T.B., Reijnders, H.F.R., 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. Nature 299, 548–550.

Vlek, P.L.G., Carter, M.F., 1983. The effect of soil environment and fertilizer modifications on the rate of urea hydrolysis. Soil Sci. 136, 56-63.

Wang, G.H., Dobermann, A., Witt, C., Sun, Q.Z., Fu, R.X., 2001. Performance of site-specific nutrient management for irrigated rice in southeast China. Agron. J. 93, 869-878.

Wang, W., Vinocur, B., Altman, A., 2003. Plant responses to drought, salinity and extreme temperatures: Towards genetic engineering for stress tolerance. Planta 218, 1–14.

Wang, Z., Zong, H., Zheng, H., Liu, G., Chen, L., Xing, B., 2015. Reduced nitrification and abundance of ammonia-oxidizing bacteria in acidic soil amended with biochar. Chemosphere 138, 576-583.

Wong, V.N.L., Dalal, R.C., Greene, R.S.B., 2009. Carbon dynamics of sodic and saline soils following gypsum and organic material additions: A laboratory incubation. Appl. Soil Ecol. 41, 29-40.

Yang, F., Tan, J., Zhao, Q., Du, Z., He, K., Ma, Y., Duan, F., Chen, G., Zhao, Q., 2011. Characteristics of PM 2.5 speciation in representative megacities and across China. Atmos. Chem. Phys. 11, 5207–5219.

Yang, Y.L., 2015. Effects of biochar on physical and chemical properties of the saline-sodic soil. University of Chinese Academy of Sciences, Beijing. (In Chinese)

Ye, L., Peng, C.Y., Tang, B., Wang, S.Y., Zhao, K.F., Peng, Y.Z., 2009. Determination effect of influent salinity and inhibition time on partial nitrification in a sequencing batch reactor treating saline sewage. Desalination 246, 556-566.

Yu, J., Lei, T., Shainberg, I., Mamedov, A.I., Levy, G.J., 2003. Infiltration and erosion in soils treated with dry PAM and gypsum. Soil Sci. Soc. Am. J. 67, 630-636.

Yu, Y., Zhao, C., Jia, H., 2016. Ability of split urea applications to reduce nitrous oxide emissions: A laboratory incubation experiment. Appl. Soil Ecol. 100, 75-80.

Yuan, B.C., Li, Z.Z., Liu, H., Gao, M., Zhang, Y.Y., 2007. Microbial biomass and activity in salt affected soils under arid conditions. Appl. Soil Ecol. 35, 319–328.

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Han, X., Yu, X., 2012. Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. Field Crops Res. 127, 153-160.

Zhou, G., Zhang, W., Ma, L., Guo, H., Min, W., Li, Q., Liao, N., Hou, Z., 2016. Effects of saline water irrigation and N application rate on NH_3 volatilization and N use efficiency in a drip-irrigated cotton field. Water Air Soil Pollut. 227, 103.

Zia, M.S., Aslam, M., Rahmatullah, Arshad, M., Ahmed, T., 1999. Ammonia volatilization from nitrogen fertilizers with and without gypsum. Soil Use Manage. 15, 133-135.

Figure caption list

Fig.1. The rate of NH_3 volatilization (a), cumulative NH_3 volatilization (b) in different saline soils and the correlation relationship between soil salinity and cumulative NH_3 volatilization (c). NS = non-saline soil, LS = low-salinity soil, MS = moderately saline soil, HS = high-salinity soil and SS = severely saline soil. Error bars denote the standard deviation for three replications. Different letters denote significant difference ($P < 0.05$) between treatments

