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Effects of Varying Rates of Nitrogen and Biochar pH on NH_3 Emissions and Agronomic Performance of Chinese Cabbage (*Brassica rapa* ssp. pekinensis)

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Abstract: NH_3 emitted into the atmosphere undergoes intricate chemical reactions to form fine particulate matter $PM_{2.5}$. Nitrogen fertilizers are one of the major sources of gaseous ammonia. Recently, research into using biochar to lessen NH_3 emissions from agricultural land has taken center stage and several studies have been executed in that regard. However, biochar's capacity to reduce emissions of gaseous NH_3 from applied nitrogen fertilizers is affected by both soil and biochar properties. While the effects of soil properties on NH_3 volatilizations have been widely studied, the data concerning the effects of biochar properties on NH_3 volatilizations from the soil are still scanty. It is against this backdrop that this study examined the effects of biochar pH on emissions of NH_3 from the soil amended with varying quantities of nitrogen, as well as the impact on the growth and productivity of Chinese cabbage. To achieve the study objectives, acidic (pH 5.7), neutral (pH 6.7) and alkaline (pH 11.0) biochars were used and each was added to the soil at a rate of 1% (w/w). Nitrogen fertilizers were applied at three rates of 160, 320, 640 kg ha^{-1}. In comparison with the control, the acidic, neutral and alkaline biochar amendments reduced NH_3 emissions by up to 18%, 20% and 15%, respectively. However, only neutral biochar produced higher Chinese cabbage yields than the urea-only amendment and the Chinese cabbage yields increased with the increasing rates of nitrogen applied. Combined applications of neutral biochar and 640 kg/ha of nitrogen are recommended for optimal cabbage yields and low NH_3 emissions.

Keywords: ammonia; biochar; Chinese cabbage; particulate matter; yield

1. Introduction

Particulate matter (PM) partitioning according to its aerodynamic diameters gives rise to three major groups including the coarse PM ($PM_{10–2.5}$), the fine PM ($PM_{2.5–0.2}$) and the ultrafine PM (UFPM) which is sometimes called nanoparticulate matter (nPM) (PM < 0.2) [1]. Review studies by Luyima et al. [1], Atkinson et al. [2] and Anderson et al. [3] give elaborate summaries of the adverse effects of PM on human health and environmental quality. Agriculture is a major source of both primary PM and secondary PM precursor gases [1]. Nitrogen fertilizers are a rich source of ammonia (NH_3) which undergoes complicated reactions in the atmosphere to form secondary PM. NH_3 volatilizations from the fertilized agricultural soils mainly result from the low use efficiencies of the applied fertilizers by the crops grown [4]. With the expected increase in the use of nitrogen fertilizers in the future, especially in developing countries where the use efficiencies of the applied nitrogen fertilizers range between 30–50%, there is a high likelihood of heightened ammonia emissions [5].

Biochar is a carbon-rich material which is obtained by pyrolyzing feedstock biomass under conditions of limited or no-oxygen supply [6,7]. Biomass composition and pyrolysis conditions play a vital role in the production process and physicochemical properties of biochar [8,9]. Biochar's popularity is premised on its capacity to sequester carbon from the atmosphere for extended periods of time, usually greater than 1000 years, as well as its potential to stabilize heavy metals in the soil. Available data also indicates that the addition of biochar can improve the physicochemical properties of the soil, crop growth and yield especially in the tropical and sub-tropical environments [10–12]. Recently, a lot of interest has ensued in using biochar to abate the emissions of gases of environmental and public health concern including greenhouse gases and PM precursor gases [9,13,14]. Indeed, studies by Mandal et al. [13] and Luyima et al. [9], for example, have found biochar amendments very efficient at lessening NH_3 volatilizations from agricultural soils fertilized with nitrogen.

However, biochar's capacity to reduce emissions of gaseous NH_3 from applied nitrogen fertilizers is affected by properties of both the soil and the biochar. While the effects of soil properties on NH_3 volatilizations have been widely studied, the data concerning the effects of biochar properties on NH_3 volatilizations from the soil are still scanty. It is against this backdrop that this study examined the effects of rice hull biochar pH on NH_3 emissions and the growth and yield of Chinese cabbage. This is important because farmers will be reluctant to use biochar for the abatement of NH_3 if it doesn't provide any agronomic benefits [1]. Chinese cabbage was chosen because it is one of the most important vegetables in South Korea and is mainly used for making kimchi, a fermented side-dish consumed all year around by almost every family.

2. Materials and Methods

2.1. Experimental Setup

The study was conducted through a field experiment that was set up at Chungnam National University farm located at Eoeun-dong, Daejeon, South Korea (latitude, 127°35′ E; longitude, 36°36′ N). The soil at the farm is a sandy loam and belongs to the Inceptisol and Udepts order and suborder, respectively according to the IUSS working group WRB classification. The study was set up in a completely randomized design and each treatment was replicated thrice. Each replicate was set up on a 3 m × 2.5 m plot which translates to an area of 7.5 m^2. The protection bands, 1 m in width, were left to prevent the contamination of the plots with fertilizers from neighboring sectors. The Chinese cabbage variety grown was Chunkwang whose seeds were purchased from Nonghyup, Seoul, South Korea and the spacing adopted was 0.4 m within the plant rows. Each plot was planted with only one row of Chinese cabbage. The study was laid out with twelve treatments which included the following; nitrogen fertilizer applied at the recommended rate (320 kg ha^{-1} N) nitrogen fertilizer applied at half the recommended rate (160 kg ha^{-1} N), nitrogen fertilizer applied at double the recommended rate (640 kg ha^{-1} N) as well as the combined applications of biochars with nitrogen fertilizers i.e., pH 6.7 biochar + 320 kg ha^{-1} N, pH 6.7 biochar + 160 kg ha^{-1} N, pH 6.7 biochar + 640 kg ha^{-1} N, pH 5.7 biochar + 320 kg ha^{-1} N, pH 5.7 biochar + 160 kg ha^{-1} N, pH 5.7 biochar + 640 kg ha^{-1} N, pH 11.0 biochar + 320 kg ha^{-1} N, pH 11.0 biochar + 160 kg ha^{-1} N and pH 11.0 biochar + 640 kg ha^{-1} N. Biochar was applied to the soil at a rate of 1% (*w*/*w*) following the recommendations of the previous study by Oh et al. [7]. Urea, phosphorus pentoxide and potassium oxide were utilized to supply nitrogen, phosphorus and potassium, respectively and for the 320 kg ha^{-1} N amendment, the quantities of phosphorus and potassium applied were 78 and 198 kg/ha, respectively. Split application of nitrogen and potassium was adopted where a third of the nutrients were applied at the transplanting stage. The next 1/3 of the nutrients were applied at 15 days after transplanting and the remaining 1/3 were applied at 30 days after transplanting. The plots were irrigated after each fertilizer application to prevent water stress. The average annual temperature and precipitation of the experimental site were 13.0 °C, 1458.7 mm. Other meteorological data during the test period are represented in

Figure 1. The physicochemical properties of the soil are given in Table 1. The experiment was carried out for 65 days between the 10 April 2020 and the 12 June 2020.

