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Mitigation of Soil Salinity by Addition of Different Rice Straw Biochar Doses in Salt-affected Acid Soil

Kyi Kyi Shwe[1,2], Nantanat Chaopayao[1] and Sukunya Yampracha[1*]

[1] Department of Plant Production Technology, School of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang, Ladkrabang, Bangkok 10520, Thailand

[2] Department of Soil and Water Science, Yezin Agricultural University, Yezin, Nay Pyi Taw 15013, The Republic of the Union of Myanmar

E-mail: sukunya.ya@kmitl.ac.th

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Abstract

The current study was carried out to evaluate the effect of rice straw biochar amendment and to identify the appropriate dose of biochar application to reduce soil acidity, salinity, toxicity, and sodicity in salt-affected acid soils. The rice straw biochar at 4 different rates of 0%, (control) 1%, 3%, and 5% (w/w) was mixed with 6 salt-affected acid soils: S1 (non-saline), S2 and S3 (low saline), and S4, S5, and S6 (moderate saline). The mixture was continuously shaken in distilled water for 7 days. The biochar application significantly increased soil pH and saturated electrical conductivity (ECe) with an increasing biochar application rate compared with the control. Significant decreases in sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) values below the critical level of sodicity were observed above the biochar application rate of 1%. Soluble chloride (Cl^-) and soluble and exchangeable sodium (Na^+) were significantly reduced above the biochar application rate of 1%. The biochar application (≥ 1%) led to a significant increase in soluble and exchangeable potassium (K^+) and declines in soluble and exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}). This study concluded that the biochar application rate of 1% was suitable for reducing soil acidity to a safe level for rice plants. The rice straw biochar application improved soil toxicity and sodicity by reducing soluble Cl^- and soluble and exchangeable Na^+, decreasing SAR and ESP. The biochar application also increased available K^+, essential for rice plant growth and development in salt-affected soils.

Keywords: Rice straw biochar, saline-sodic soil, potassium, sodium adsorption ratio, exchangeable sodium percentage

1. Introduction

Climatic changes have caused a significant increase in salinity. Climate changes have also increased the frequency, intensity, and duration of extreme hydrological events, such as floods and droughts (Tabari 2021). These changes have caused rising sea levels, bringing salinity to coastal areas. This leads to seawater intrusion, which causes the salinization of freshwater and alters the accumulation of nutrients, resulting in the water source being less adequate for agricultural use or human consumption. Salinity is defined as increased salt concentrations beyond a certain level in water and soil, which can induce water stress for plants, affecting their growth (Eswar *et al* 2021).

Saline soils are a severe issue for agriculture worldwide, impacting the capability for agricultural practice and reducing yields in salt-affected soils (Hopmans *et al* 2021). The soil salinity problem in Thailand covers 1.28% of the total land area, reducing agricultural productivity. Approximately 2.30 million ha face salt-affected soils in Thailand, divided into three primary locations: the central plain, the coastal area, and the northeast plateau basin (Arunin and Pongwichian 2015). Recently, seawater intrusion has caused the soil to become salt-affected soils in the central plain of Thailand due to rising sea levels. Seawater intrusion has occurred from major rivers, such as Chao Phraya, Pa Sak, Mae Klong, Phetchaburi, and Bang Pakong, which are connected to Thailand's Gulf. Generally, the seawater intrusion in Bang Pakong River occurs 6 months a year, and the maximum seawater mixing is 25.40% (v/v) in the dry season (Shwe *et al* 2022). Huaihongthong and Yampracha (2023) found that the seawater intrusion in Bang Pakong River diffused and mixed with irrigation water of agricultural area by more than 2%(v/v), resulting in the electrical conductivity (EC), salinity, Na ion, SAR, and soluble sodium percentage exceeded the acceptable limits. In addition, most salt-affected soils along the Bang Pakong River are acid soils and acid sulfate soils (pH < 4-6), which are significant limitations for plant growth (Kroeksakul *et al* 2021). Chachoengsao soil series is one of acid soil that has developed on sediment deposited during the Holocene epoch and occupied a moderate extent in the eastern part of the central plain (Sukitprapanon *et al* 2016). Still, these areas are significant areas for economic crops, especially rice.

Salinity is one of the critical factors for crop production, including rice production (Hopmans *et al* 2021). Saline soil exhibits poor physical conditions, such as poor drainage, low fertility, and soil toxicity from Na^+ and $Cl^–$ ions (Dahlawi *et al* 2018). Therefore, it is not an ideal condition for agriculture. The increasing salinity reduces nutrient uptake by rice plants (Kordrostami *et al* 2017). The high concentrations of Na^+ and $Cl^–$ cause ionic imbalance in plant tissues and inhibit the uptake of mineral nutrients (Alharbi *et al* 2022), especially the accumulation of excess Na^+ in the cytoplasm imbalances K^+ uptake and other macro/ micronutrients. The Na^+ and $Cl^–$ accumulation causes the senescence of premature leaves and, ultimately, plant death (Megha *et al* 2022).