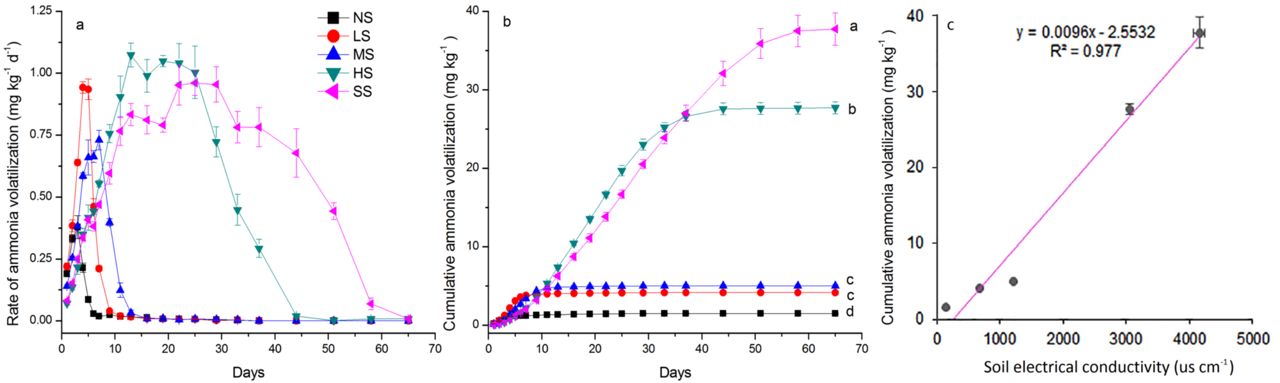
Fig.2. The NH_3 volatilization rate and cumulative NH_3 volatilization of different N sources in non-saline soil (a), low-salinity soil (b) and moderately saline soil (c). Error bars denote the standard deviation for three replications. Different letters denote significant difference ($P < 0.05$) between treatments

Fig.3. The cumulative NH_3 volatilization of non-saline soil (a) and moderately saline soil (b) added with amendments. BCH = high biochar addition, BCL = low biochar addition, SGH = high gypsum addition, SGL = low gypsum addition, CK = soil without amendments addition. Error bars denote the standard deviation for three replications. Different letters denote significant difference ($P < 0.05$) between treatments.

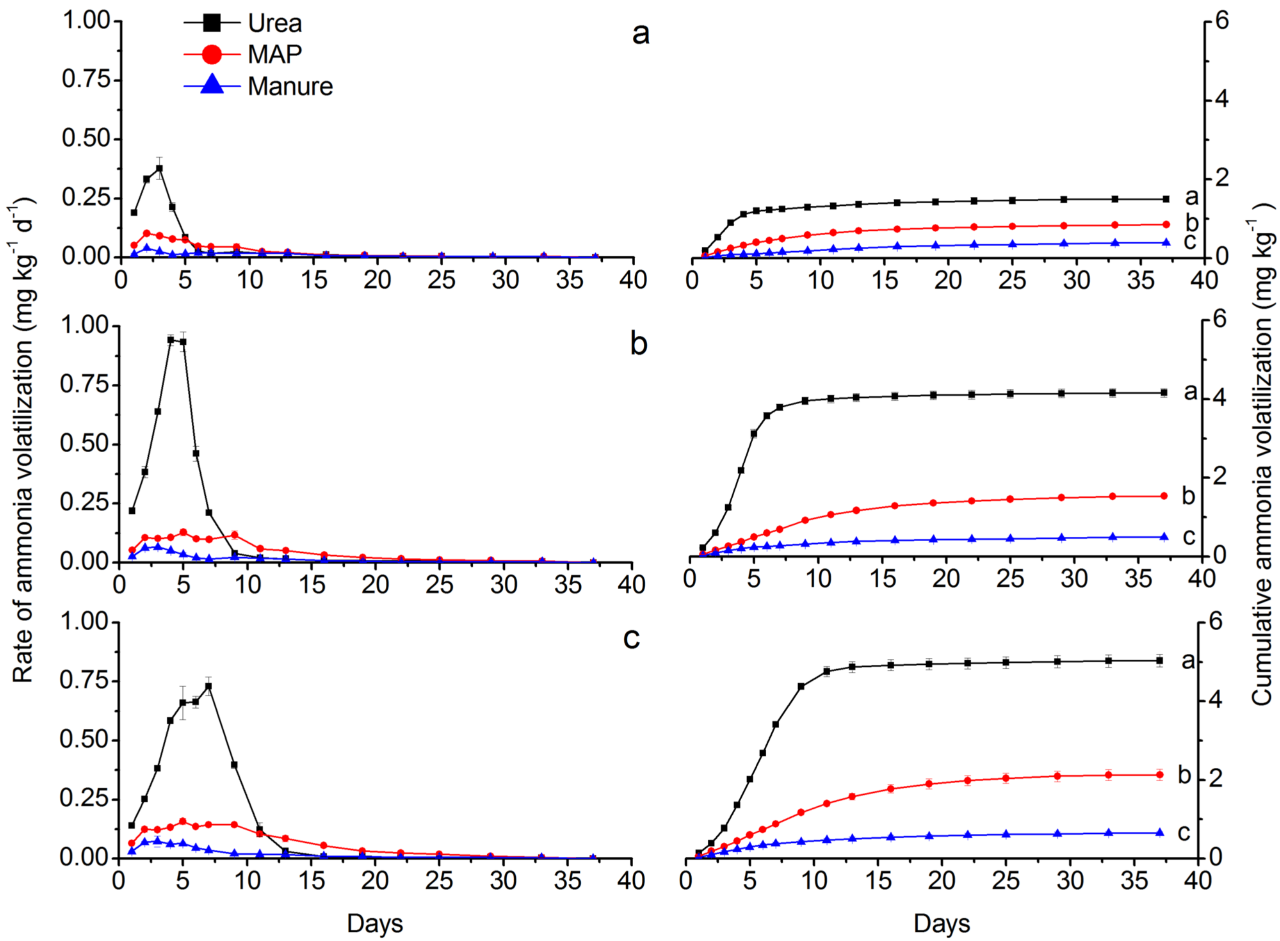
Fig.4. The NO_3^--N (a) and NH_4^+-N (b) concentration in different saline soils. NS = non-saline soil, LS = low-salinity soil, MS = moderately saline soil, HS = high-salinity soil and SS = severely saline soil. Error bars denote the standard deviation for three replications.