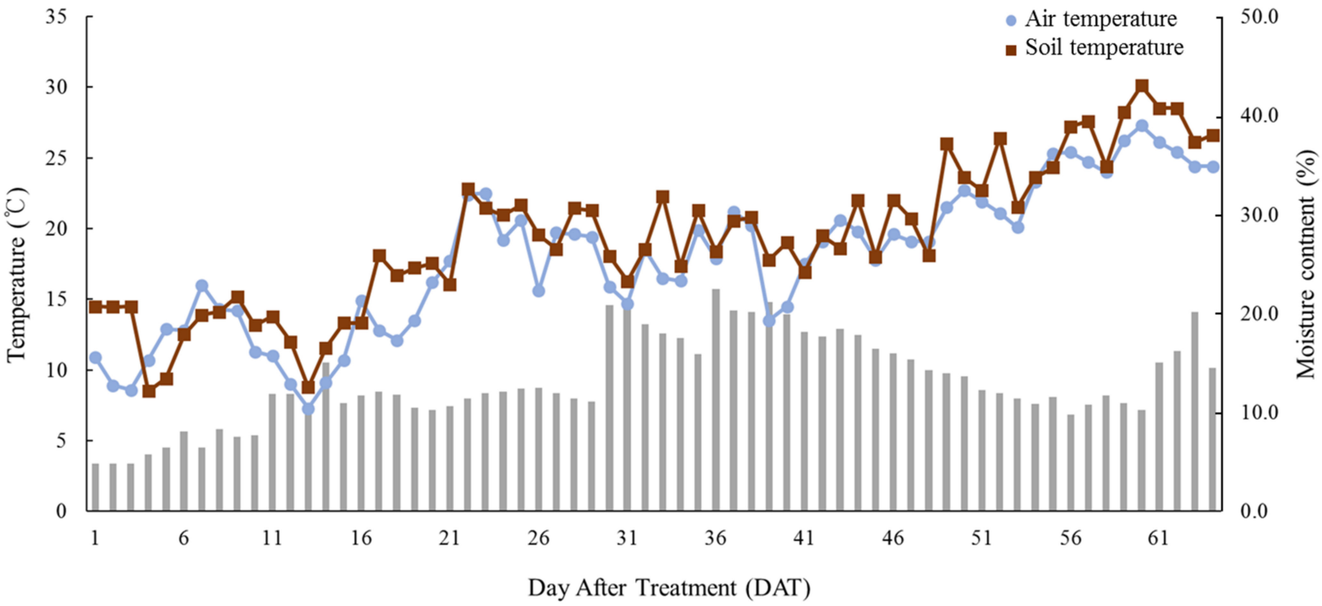

Figure 1. The meteorological data during the experimental period.

Table 1. Chemical properties of soil used in this experiment.

pH	EC	T-C	T-N	Av. P_2O_5	Ca^{2+}	K^+	Mg^{2+}	Na^+
(1:5, H_2O)	(dS m^{-1})	(%)		(mg kg^{-1})	(cmol$_c$ kg^{-1})			
5.8 ± 0.2	0.34 ± 0.01	0.62 ± 0.01	0.14 ± 0.01	34.65 ± 35.48	3.20 ± 0.05	0.40 ± 0.02	1.94 ± 0.01	0.08 ± 0.01

Abbreviations: EC, electrical conductivity; T-C, total carbon; T-N, total nitrogen; Av. P_2O_5, available phosphate.

2.2. Ammonia Volatilization Field Experiment

Measurement of ammonia (NH_3) was conducted using static chambers each with a height of 30 cm and diameter of 12 cm made of acrylic material. Volatilized NH_3 was captured with a glycerol–phosphoric acid mixture made by mixing 40 mL L^{-1} of glycerol with 68.6 mL L^{-1} of phosphoric acid. The capturing mixture was soaked into pieces of sponge and each static chamber was fitted with two pieces of sponge, the upper sponge to prevent the ingress of external contamination, and the lower sponge for capturing NH_3 emitted from the soil. The NH_3 absorbed by the lower sponge was extracted by 2 M KCl solution. The NH_4^+ concentration in KCl extracts was determined by paying strict adherence to the Indophenol blue method espoused by Searl [15]. Daily NH_3 emissions were calculated based on surface area covered by the chambers and temperature inside the chamber. Total NH_3 emissions were calculated by summing daily NH_3 emissions.

2.3. Preparation of Biochar, and Laboratory Analysis of the Soil, Biochar and Plant Tissue

The biochar used in the study was purchased from Purnnature, Suncheon, Korea and Yoogi Lnd, Gochang, Korea and was prepared by charring rice hull, a readily available agricultural waste in South Korea, at different temperatures of 330 °C, 400 °C and 550 °C. The biochars produced at 330 °C were acidic while those produced at 400 °C and 550 °C were neutral and basic, respectively. Levels of pH and EC were determined in water following a method espoused by Singh et al. [16]. The total carbon and nitrogen were assessed with the CHN elemental analyzer (LECO, TruSpec, Dowagiac, MI, USA). The total phosphorus was determined colorimetrically following a method developed by Murphy and Riley [17] after extraction from the biochar ashes by wet ashing with aqua regia solution. The concentration of cations in the biochar was quantified by ICP-OES after extraction from the biochar ashes as instructed by Enders et al. [18]. The available phosphorus was determined colorimetrically following the vanadate-molybdate method after extraction with 2% formic acid. The properties of biochar obtained from the analysis are given in Table 2. The soil cations were determined with ICP-OES after extraction from the soil with 1.0 M neutral ammonium acetate solution. Soil pH and EC were determined in 5 parts of water and 1 part of soil suspension. Total carbon and nitrogen were assessed with the CHN elemental analyzer (LECO, TruSpec, Marietta, GA, USA). Both total and available phosphorus were determined colorimetrically following a method espoused by Murphy and Riley [17] after extraction with aqua regia solution for total phosphorus and 2% formic acid for available phosphorus. The studied yield parameters included; plant weight, water content, head diameter, head length, leaves diameter, leaves length, chlorophyll (SPAD). The fresh weight of the plant was measured immediately after harvest. The 3 largest leaves were used to measure leaf length and width. The leaf chlorophyll content of each plant was determined using a MINOLTA Chlorophyll meter (SPAD-502, Konica Minolta, Tokyo, Japan). Shoot and root of plant were oven-dried at 75 °C to measure dry weight and water content. The selected chemical properties of the soil are shown in Table 1 while those of the biochars are given in Table 2.