Organic residue application has been used to increase soil fertility and crop yields in farmland for extended periods, improving soil salinity and enhancing plant growth in saline soils (Chen *et al* 2021). Recycling large amounts of organic residues, such as rice straw, can increase soil fertility and carbon sequestration by returning it to the soil. In Thailand, rice straw production is estimated to be over 20 million tons annually (Arunrat *et al* 2023). The central plain region produces about 10 million tons of rice straw residues annually. Open-field burning is a common agricultural practice in Thailand, where approximately 69% of the produced straw is burned in the fields (Maneepitak *et al* 2019). Rice residue burning after harvest is common for residue management among farmers because there is a short duration between harvesting and cultivation (Arunrat *et al* 2023). However, burning residue has adverse effects on the environment, especially causing air pollution and climate change. Converting rice straw to biochar is a better consideration of rice straw management to improve carbon sequestration and nutrient retention, including reclamation of acidity and salinity. Their application in saline soils increases organic matter and nutrient contents and improves soil physicochemical properties and structure in saline soils (Mohanavelu *et al* 2021).

Biochar is generally synthesized from organic residues under limited or no oxygen at temperatures between 300 °C and 1000 °C (Yaashikaa *et al* 2020), providing organic carbon compounds and staying longer in the soil than other organic material applications (Guo *et al* 2020). It has significant potential for adsorbing salt ions like K^+, Ca^{2+}, and Na^+ because of its strong adsorption capacity and large surface area that decreases the amount of salts in both soil and solution. It also adsorbs Na^+ ions and reduces its hazards while releasing mineral nutrients such as Mg^{2+} and Ca^{2+} into the soil (Tan *et al* 2021), supplying Ca^{2+} and reducing Na^+ from the exchange sites (Mohanavelu *et al* 2021), leading to a lower ESP or SAR of saline soil (Yue *et al* 2016). Biochar amendment is effective in decreasing salinity stress on plants by reducing soil EC, soluble $Cl^–$, soluble and exchangeable Na^+, and increasing soluble and exchangeable K^+ in soil (Sudratt and Faiyue 2023).

The high pH and high buffer capacity of biochar reduce soil acidity by adsorbing H^+ ions and the decarboxylation process (Juriga and Šimanský 2019). Occasionally, biochar can be substituted for lime to increase the pH of acidic soils. The high pH can improve soil quality and increase the availability of macronutrient nutrients such as Mg^{2+}, Ca^{2+}, and K^+ or decrease micronutrient availability (Jemal and Yakob 2021). The biochar application improved soil physical properties, such as total porosity, water holding capacity, and bulk density, of salt-affected soil because of high porous material, although the effect changed depending on the amount of biochar applied to the soil (Saifullah *et al* 2018). Moreover, biochar application increased soil surface area, which improved soil water and nutrient retention and soil aeration, especially in fine-textured soils. Besides, biochar can enhance soil biological properties by providing a suitable environment for soil microbial communities (Amesalu *et al* 2020). Biochar application from a lower to a higher rate reduces acidity and gives different benefits (Jemal and Yakob 2021). Although the increasing rate of biochar (1, 3, 5%) increased EC and soluble K^+, Ca^{2+}, and Mg^{2+} in soil (Gerges *et al* 2023), the biochar amendment at the rate of 5% improved most of the soil properties to reclaim salt-affected acid soil (Gunarathne *et al* 2020). Based on this concept, biochar can be used as positive or negative effects on both soil salinity and acidity in salt-affected soils. Therefore, the objectives of this study were to evaluate the effect of different rates of application of rice straw biochar in soil properties related to salinity in salt-affected soils and to identify the appropriate dose of biochar application to reduce acidity, salinity, toxicity, and sodicity in salt-affected soils.

2. Materials and Methods

2.1 Experimental site

The experiment was conducted at the Department of Plant Production Technology, School of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang, Ladkrabang District, Bangkok, Thailand from October 2022 to November 2023.

2.2 Collection and preparation of soil

The soil sample was collected at 0 to 20 cm depth from a paddy field at Khlong Khuean District, Chachoengsao Province (13°47'12.47"N, 101°9'2.66"E), where the soil was affected by seawater intrusion. The soil was Chachoengsao soil series (Isohyperthermic Vertic Endoaquepts). Chachoengsao soils are formed by mixing marine sediments and riverine alluvium under the influence of brackish water (Udomsri 2004). The experimental soil is clay soil texture (clay content 621 g kg^{-1}) with pH 4.38(soil:water;1:5), soil organic carbon 12 g kg^{-1}, saturated soil electrical conductivity

(ECe) 2.01 dS m^{-1} (low saline), exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ were 100, 1228, 1011, and 408 mg kg^{-1}, respectively, soluble Cl^- 397.60 mg L^{-1}, cation exchange capacity (CEC) 35.36 $cmol_c$ kg^{-1}, SAR 2.09 and ESP 5.05%.