Fig.5. The NO_3^--N and NH_4^+-N concentration of different N sources in non-saline soil (a), low-salinity soil (b) and moderately saline soil (c). Error bars denote the standard deviation for three replications.

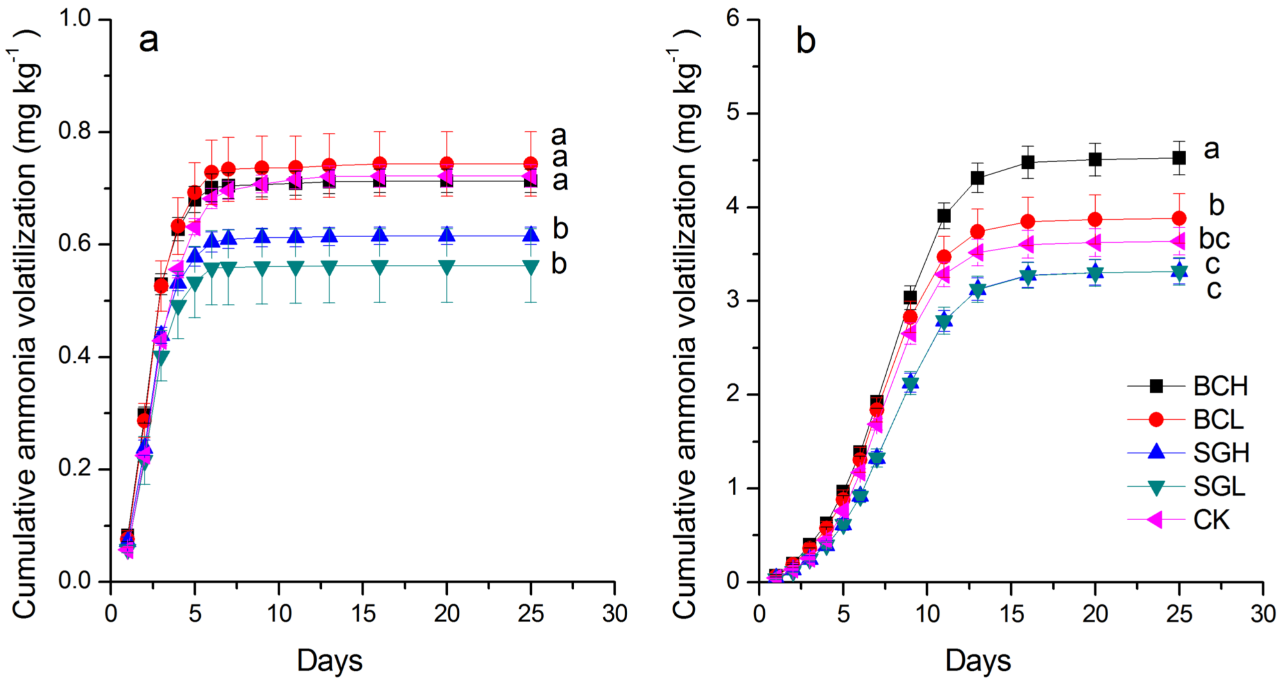
Fig.6. The pH of non-saline soil (a) and moderately saline soil (b) added with amendments after the incubation experiment. BCH = high biochar addition, BCL = low biochar addition, SGH = high gypsum addition, SGL = low gypsum addition, CK = soil without amendments addition. Error bars denote the standard deviation for three replications. Different letters denote significant difference ($P < 0.05$) between treatments.