Table 2. Chemical properties of rice hull biochar.

Pyrolysis Temp.	pH	EC	T-C	T-N	T-P	Ca	K	Mg	Na
(°C)	(1:10)	(dS m^{-1})				(%)			
350	5.7 ± 0.14	3.40 ± 0.24	41.3 ± 4.87	0.38 ± 0.04	0.14 ± 0.03	0.14 ± 0.03	0.34 ± 0.01	0.04 ± 0.00	0.02 ± 0.00
450	6.7 ± 0.21	1.33 ± 0.11	44.1 ± 4.20	0.36 ± 0.07	0.06 ± 0.01	0.15 ± 0.02	0.48 ± 0.09	0.05 ± 0.01	0.01 ± 0.00
600	11.0 ± 0.18	1.83 ± 0.15	54.9 ± 6.23	0.58 ± 0.09	0.21 ± 0.05	0.33 ± 0.01	0.81 ± 0.04	0.12 ± 0.04	0.05 ± 0.02

Abbreviations: EC, electrical conductivity; T-C, total carbon; T-N, total nitrogen; T-P, total phosphorus.

2.4. Statistical Analysis

The NH_3 emissions during cultivation and the growth results of the crop were expressed as average values. Significance between treatments was compared using Duncan's multiple range test after one-way analysis of variance (ANOVA) using a statistical analysis program (IBM SPSS Statistics version 24, New York, NY, USA). Statistical significance could have been set on the basis of the 95% confidence interval.

3. Results and Discussion

3.1. Ammonia Volatilization

The daily NH_3 emissions obtained from the different rates of N fertilizer applied to the soil are shown in Figures 2–4 while their cumulative volatilized quantities are given in Figures 5–7. For the recommended and half the recommended N application rates, the alkaline biochar led to emissions of the lowest amounts of NH_3 which stood at 7.32 kg/ha and 5.13 kg/ha, respectively. The cumulative NH_3 emissions from the soils amended with the recommended and half the recommended quantities of N reduced with increasing biochar pH although there were no statistical differences amongst the different treatments of the N applied at the recommended rate. For the N applied at double the recommended rate, there were no statistical differences across all treatments as far as the cumulative amount of NH_3 was concerned. All treatments volatilized similar amounts of NH_3 from the beginning of the experiment to the 40th day (2nd topdressing) when emissions increased to their highest level. The total cumulative NH_3 lost from urea applied to the soil increased with application rates to reach 6.02, 9.25, and 18.52 kg ha^{-1} in the 160 kg ha^{-1}, 320 kg ha^{-1} and 640 kg ha^{-1} N application rates, respectively.

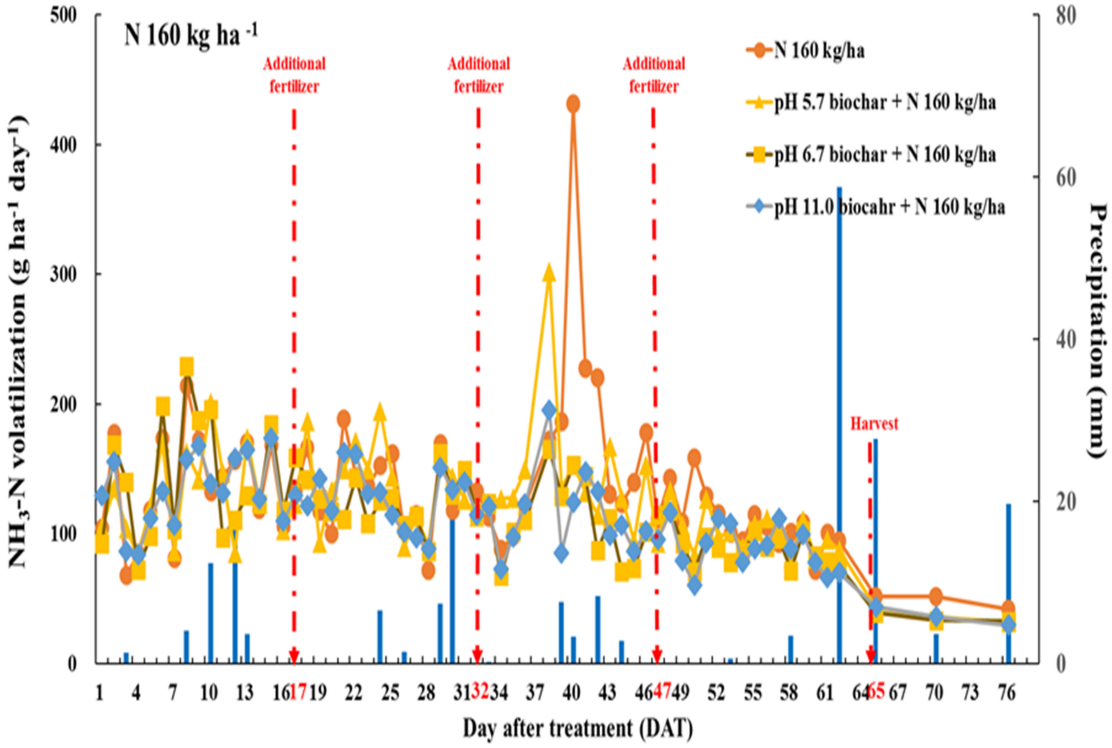

Figure 2. Effect of biochar pH and N 160 kg ha^{-1} in NH_3 emission.