The soil sample was made as salt-affected soils using artificial seawater, and prepared according to American Society for Testing and Materials (ASTM) standard D1141-98 (ASTM Synthetic Seawater, 2019). Twenty kilograms of soil sample was weighed and put into six pots. The desired seawater solutions (0%, 2%, 4%, 6%, 8%, and 10% (v/v)) were added at a 5-10 cm depth from the soil surface as respective treatments. The chemical properties of different seawater levels are described in Table 1. The artificial seawater was applied every 4 months, and the soil was left to incubate for 12 months. At the end of incubation, the salt-affected soil samples were moved from the pot and then air-dried at ambient temperature. The six types of soils were labeled as S1 (0%), S2 (2%), S3 (4%), S4 (6%), S5 (8%), and S6 (10%). The soils were crushed and passed through a 2 mm sieve for analyzed ECe and incubation study. The ECe values of salt-affected soils were 1.91, 2.53, 4.02, 4.37, 4.99, and 5.93 dS m^{-1} in S1, S2, S3, S4, S5, and S6, respectively. Based on the classification of salinity by US Salinity Laboratory staff, soil ECe < 2, 2-4, and 4-8 dS m^{-1} are non-saline, low saline, and moderate saline, respectively (Yang *et al* 2022). Therefore, S1 is non-saline, S2 and S3 are low saline, and S4, S5, and S6 are moderate saline.

2.3 Collection of biochar

The biochar was synthesized from rice straws at a pyrolysis temperature of approximately 500 °C for 2 hours using a modified small-scale biochar kiln (Petchaihan *et al* 2020; Yaashikaa *et al* 2020). The average rice straw biochar yield was 30%. The biochar was sieved through 0.1 mm to mix with salt-affected acid soils. The rice straw biochar has pH 7.98 (moderately alkaline), EC 1.98 dS m^{-1}, total C 533 g kg^{-1}, total N 9.32 g kg^{-1}, total K 28.47 g kg^{-1}, total Ca 5.38 g kg^{-1}, total Mg 2.71 g kg^{-1}, total Na 0.63 g kg^{-1}, and CEC 21.20 $cmol_c$ kg^{-1} (table 2).

Table 1. The chemical properties of different seawater mixing levels.

Parameters	**Seawater mixing levels**				
	2%	**4%**	**6%**	**8%**	**10%**
pH	7.35	6.92	6.76	6.58	6.50
EC (dS m^{-1})	1.28	2.43	3.54	4.58	5.60
SAR	7.28	10.68	12.90	15.16	17.13
Soluble K^+ (mg L^{-1})	13.0	20.0	27.0	37.0	43.0
Soluble Ca^{2+} (mg L^{-1})	43.0	48.0	50.0	59.0	61.0
Soluble Mg^{2+} (mg L^{-1})	25.52	51.04	76.56	102.08	127.6
Soluble Na^+ (mg L^{-1})	244	446	622	830	1025
Soluble SO_4^{2-} (mg L^{-1})	59.0	77.0	104	140	170
Soluble Cl^- (mg L^{-1})	373	781	1118	1473	1846

Table 2. The chemical compositions of rice straw biochar.

Name	pH	EC (dS m^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})	Total K (g kg^{-1})	Total Ca (g kg^{-1})	Total Mg (g kg^{-1})	Total Na (g kg^{-1})	CEC ($cmol_c$ kg^{-1})
Rice straw biochar	7.98	1.98	533	9.32	28.47	5.38	2.71	0.63	21.20