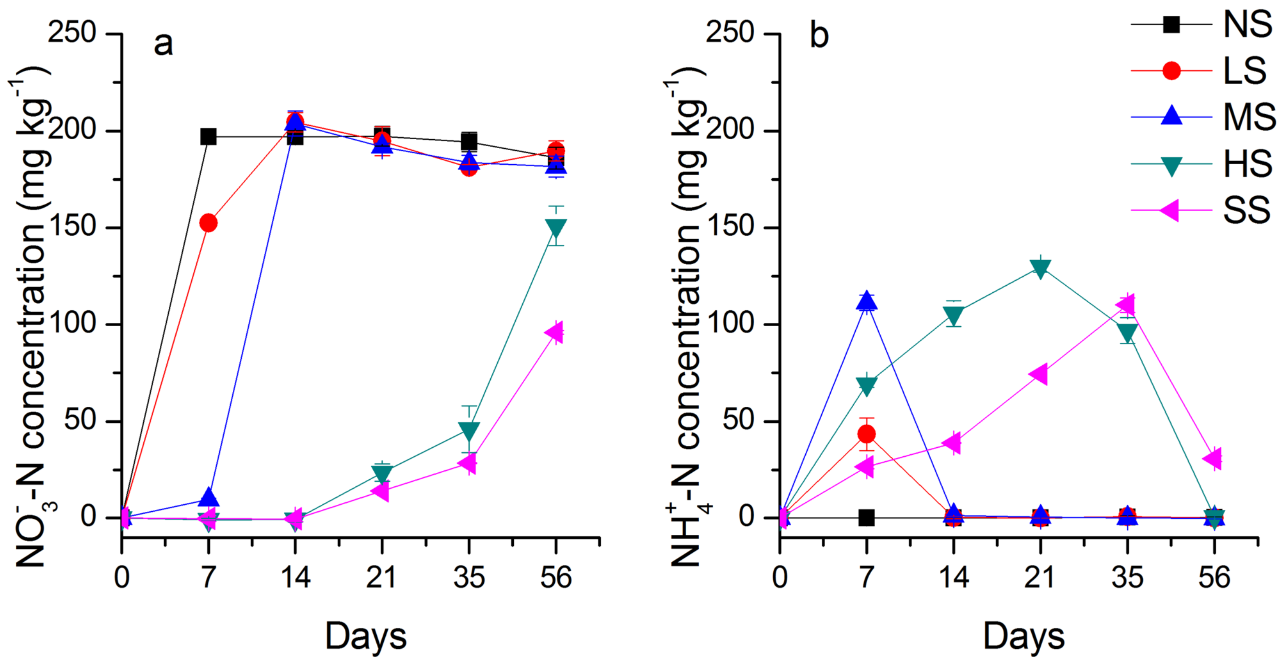


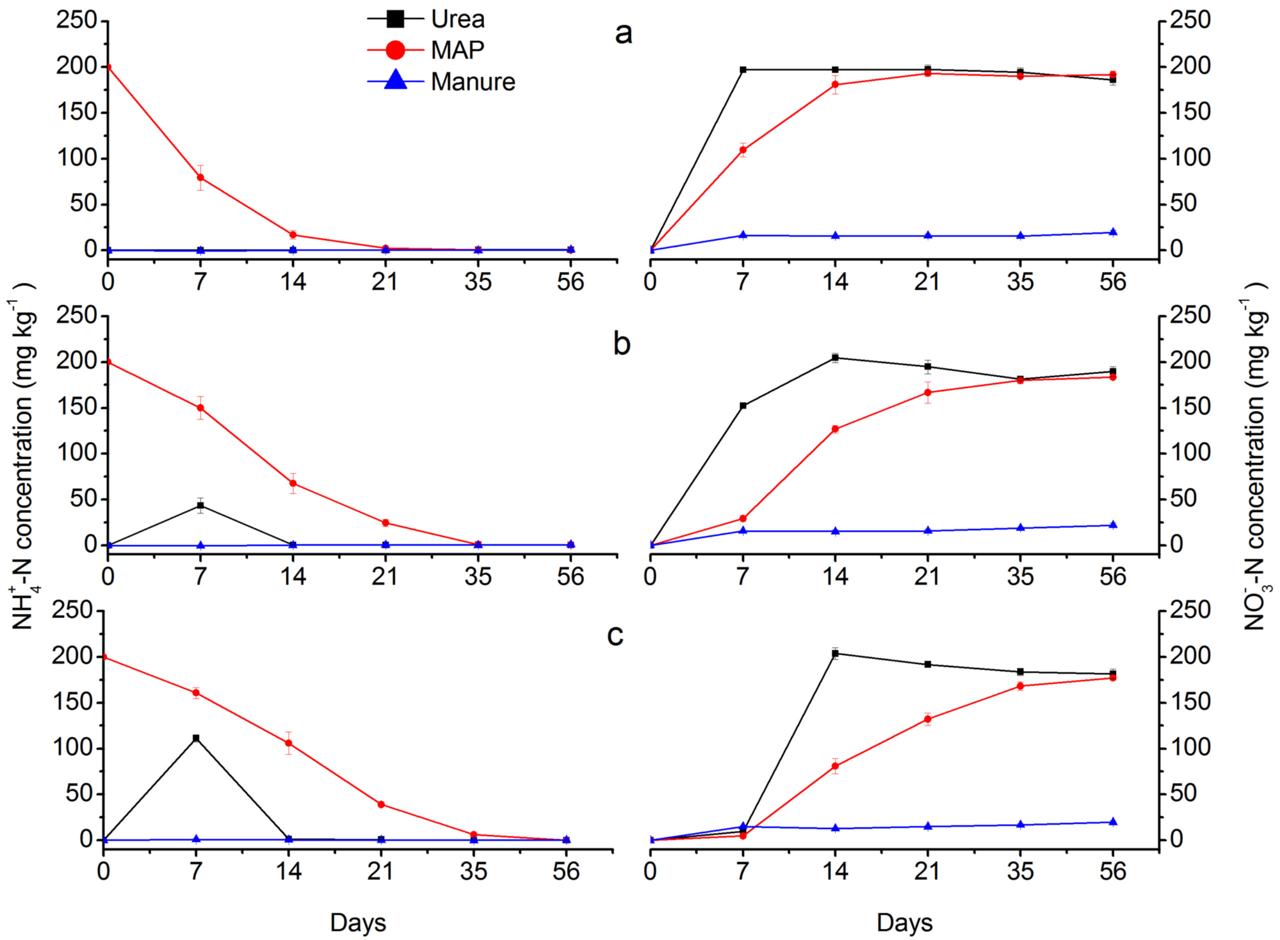
a
NS
LS
MS
HS
SS
Rate of ammonia volatilization (mg kg-1 d-1)
Days
b
Cumulative ammonia volatilization (mg kg-1)
Days
a
b
c
c
d
c
y = 0.0096x - 2.5532
R² = 0.977
Cumulative ammonia volatilization (mg kg-1)
Soil electrical conductivity (us cm-1)