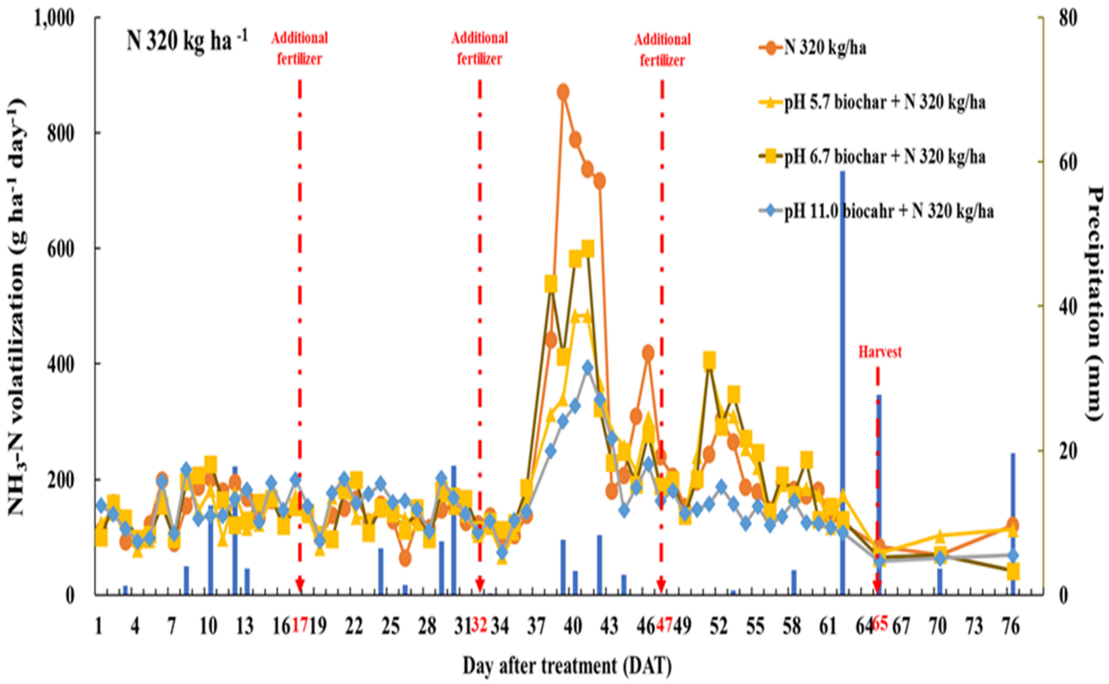

Figure 3. Effect of biochar pH and N 320 kg ha^{-1} in NH_3 emission.

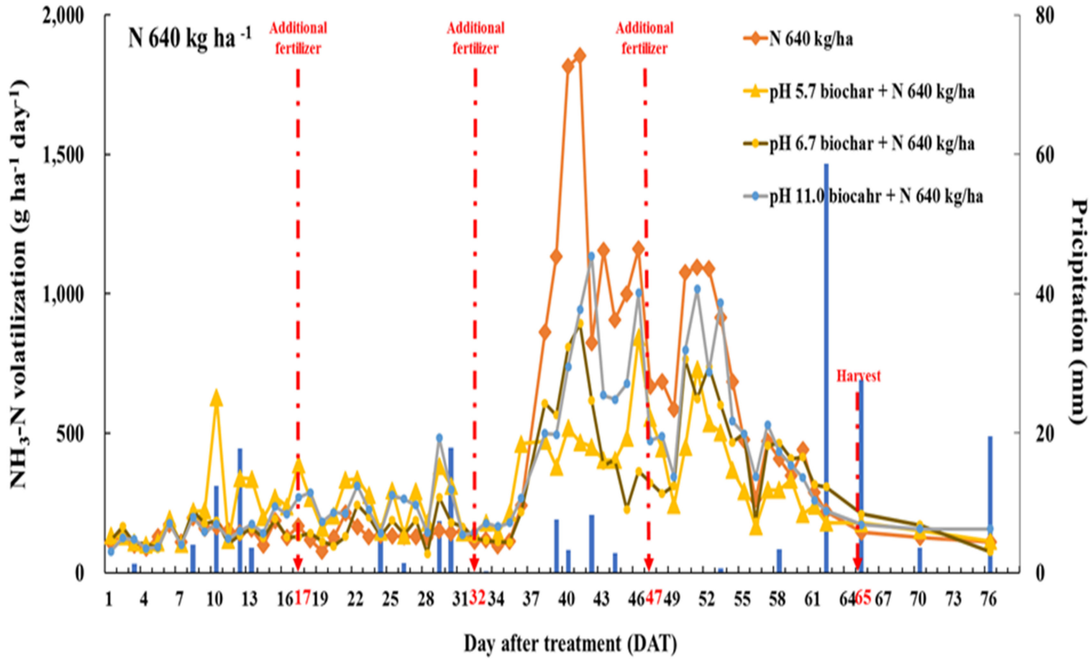

Figure 4. Effect of biochar pH and N 640 kg ha^{-1} in NH_3 emission.

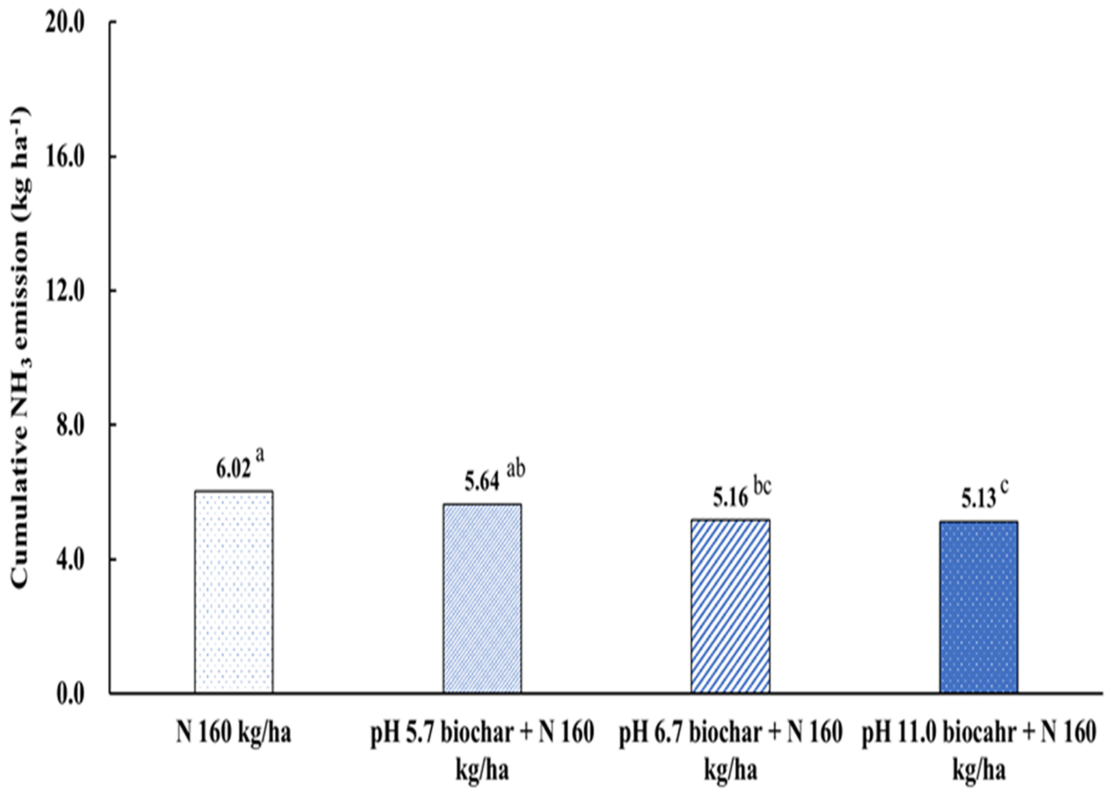

Figure 5. Total NH_3 emission by biochar pH and N 160 kg ha^{-1}.