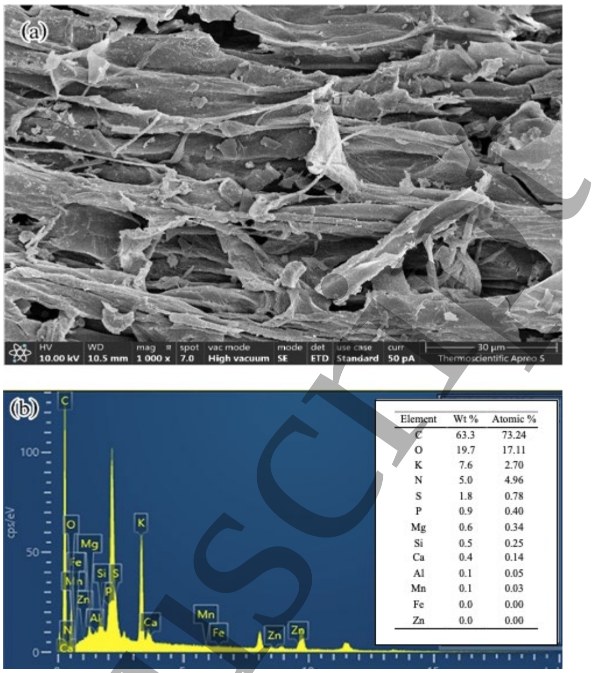
2.4 Methods of biochar analysis

The pH and EC were measured at 1:5 (biochar: water) by pH and EC meter (CONSORT C830). The total C and N were measured by CN analyzer (FAO 2019). The total Na, K, Ca, and Mg were analyzed by an inductively coupled plasma optical emission spectrometer (ICP-OES) after digestion with aqua regia (Chen *et al* 2023). The CEC was estimated using 1N ammonium acetate, pH 7.0 method (FAO 2022).

2.5 Scanning electron microscope (SEM), Energy-dispersive X-ray (EDX), and Fourier transform infrared spectroscopy (FT-IR) analysis

The scanning electron microscopy (SEM) image and X-ray spectroscopy (EDX) spectra of rice straw biochar were investigated to determine the weight and atomic percentage of the components. Specific surface area and total porosity were measured by the Brunauer–Emmett–Teller (BET) method (Brunauer *et al* 1938). The functional group determination of the rice straw biochar was performed by the Fourier transform infrared spectroscopy (FT-IR) (model: Perkin Elmer Spectrum One). All spectra were attained for the wavenumber range of 500 - 4000 cm^{-1}.

The SEM and EDX provide the morphological information and the elemental distribution (Afroze *et al* 2020). Figure 1(a) shows the SEM image of rice straw biochar in this study. The major compositions of the rice straw biochar were carbon and oxygen. The K content was the highest in the biochar among other elements (figure 1(b)). The specific surface area and total pores volume were 3.10 m^2 g^{-1} and 0.025 cm^3 g^{-1}, which were the normal range of rice straw biochar (Lui *et al* 2017). The FT-IR spectra identified the functional groups of the rice straw biochar (figure 2). The functional groups and literature are described in Table 3.



Element	Wt %	Atomic %
C	63.3	73.24
O	19.7	17.11
K	7.6	2.70
N	5.0	4.96
S	1.8	0.78
P	0.9	0.40
Mg	0.6	0.34
Si	0.5	0.25
Ca	0.4	0.14
Al	0.1	0.05
Mn	0.1	0.03
Fe	0.0	0.00
Zn	0.0	0.00

Figure 1. Scanning electron microscopy (SEM) image (1000x magnification) (a) and X-ray spectroscopy (EDX) spectra (b) of rice straw biochar.

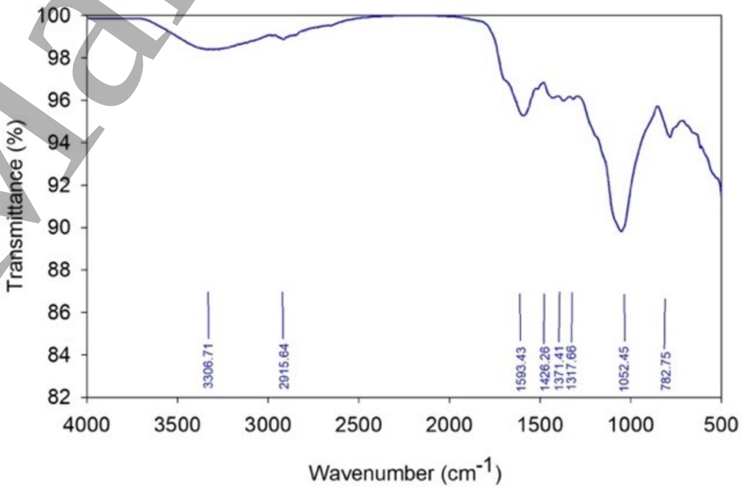


Figure 2. Fourier Transform Infrared (FT-IR) spectra of rice straw biochar.

Table 3. Functional groups of rice straw biochar and literature data by Fourier Transform Infrared spectroscopy (FT-IR) analysis.