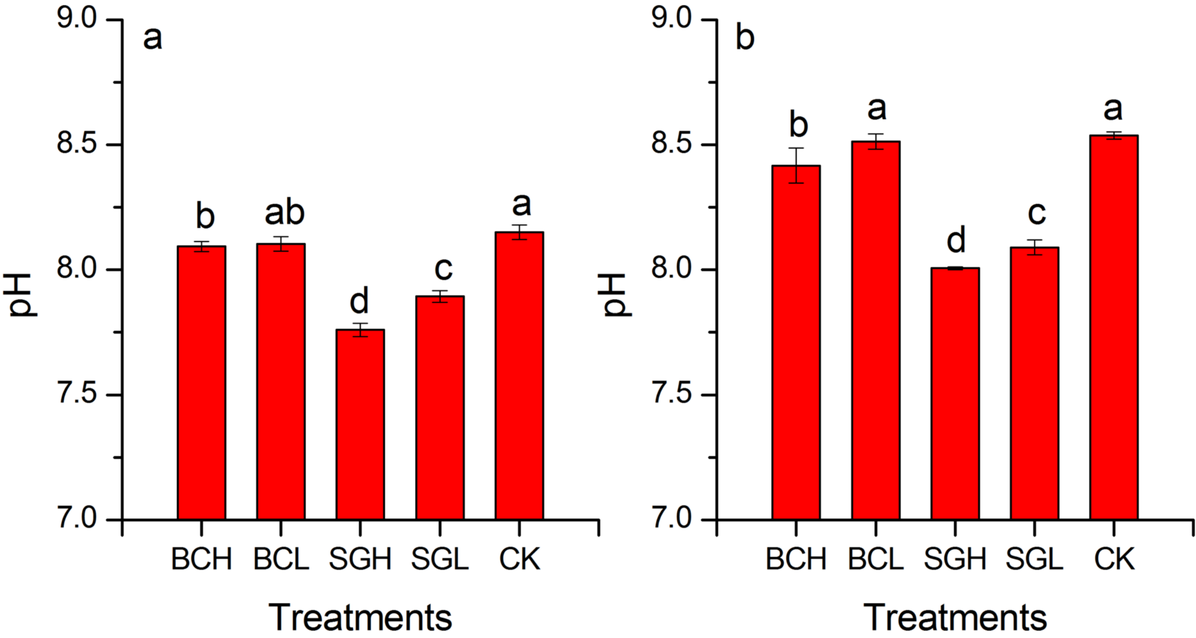
Urea
MAP
Manure
a
b
c
Rate of ammonia volatilization (mg kg^{-1} d^{-1})
Cumulative ammonia volatilization (mg kg^{-1})
Days
Days


a
b
Cumulative ammonia volatilization (mg kg-1)
Days
BCH
BCL
SGH
SGL
CK
a
a
a
b
b
a
b
bc
c
c
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
0
5
10
15
20
25
30


a
b
NO_3^--N concentration (mg kg^{-1})
NH_4^+-N concentration (mg kg^{-1})
0
50
100
150
200
250
0
7
14
21
35
56
Days
NS
LS
MS
HS
SS



Urea
MAP
Manure
a
b
c
NH_4^+-N concentration (mg kg^{-1})
NO_3^--N concentration (mg kg^{-1})
250
200
150
100
50
0
0
7
14
21
35
56
Days
Days



a
b
9.0
8.5
8.0
7.5
7.0
pH
b
ab
d
c
a
b
a
d
c
a
BCH
BCL
SGH
SGL
CK
Treatments

Table 1 Physicochemical-characteristics of soils, biochar and gypsum.

	Sand (%)	Silt (%)	Clay (%)	EC (us cm^{-1})	pH	Total N (g kg^{-1})	TOC (g kg^{-1})	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	CEC (cmol kg^{-1})	ES (cmol kg^{-1})	BET surface (m^2 g^{-1})	PV (cm^3 g^{-1})	VM (%)	Ash (%)	FC (%)
NS	30.73±1.59	62.24±1.68	7.03±0.55	147.90±7.78	8.57±0.08	0.31±0.01	3.48±0.03	17.79±0.44	5.39±0.19	6.23±0.31	0.06±0.03					
LS	31.95±1.08	61.60±1.72	6.45±0.83	686.70±16.12	8.88±0.01	0.24±0.02	2.69±0.11	7.09±0.30	4.63±0.13	5.69±0.15	0.25±0.03					
MS	31.10±2.67	61.18±1.35	7.72±1.33	1215.50±17.68	8.97±0.02	0.22±0.01	2.43±0.03	16.75±0.16	4.85±0.06	5.79±0.15	0.51±0.03					
HS	30.06±1.78	61.81±0.97	8.13±0.86	3048.50±14.85	8.45±0.04	0.22±0.01	2.65±0.08	25.90±0.19	5.17±0.38	5.76±0.20	0.49±0.07					
SS	33.30±1.43	59.48±0.97	7.21±0.89	4155.50±91.22	8.42±0.01	0.19±0.01	1.90±0.10	50.89±0.47	4.94±0.32	4.78±0.12	0.43±0.04					
SG	——	——	——	27160±1.41	6.36±0.17	0.06±0.00	0.56±0.02	1.34±0.02	7.84±0.24	——	——					
BC	——	——	——	7581.50±81.32	9.13±0.05	6.64±0.12	——	35.01±1.65	2.40±0.09	46.60±3.72	0.67±0.03	20.968	0.025	13.71	19.52	66.77