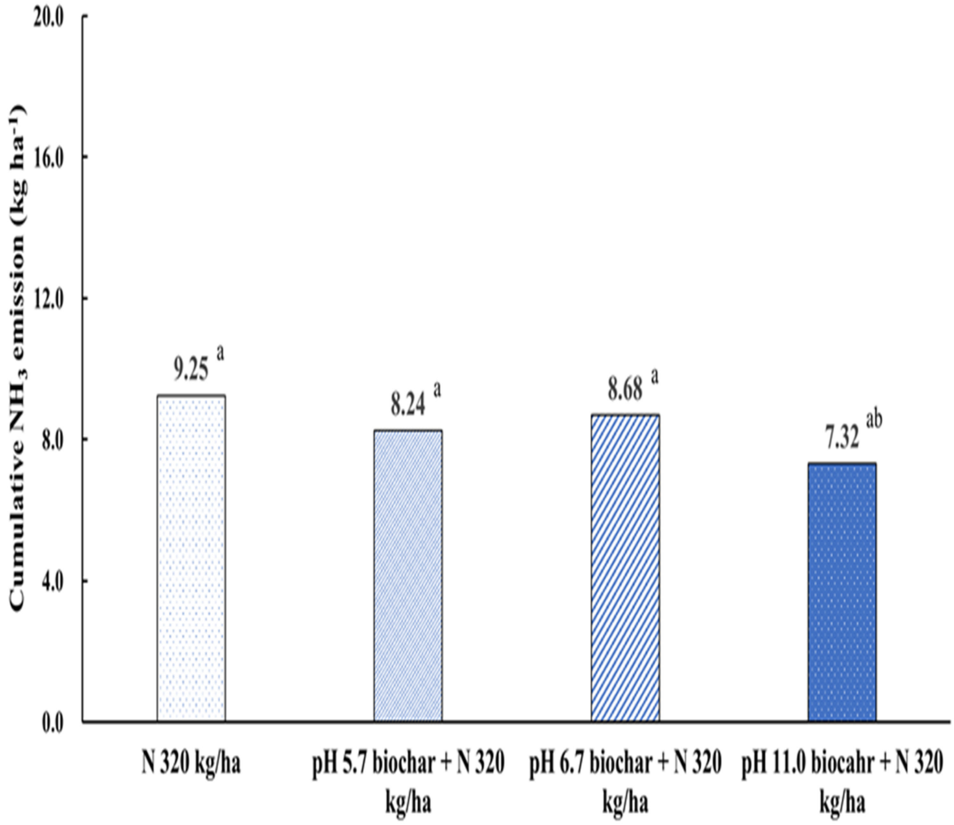

Figure 6. Total NH_3 emission by biochar pH and N 320 kg ha^{-1}.

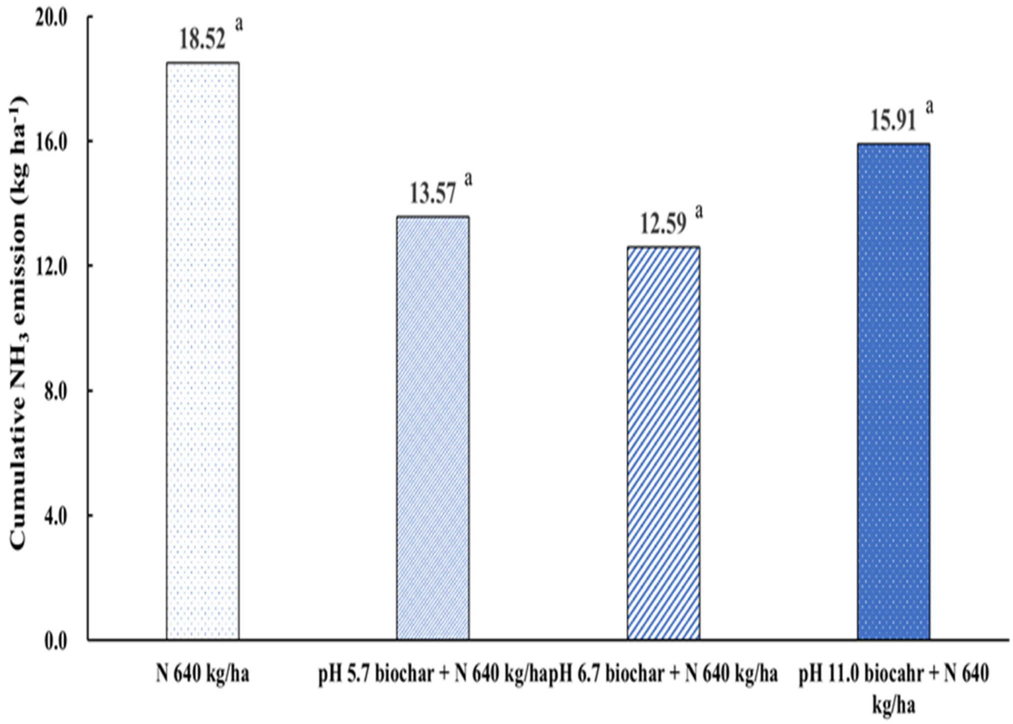

Figure 7. Total NH_3 emission by biochar pH and N 640 kg ha^{-1}.