Functional group	**Class**	**Intensity**	**Wavenumber (cm^{-1})**	
			In Literature (Nandiyanto *et al* 2023)	**Rice straw biochar**
O-H stretching	alcohol	Strong	3200-3550	3306.71
C-H stretching	alkane	Medium	2840-3000	2915.64
C=C stretching	cyclic alkene	Medium	1566-1650	1593.43
O-H bending	carboxylic acid	Medium	1395-1440	1426.26
O-H bending	alcohol	Medium	1330-1420	1371.41
S=O stretching	sulfone	Strong	1300-1350	1317.66
C-O stretching	primary alcohol	Strong	1050-1085	1052.45
C-H bending	1,2,3-trisubstituted	Strong	760-800	782.75

2.6 Incubation experiment and methods of soil analysis

The incubation experiment was laid out in a 4 × 6 factorial arrangement with two factors and 3 replications (factor A: 4 doses of biochar application and factor B: 6 salt-affected acid soils). Four grams of 6 salt-affected acid soil samples were weighed and mixed with the sieved biochar at the rate of 1%, 3%, and 5% (w/w). Six salt-affected acid soils without biochar (0%) were measured as control treatments. Twenty milliliters of distilled water were added to the 30 ml centrifuge tube and continuously gently shaken at 120 rpm for 7 days to reach the equilibrium (Wang *et al* 2019). The soil suspension was measured for soil pH and EC at the 1:5 soil water ratio based on the soil: water ratio of incubation condition using a pH and EC meter (CONSORT C830). The soil ECe for incubation study was estimated from EC 1:5 solution by a conversion factor (Gharaibeh *et al* 2021). The soil suspension was centrifuged for 10 min at a speed of ×10000 g and filtered by a 0.45 μm membrane. The soil-extracted solution was used for measuring soluble Cl^-, soluble K^+, Ca^{2+}, Mg^{2+}, and Na^+. The Cl- content was assessed by the titration method using standard silver nitrate (0.01 N) with a 5% potassium chromate indicator (Iqbal *et al* 2018). The mixture of soil and biochar was extracted with 1M ammonium acetate at pH 7 and measured for exchangeable bases: K^+, Ca^{2+}, Mg^{2+}, and Na^+ (FAO 2022). The soluble and exchangeable cations, such as Na^+, K^+, Ca^{2+}, and Mg^{2+} were analyzed by ICP-OES. The SAR and ESP were calculated as expressed in equations (1) and (2) (Olorunfemi and Fasinmirin 2017).

$$\mathrm{SAR} = \frac{[Na^+]}{\sqrt{\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2}}} \qquad (1)$$

$$\mathrm{ESP} = \frac{\text{Exchnageable sodium}}{\text{Soil CEC}} \times 100 \qquad (2)$$

2.7 Statistical analysis

Two-way analysis of variance (ANOVA) was performed to analyze the effect of different biochar application rates on six salt-affected soils and their interactions according to factorial laid out. One-way ANOVA was used to analyze the mean-variance in each biochar application rate. Means were compared by Tukey test at $P < 0.05$ level. All statistical analysis used IBM SPSS Statistics version 28.

3. Results

3.1 Soil acidity

The ANOVA demonstrated that the biochar application and the salt-affected soil had significant effects ($P < 0.01$) on soil pH; however, there was no interaction between the biochar application and the salt-affected soil (table 4). There was a significant difference ($P < 0.01$) in soil pH among biochar applications (figure 3). The average values of soil pH were 5.29, 5.30, 5.56, and 5.78 in 0%, 1%, 3%, and 5% applications, respectively. The highest value was found in 5%, followed by 3 %, 1%, and 0% applications. The soil pH value was significantly different ($P < 0.01$) among S1 to S6 only in the control, whereas it was not significantly different in other biochar application rates (figure 3). The statistically significant difference in the soil pH among salt-affected soils in the control might be due to the effect of various seawater application levels. The statistically significant difference in the soil pH between the control and 5% biochar application rate might be that the rice straw biochar reduced the soil acidity of salt-affected soils.

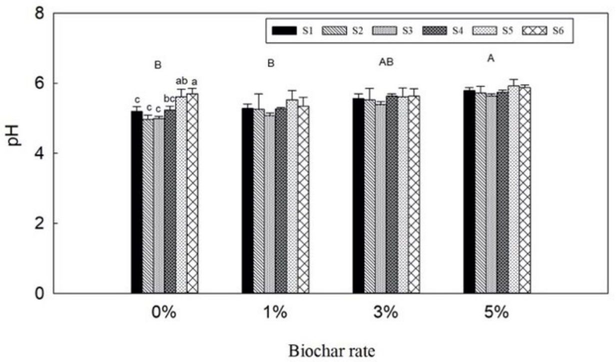


Figure 3. The various levels of rice straw biochar application effects on soil pH in salt-affected soils. The different uppercase letters denoted significant differences between biochar applications, and the different lowercase letters indicated significant differences between soils in each biochar application rate at $P < 0.05$. Error bar = standard error.