Note: Data were mean ± standard deviation (n = 3), NS = non-saline soil, LS = low-salinity soil, MS = moderately saline soil, HS = high-salinity soil and SS = severely saline soil, SG=gypsum, BC=biochar, PV = pore volume, ES=.exchangeable sodium, VM=volatile matter, FC=fixed carbon.

Table 2 The NO_3^--N and NH_4^+-N concentration of non-saline soil added with biochar and gypsum.

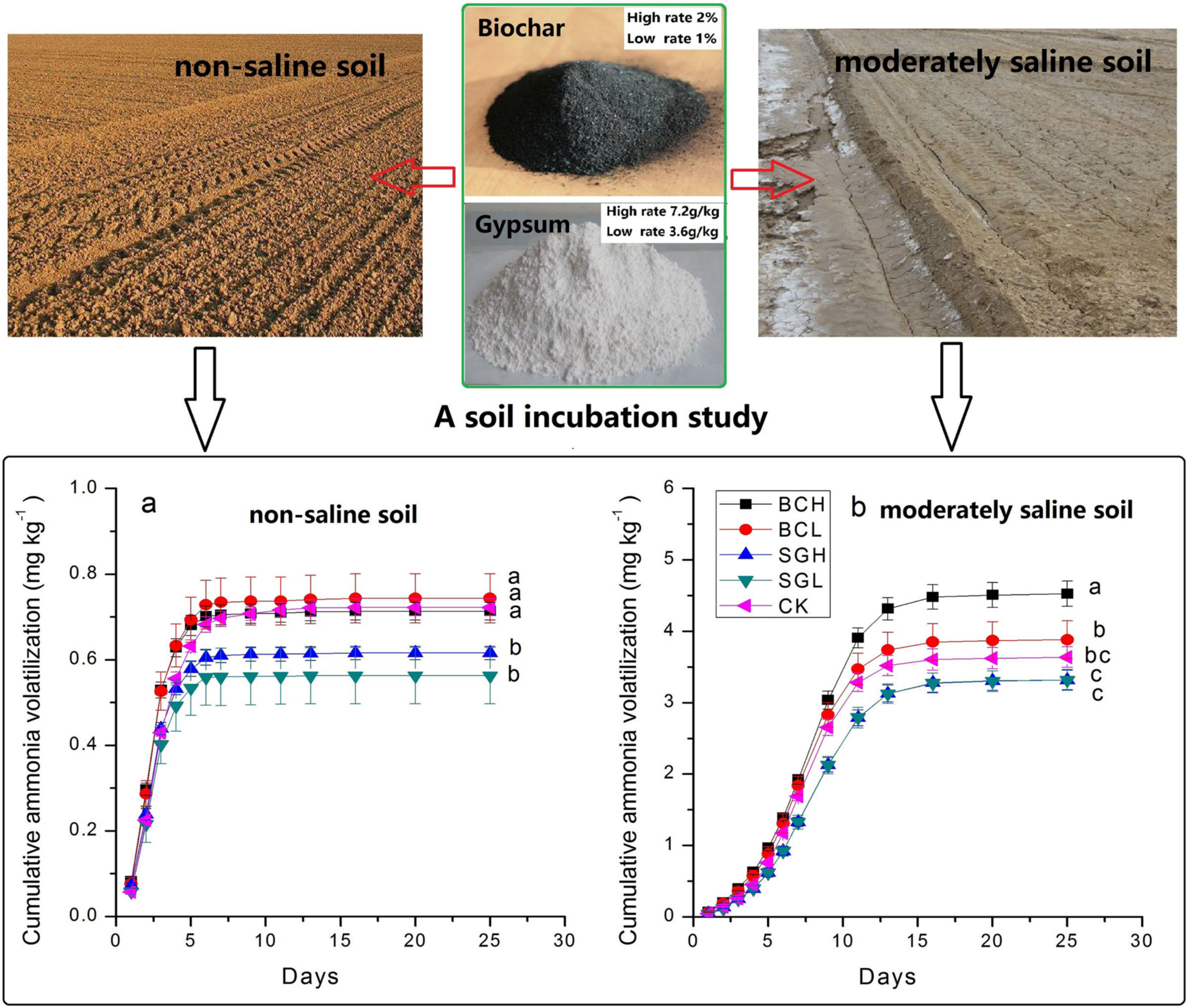
Days	NO_3^--N concentration (mg kg^{-1})					NH_4^+-N concentration (mg kg^{-1})				
	BCH	BCL	SGH	SGL	CK	BCH	BCL	SGH	SGL	CK
3	64.79±1.28	61.51±1.67	53.90±4.95	66.86±0.99	78.73±1.85	17.49±1.35	17.99±0.50	19.25±0.54	18.28±0.23	18.32±0.58
7	221.79±14.53	220.40±9.98	228.50±5.63	235.36±9.05	235.06±1.01	2.54±0.11	3.21±0.58	2.35±0.23	2.43±0.20	2.33±0.24
14	207.54±5.23	213.56±8.13	220.10±1.12	222.90±3.68	218.35±5.79	1.53±0.44	1.72±0.00	1.92±0.34	1.62±0.22	1.83±0.11
21	206.73±3.39	212.50±1.93	228.12±4.79	222.97±2.97	212.67±4.82	2.02±0.40	2.02±0.40	1.80±0.22	1.58±0.16	1.65±0.41
35	208.16±10.02	208.94±4.16	226.20±6.87	226.13±8.13	224.77±6.09	2.04±0.55	2.07±0.11	2.04±0.19	1.70±0.13	2.18±0.22