The strong linear relationship obtained between the N application rates and the quantity of NH_3 volatilized from the soil as shown in Figure 8 accentuates the abovementioned fact. This observation concurred with the one made by Degaspari et al. [19] who indicated that N applied as urea at 180 kg/ha in sugarcane volatilized more NH_3 than both the 60 kg/ha and 120 kg/ha rates which didn't significantly differ statistically. On the other hand, studies by Luyima et al. [1,9], Mandal et al. [13], and others indicated that biochar amendments greatly reduced NH_3 emissions, findings which concur with the observations made in the present study. Several reasons have been given to account for the reductions in NH_3 emissions from the soil following the application of biochar. These include; protonation induced conversion of NH_3 to NH_4^+, absorption of NH_3 into the biochar micro pores, oxidation of NH_4^+ to NO_3^-, and immobilization of N by soil microbes induced by increased carbon to nitrogen ratios and others [9,13].

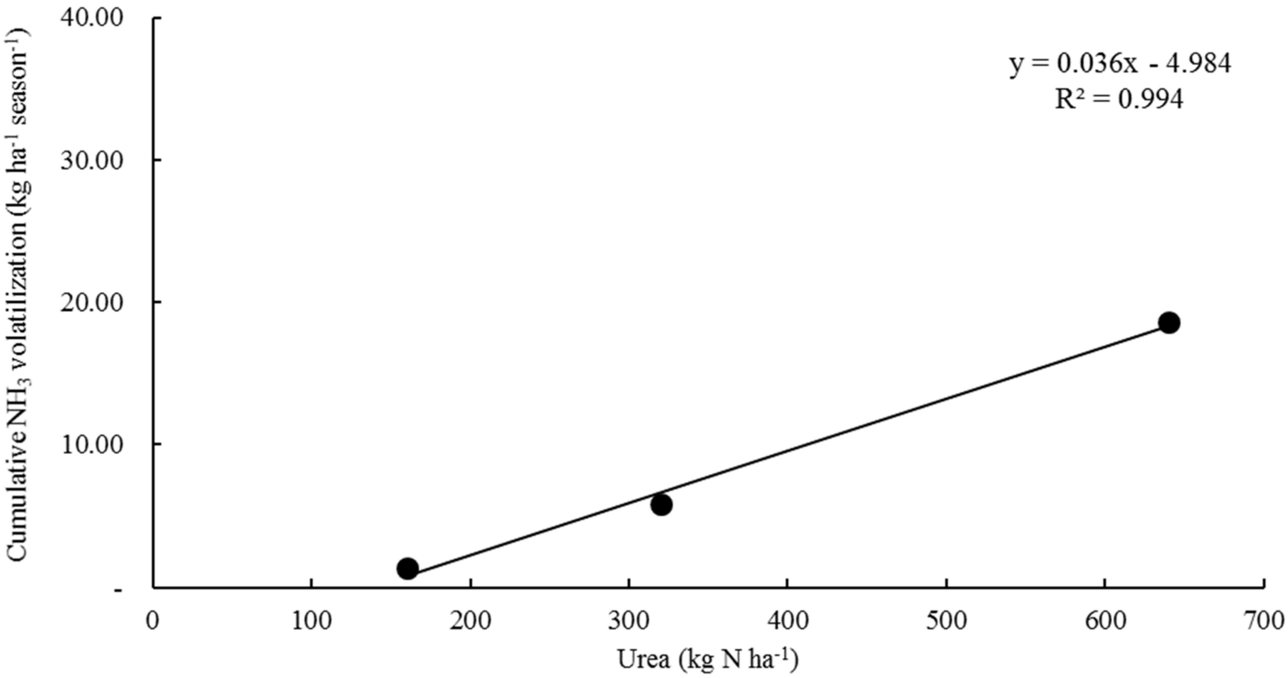

Figure 8. Correlations between NH_3 volatilization and urea amount.

The alkaline biochar led to the highest decreases in NH_3 at both the 160 kg/ha and 320 kg/ha N application rates, possibly due to the presence of exceedingly large numbers of hydroxyl functional groups on the biochar surfaces. Indeed, Fan et al. [20] indicated that increased concentration of the surfaces of hydrous biochar led to increment in NH_4^+ adsorption from water. They observed that NH_4^+ formed surface complexes with the negatively charged surface hydroxyl species. At the 640 kg/ha N rate, the adsorptive capacity of NH_4^+ by the biochar fades, possibly due to the excess NH_4^+ present in the soil which surpasses the adsorptive power of the hydroxyl ions on the biochar surface. At the high N application rate, factors other than the amount of hydroxyl ions on the biochar surface, including biochar's micro pores, cation and anion exchange sites, etc. seem to play vital roles in the abatement of NH_3 emissions. An early study by Sommer et al. [21] examined the effects of temperature and humidity on NH_3 fluxes from soil amended with cattle slurry and noted that NH_3 emissions increased with augmentations in both temperature and humidity. It can be observed from Figure 1 that the average temperatures from the 30th day of the experiment were higher than those at the beginning of the experiment which may explain why the daily emissions were higher after the 30th day than at the beginning of the experiment.

3.2. Chinese Cabbage Yield and Soil Chemical Properties

The selected chemical properties of the soil after experiment are shown in Table 3. No statistically significant differences were observed in the soil pH. Additionally, apart from the alkaline biochar + 160 kg/ha N rate and acidic biochar + 320 kg/ha N rate amendments, which produced higher statistically significant EC than the control, the urea-only amendment led to either higher statistically significant EC than the rest of the biochar amendments or no significant statistically different EC values as compared with the rest of the biochar amendments. These observations contravene those made by several previous studies including those of Lee et al. [22], Luyima et al. [23,24], Yoo et al. [25] and others which indicate that biochar amendments generally increased both the soil pH and EC. The increases in soil pH and EC following biochar application to the soil can been generally attributed to the build-up of ash residues during pyrolysis [26]. The potential of ash to ameliorate soil acidity has been highlighted by Arocena and Opio [27], Khanna et al. [28], Chintala et al. [29] and others.

Table 3. Chemical properties of soil in different biochar treatments.