3.2 Soil salinity

The ANOVA demonstrated that biochar application and salt-affected soil had significant effects ($P < 0.01$) on ECe; however, there was no interaction between biochar application and salt-affected soil (table 4). The ECe values were highly significantly different ($P < 0.01$) among different biochar applications (figure 4). The average values of ECe were 3.96, 6.43, 7.72, and 8.79 dS m^{-1} in 0%, 1%, 3%, and 5% applications, respectively. The ECe value increased with increasing biochar application. The highest value was observed in 5%, followed by 3 %, 1%, and 0% applications. The ECe values significantly increased ($P < 0.01$) among salt-affected soils (S1 to S6) regardless of biochar application rates (figure 4). The highest value was observed in S6, whereas the smallest value was observed in S1. The higher level of seawater applications might have increased ECe. In addition, the ECe increased with increasing biochar applications in all salt-affected soils.

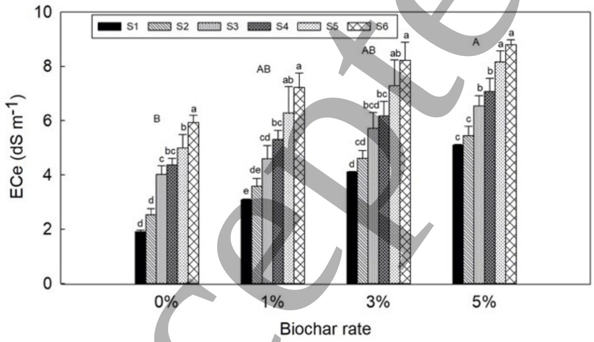


Figure 4. The various levels of rice straw biochar application effects on the ECe of salt-affected soils. The different uppercase letters denoted significant differences between biochar applications. The different lowercase letters indicated significant differences between soils in each biochar application rate at $P < 0.05$. Error bar = standard error.

3.3 Soil sodicity

The ANOVA demonstrated that the application of biochar, salt-affected soil, and the interaction of biochar application and salt-affected soil had significant effects ($P < 0.01$) on SAR and ESP (table 4). There was a significant difference ($P < 0.01$) in SAR and ESP values among different biochar application rates (figure 5(a) and 5(b)). The average values were 10.70, 5.04, 4.76, and 4.75 for SAR and 18.17%, 6.80%, 6.24%, and 6.38% for ESP in 0%, 1%, 3%, and 5% applications, respectively. The SAR and ESP values were significantly reduced with biochar application (approximately 50 %) compared with the control (figure 5(a) and 5(b)). The SAR and ESP values in biochar applications with 1%, 3%, and 5% did not significantly differ from each other. The SAR and ESP were significantly different ($P < 0.01$) among salt-affected soils (S1 to S6) in 0%, 1%, 3%, and 5% biochar application rates (figure 5(a) and 5(b)). The soils with a high salinity content had higher amounts of SAR and ESP than the soils with low salinity in control. The largest values of SAR and ESP occurred in S6, whereas the smallest value was observed in S1.

Table 4. Summary of the analyses of variance of soil chemical parameters in four biochar application rates and six salt-affected soils.

Soil chemical properties	**Biochar**					**Salt-affected soil**					**Biochar × Salt-affected soil interaction**				
	df	**SS**	**MS**	**F**	***p*-value**	**df**	**SS**	**MS**	**F**	***p*-value**	**df**	**SS**	**MS**	**F**	***p*-value**
pH	3	3.03	1.01	30.91	<0.0001	5	1.34	0.27	8.19	<0.0001	15	0.03	0.04	1.32	0.23
ECe (dS m^{-1})	3	84.51	28.17	115.80	<0.0001	5	140.14	28.03	115.22	<0.0001	15	0.89	0.06	00.24	0.99
SAR	3	468.59	156.20	1242.14	<0.0001	5	289.95	57.99	461.15	<0.0001	15	47.50	3.17	25.18	<0.0001
ESP (%)	3	1852.01	617.34	1625.20	<0.0001	5	761.98	152.40	401.20	<0.0001	15	275.25	18.35	48.31	<0.0001
Soluble Cl^{-} (mg L^{-1})	3	20570000	6857950	1256.15	<0.0001	5	6127904	1225581	224.49	<0.0001	15	6620988	441399	80.85	<0.0001
Soluble Na^{+} (mg L^{-1})	3	6172080	2057360	1463.29	<0.0001	5	1226370	245274	174.45	<0.0001	15	945445	63030	44.83	<0.0001
Exchangeable Na^{+} (mg kg^{-1})	3	5937557	1979186	1944.95	<0.0001	5	2433508	486702	478.28	<0.0001	15	887221	59148	58.12	<0.0001
Soluble K^{+} (mg L^{-1})	3	128434	42811.7	5804.98	<0.0001	5	1711	342.1	46.39	<0.0001	15	134	8.9	1.21	0.2961
Exchangeable K^{+} (mg kg^{-1})	3	8446447	2815482	21771.8	<0.0001	5	33599	6720	51.96	<0.0001	15	4958	331	2.56	0.0070
Soluble Ca^{2+} (mg L^{-1})	3	343051	114350	2970.20	<0.0001	5	11523	2305	58.59	<0.0001	15	17712	1181	30.02	<0.0001
Exchangeable Ca^{2+} (mg kg^{-1})	3	296858	98952.5	10.32	<0.0001	5	175998	35199.6	3.67	0.0068	15	42819	2854.6	0.30	0.9935
Soluble Mg^{2+} (mg L^{-1})	3	189057	63019.0	2343.14	<0.0001	5	7302	1460.4	54.30	<0.0001	15	11979	798.6	29.69	<0.0001
Exchangeable Mg^{2+} (mg kg^{-1})	3	978412	326137	462.88	<0.0001	5	24701	4940	7.01	0.0001	15	2532	169	0.24	0.9980