Note: BCH = high biochar addition, BCL = low biochar addition, SGH = high gypsum addition, SGL = low gypsum addition, CK = soil without amendment addition. Data in the table are average values and standard deviations (n=3).

Table 3 The NO_3^--N and NH_4^+-N concentration of moderately saline soil added with biochar and gypsum.

Days	NO_3^--N concentration (mg kg^{-1})					NH_4^+-N concentration (mg kg^{-1})				
	BCH	BCL	SGH	SGL	CKU	BCH	BCL	SGH	SGL	CKU
3	15.36±0.22	16.06±0.15	16.6±0.18	16.61±0.18	17.43±0.08	12.87±0.08	12.07±0.17	11.95±0.18	11.47±0.12	12.99±0.15
7	28.94±0.99	30.52±0.53	27.05±1.08	28.28±1.37	33.60±0.42	117.57±4.38	117.21±5.57	109.66±0.54	105.26±3.55	102.39±13.59
14	194.65±1.22	204.13±8.09	173.52±7.43	181.09±5.71	222.71±3.14	17.27±4.33	13.51±2.30	41.87±5.86	31.67±6.74	10.57±3.23
21	206.27±3.51	214.09±3.72	217.23±4.62	225.13±3.65	223.33±4.81	1.94±0.29	1.81±0.24	2.62±0.31	2.43±0.23	2.16±0.21
35	186.27±3.11	203.80±2.99	200.15±3.58	203.99±9.00	208.17±5.08	2.11±0.08	2.20±0.23	1.98±0.14	2.46±0.21	2.73±0.18

Note: BCH = high biochar addition, BCL = low biochar addition, SGH = high gypsum addition, SGL = low gypsum addition, CK = soil without amendment addition. Data in the table are average values and standard deviations (n=3).


non-saline soil
Biochar
High rate 2%
Low rate 1%
Gypsum
High rate 7.2g/kg
Low rate 3.6g/kg
moderately saline soil
A soil incubation study
a
non-saline soil
Cumulative ammonia volatilization (mg kg-1)
Days
b moderately saline soil
BCH
BCL
SGH
SGL
CK