Treatment		pH (1:5, H_2O)	EC (dS m^{-1})	T-C	T-N	Avail. P (mg kg^{-1})	Ca^{2+}	K^{+}	Mg^{2+}	Na^{+}
				(%)			(cmol$_c$ kg^{-1})			
N 160 kg ha^{-1}	Only urea	6.5 ± 0.4 ^{a}	0.94 ± 0.47 ^{ab}	0.56 ± 0.13 ^{c}	0.20 ± 0.10 ^{a}	122.27 ± 50.14 ^{a}	2.48 ± 0.12 ^{a}	0.95 ± 0.40 ^{a}	1.65 ± 0.39 ^{a}	0.16 ± 0.08 ^{a}
	pH 5.7 biochar	6.7 ± 0.1 ^{a}	0.67 ± 0.15 ^{b}	1.24 ± 0.23 ^{a}	0.23 ± 0.08 ^{a}	74.61 ± 2.56 ^{d}	2.35 ± 0.22 ^{a}	0.69 ± 0.36 ^{a}	1.50 ± 0.21 ^{a}	0.11 ± 0.03 ^{a}
	pH 6.7 biochar	6.5 ± 0.4 ^{a}	0.81 ± 0.11 ^{b}	1.14 ± 0.56 ^{ab}	0.20 ± 0.06 ^{a}	90.80 ± 31.61 ^{c}	2.46 ± 0.10 ^{a}	0.70 ± 0.07 ^{a}	1.71 ± 0.08 ^{a}	0.14 ± 0.03 ^{a}
	pH 11.0 biochar	6.7 ± 0.2 ^{a}	1.32 ± 0.08 ^{a}	1.74 ± 0.03 ^{a}	0.21 ± 0.04 ^{a}	105.14 ± 38.23 ^{b}	2.57 ± 0.36 ^{a}	0.99 ± 0.17 ^{a}	1.78 ± 0.41 ^{a}	0.16 ± 0.01 ^{a}
N 320 kg ha^{-1}	Only urea	6.4 ± 0.1 ^{a}	0.81 ± 0.32 ^{ab}	0.55 ± 0.09 ^{c}	0.19 ± 0.04 ^{a}	114.57 ± 63.92 ^{c}	2.72 ± 0.38 ^{a}	0.58 ± 0.14 ^{a}	1.69 ± 0.09 ^{a}	0.12 ± 0.02 ^{a}
	pH 5.7 biochar	6.4 ± 0.4 ^{a}	1.08 ± 0.22 ^{b}	0.72 ± 0.21 ^{b}	0.18 ± 0.11 ^{a}	121.07 ± 50.44 ^{b}	2.45 ± 0.08 ^{a}	0.62 ± 0.05 ^{a}	1.73 ± 0.24 ^{a}	0.11 ± 0.01 ^{a}
	pH 6.7 biochar	6.3 ± 0.2 ^{a}	0.72 ± 0.18 ^{b}	0.97 ± 0.12 ^{ab}	0.24 ± 0.06 ^{a}	63.72 ± 33.20 ^{d}	2.57 ± 0.21 ^{a}	0.63 ± 0.36 ^{a}	1.64 ± 0.02 ^{a}	0.22 ± 0.16 ^{a}
	pH 11.0 biochar	6.6 ± 0.4 ^{a}	0.82 ± 0.30 ^{a}	2.02 ± 0.14 ^{a}	0.19 ± 0.06 ^{a}	134.88 ± 45.47 ^{a}	2.38 ± 0.15 ^{a}	0.89 ± 0.30 ^{a}	1.66 ± 0.07 ^{a}	0.20 ± 0.13 ^{a}
N 640 kg ha^{-1}	Only urea	6.3 ± 0.2 ^{a}	1.38 ± 0.13 ^{a}	0.51 ± 0.11 ^{c}	0.18 ± 0.05 ^{b}	80.18 ± 14.54 ^{b}	2.44 ± 0.08 ^{a}	0.61 ± 0.08 ^{a}	1.67 ± 0.10 ^{a}	0.12 ± 0.02 ^{a}
	pH 5.7 biochar	6.4 ± 0.4 ^{a}	0.93 ± 0.03 ^{a}	0.77 ± 0.18 ^{b}	0.22 ± 0.06 ^{b}	61.73 ± 49.65 ^{c}	2.50 ± 0.24 ^{a}	0.61 ± 0.22 ^{a}	1.75 ± 0.26 ^{a}	0.14 ± 0.06 ^{a}
	pH 6.7 biochar	6.4 ± 0.1 ^{a}	1.01 ± 0.49 ^{a}	1.19 ± 0.31 ^{ab}	0.19 ± 0.05 ^{b}	81.78 ± 33.33 ^{b}	2.37 ± 0.13 ^{a}	0.52 ± 0.20 ^{a}	1.58 ± 0.33 ^{a}	0.10 ± 0.02 ^{a}
	pH 11.0 biochar	6.5 ± 0.3 ^{a}	1.36 ± 0.42 ^{a}	2.01 ± 0.51 ^{a}	0.42 ± 0.25 ^{a}	127.44 ± 23.99 ^{a}	2.51 ± 0.19 ^{a}	0.64 ± 0.24 ^{a}	1.65 ± 0.26 ^{a}	0.11 ± 0.00 ^{a}

Abbreviations: EC, electrical conductivity; T-C, total carbon; T-N, total nitrogen; Avail. P, available phosphorus. The letters (a–d) denote the significant differences between the different treatments based on the result of the Tukey posthoc test.

Another reason that can account for the increase in soil pH is the large surface area and porosity of biochar which increase the cation exchange capacity (CEC) of the soil with an accompanying increased likelihood of Al and Fe binding [23,26]. The somewhat aberrant observations made in the case of soil pH and EC following biochar applications to the soil in this study require further probing but they may have ensued from the differences in experimental set ups since most of the former studies cited were pot experiments. However, in agreement with all the above-cited studies, the biochar amendments increased soil carbon content. On the other hand, biochar amendments caused no statistically significant differences in the contents of soil cations in comparison with the control experiment. These observations contravene those of Nigussie et al. [26], Yoo et al. [25] and others who found that biochar amendments increased the concentrations of soil cations. However, a study by Hailegnaw et al. [30] assessed the effects of different rates of biochar applied to soils with a wide range of soil physicochemical properties on the contents of soil cations and observed both increments and decrements in the cationic contents. The increases and decreases were observed in soils that originally contained low and high cationic contents. Another contradicting observation in the study was that of the available soil phosphorus because all the above-cited studies found increases in available soil phosphorus upon biochar application. The generally higher contents of soil available phosphorus observed in the control experiment over some of the biochar amendments might have ensued from the continuous previous applications of phosphorus on the field that was used for the experiment.

Growth characteristics and yield parameters of Chinese cabbage are presented in Table 4. Generally, the fresh weight of the Chinese cabbage increased with increasing application rates of nitrogen fertilizer. This observation concurs with those made in several previous studies, for example by Vavrina and Obreza [31], Yeshiwas et al. [32], Baiga & Rajashekhar Rao [33], etc. Combined applications of biochar and biochar and urea generally led to decreases in fresh Chinese cabbage yield in comparison with the urea only treatment except where neutral biochar (pH 6.7) was used. In the same vein, the urea only amendment produced Chinese cabbage with the heaviest dry weight. These observations contravene those made by Baiga & Rajashekhar Rao [33] who obtained both higher fresh yields and heavier dry matter of the Chinese cabbage from the combined applications of biochar and urea than from urea only amendments. In agreement with the observations made in the current study, Qi et al. [34] found acidic biochar to offer no agronomic benefits while the neutral biochar did. However, more studies are needed in this field to explicitly delineate the reasons behind the observed effects.