3.4 Toxicity elements

3.4.1 Soluble chloride

The ANOVA demonstrated that biochar application, salt-affected soil, and interaction of biochar application and salt-affected soil had significant effects ($P < 0.01$) on soluble Cl^- content (table 4). There was a highly significant difference ($P < 0.01$) in soluble Cl^- among different biochar application rates (figure 6). The average values of soluble Cl^- were 1535.88, 254.42, 303.72, and 354.01 mg L^{-1} in 0%, 1%, 3%, and 5% applications, respectively. The highest value was found in 0%, which was significantly different from other biochar applications; however, the application rates of 1%, 3%, and 5% were not significantly different in soluble Cl^- content from each other. The soluble Cl^- value was significantly different ($P < 0.01$) among salt-affected soils (S1 to S6) in each biochar application rate (figure 6). The highest values occurred in S6, whereas the smallest values occurred in S1. This was because the soils with higher salinity had more soluble Cl^- contents than S1 (non-saline soil) in all biochar application rates.

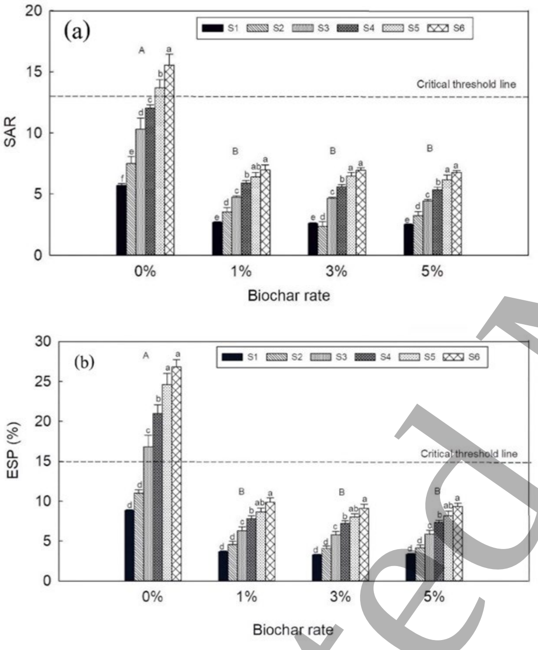


Figure 5. The various levels of rice straw biochar application effects on SAR (a) and ESP (b) in salt-affected soils. The different uppercase letters denoted significant differences between biochar applications. The different lowercase letters indicated significant differences between soils in each biochar application rate at $P < 0.05$. Error bar = standard error.

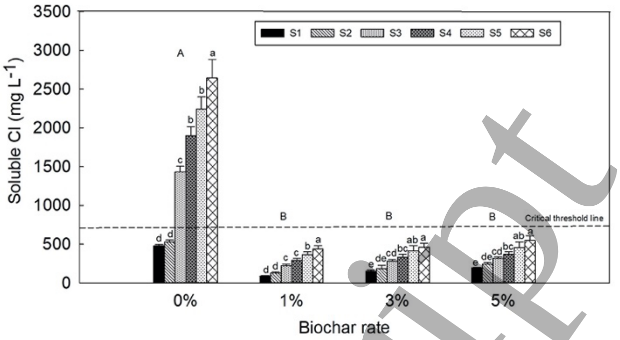


Figure 6. The various levels of rice straw biochar application effects on soluble Cl^- in salt-affected soils. The different uppercase letters denoted significant differences between biochar applications. The different lowercase letters indicated significant differences between soils in each biochar application rate at $P< 0.05$. Error bar = standard error.