Table 4. Growth characteristics of Chinese cabbage effected by biochar pH and different nitrogen application.

Treatment		Head					Leaf		Chlorophyll
		Fresh Weight	Dry Weight	Water Content	Height	Width	Length	Width	
		(g)		(%)	(mm)		(mm)		(SPAD)
Control		1364.0 ± 331.0 ^{g}	116.0 ± 20.9 ^{f}	90.4 ± 2.2 ^{a}	204.8 ± 20.9 ^{b}	120.9 ± 48.2 ^{b}	264.1 ± 54.9 ^{b}	191.1 ± 54.1 ^{b}	75.4 ± 14.4 ^{a}
N 160 kg ha^{-1}	**Only urea**	2096.54 ± 257.5 ^{ef}	148.6 ± 23.1 ^{e}	92.8 ± 0.7 ^{a}	254.7 ± 18.7 ^{ab}	151.8 ± 14.1 ^{ab}	317.1 ± 5.1 ^{a}	212.1 ± 9.6 ^{ab}	90.4 ± 10.5 ^{a}
	pH 5.7 biochar	1716.8 ± 201.8 ^{fg}	141.8 ± 14.2 ^{e}	92.0 ± 1.5 ^{a}	239.6 ± 63.6 ^{ab}	135.9 ± 22.8 ^{ab}	292.3 ± 9.3 ^{ab}	196.7 ± 17.6 ^{b}	79.5 ± 18.6 ^{a}
	pH 6.7 biochar	2118.0 ± 11.5 ^{ef}	171.8 ± 0.4 ^{c}	91.6 ± 0.7 ^{a}	256.3 ± 6.3 ^{ab}	147.9 ± 21.7 ^{ab}	299.6 ± 16.5 ^{ab}	209.3 ± 22.7 ^{ab}	85.2 ± 17.9 ^{a}
	pH 11.0 biochar	1581.3 ± 242.8 ^{g}	131.9 ± 14.4 ^{e}	91.0 ± 0.8 ^{a}	237.5 ± 37.3 ^{ab}	131.5 ± 32.6 ^{ab}	298.2 ± 27.0 ^{ab}	202.4 ± 33.3 ^{b}	74.9 ± 15.8 ^{a}
N 320 kg ha^{-1}	**Only urea**	2533.7 ± 752.3 ^{cde}	179.4 ± 51.4 ^{bc}	92.8 ± 0.1 ^{a}	255.9 ± 65.1 ^{ab}	162.3 ± 11.2 ^{ab}	320.9 ± 4.4 ^{a}	223.8 ± 19.9 ^{ab}	80.7 ± 19.8 ^{a}
	pH 5.7 biochar	2303.5 ± 156.0 ^{de}	168.0 ± 3.0 ^{c}	92.3 ± 0.7 ^{a}	253.9 ± 15.1 ^{ab}	146.8 ± 17.1 ^{ab}	307.8 ± 10.4 ^{a}	222.4 ± 30.6 ^{abb}	80.8 ± 14.9 ^{a}
	pH 6.7 biochar	2782.5 ± 23.5 ^{cd}	174.3 ± 24.0 ^{c}	92.9 ± 1.3 ^{a}	239.9 ± 17.4 ^{ab}	172.3 ± 29.0 ^{ab}	332.9 ± 8.6 ^{a}	255.0 ± 9.2 ^{a}	82.9 ± 18.4 ^{a}
	pH 11.0 biochar	2166.3 ± 86.8 ^{ef}	152.6 ± 5.3 ^{d}	92.3 ± 1.0 ^{a}	272.1 ± 54.1 ^{ab}	161.5 ± 9.8 ^{ab}	334.8 ± 19.7 ^{a}	224.1 ± 19.7 ^{ab}	84.7 ± 7.3 ^{a}
N 640 kg ha^{-1}	**Only urea**	3307.5 ± 312.0 ^{ab}	219.8 ± 34.5 ^{ab}	93.0 ± 0.61 ^{a}	271.7 ± 56.6 ^{ab}	179.6 ± 8.3 ^{a}	315.3 ± 20.3 ^{a}	225.5 ± 25.4 ^{ab}	85.2 ± 13.2 ^{a}
	pH 5.7 biochar	2505.8 ± 25.3 ^{cde}	169.8 ± 10.7 ^{c}	92.1 ± 1.57 ^{ab}	234.7 ± 3.2 ^{abb}	169.2 ± 43.4 ^{ab}	317.6 ± 12.3 ^{a}	227.1 ± 10.1 ^{ab}	82.2 ± 15.0 ^{a}
	pH 6.7 biochar	3521.0 ± 294.0 ^{a}	242.1 ± 0.9 ^{a}	92.2 ± 0.73 ^{a}	280.5 ± 22.0 ^{a}	183.9 ± 41.9 ^{a}	307.1 ± 21.8 ^{a}	218.6 ± 38.8 ^{b}	80.7 ± 11.7 ^{a}
	pH 11.0 biochar	2992.7 ± 215.9 $^{b\ c}$	196.0 ± 4.4 ^{b}	93.4 ± 0.43 ^{a}	264.6 ± 23.9 ^{ab}	169.2 ± 11.2 ^{ab}	323.3 ± 20.0 ^{a}	226.6 ± 19.6 ^{ab}	84.2 ± 18.3 ^{a}

The letters (a–f) denote the significant differences between the different treatments based on the result of the Tukey posthoc test.

4. Conclusions

The results of the study indicate that biochar pH greatly impacts both NH_3 emissions from the soil and the agronomic performance of the crops. Generally, the neutral biochar amendments resulted in the greatest reductions in gaseous NH_3 emissions as well as the highest marketable yields of the Chinese cabbage. It was also observed that the NH_3 emissions form the soil increased with the increasing application rates of the N fertilizer. Additionally, combined applications of biochar and N fertilizers reduced the Chinese cabbage yields in comparison with the control i.e., urea-only amendment except where the neutral biochar was used. In fact, combining neutral biochar applications with N increased Chinese cabbage yields. Therefore, combined applications of the neutral biochar and 640 kg/ha of N are recommended for optimal Chinese cabbage yields and low NH_3 emissions.

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