3.4.2 Soluble and exchangeable sodium

The ANOVA demonstrated that biochar application, salt-affected soil, and the interaction of biochar application and salt-affected soil had significant effects ($P < 0.01$) on soluble and exchangeable Na^+ (table 4). The soluble and exchangeable Na^+ values were significantly different ($P < 0.01$) among different biochar application rates (figure 7(a) and 7(b)). The average values were 854.43, 167.32, 181.87, and 186.17 mg L^{-1} for soluble Na^+ and 1028.90, 384.60, 353.20, and 360.90 mg kg^{-1} for exchangeable Na^+ in 0% 1%, 3%, and 5% applications, respectively. The highest values of soluble and exchangeable Na^+ were found in the control (0%), which was significantly higher than other biochar application rates; however, the biochar application rates of 1%, 3%, and 5% were not significantly different from each other. There was a significant difference ($P < 0.01$) in soluble Na^+ and exchangeable Na^+ values among salt-affected soils (S1 to S6) in each biochar application rate (figure 7(a) and 7(b)). The highest values of soluble and exchangeable Na^+ were observed in S6, while the smallest values were observed in S1. The soils with higher salinity (S6) increased Na^+ contents compared with non-saline soil (S1) among salt-affected soils.

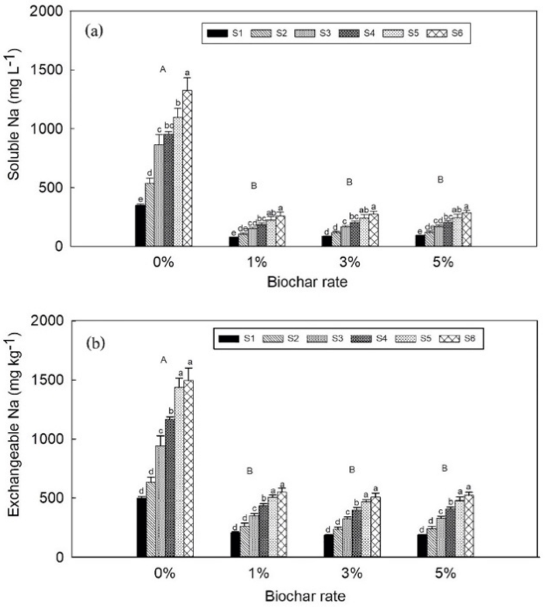


Figure 7. The various levels of rice straw biochar application effects on soluble Na^+ (a) and exchangeable Na^+ (b) in salt-affected soils. The different uppercase letters denoted significant differences between biochar applications. The different lowercase letters indicated significant differences between soils in each biochar application rate at $P < 0.05$. Error bar = standard error.

3.5 Soluble and exchangeable potassium, calcium, and magnesium

The ANOVA showed that biochar application, salt-affected soil, and the interaction of biochar and salt-affected soil had significant effects ($P < 0.01$) on soluble and exchangeable K^+ except the interaction effects on soluble K^+ (table 4). There were significant differences ($P < 0.01$) in soluble and exchangeable K^+ values among different biochar application rates (figure 8(a) and 8(b)). The highest values of soluble and exchangeable K^+ were found in 5%, followed by 3%, 1%, and 0%. The soluble and exchangeable K^+ values were significantly different ($P < 0.01$) among soil-affected soils (S1 to S6) in each biochar application rate (figure 8(a) and 8(b)). The highest soluble and exchangeable K^+ values were observed in S6, whereas the lowest values were found in S1 among salt-affected soils in all biochar application rates except for the exchangeable K in the 3% application rate. It demonstrated that the soils with higher salinity had more K^+ contents than non-saline soils.

The ANOVA demonstrated that biochar application, salt-affected soil, and the interaction of biochar application and salt-affected soil had significant effects ($P < 0.01$) on soluble and exchangeable Ca^{2+} and Mg^{2+}, except salt affected-soils and the interaction effects on exchangeable Ca^{2+} and Mg^{2+} (table 4). The soluble and exchangeable Ca^{2+} and Mg^{2+} values were significantly different ($P < 0.01$) among different biochar application rates (figures 8(c)-(f)). There were significant differences ($P < 0.01$) in soluble Ca^{2+} and Mg^{2+} among S1 to S6 in the control and the 1% biochar application rate, whereas the values were not significantly different among different salt-affected soils at 3% and 5% application rates (figure 8(c) and 8(e)). Higher amounts of soluble Ca^{2+} and Mg^{2+} were observed in S6 among salt-affected soils in each biochar application, except soluble Ca^{2+} in the control. The exchangeable Ca^{2+} and Mg were not significantly different among different salt-affected soils in each biochar application rate (figure 8(d) and 8(f)). The results showed that biochar application decreased soluble and exchangeable Ca^{2+} and Mg^{2+} in salt-affected soils.

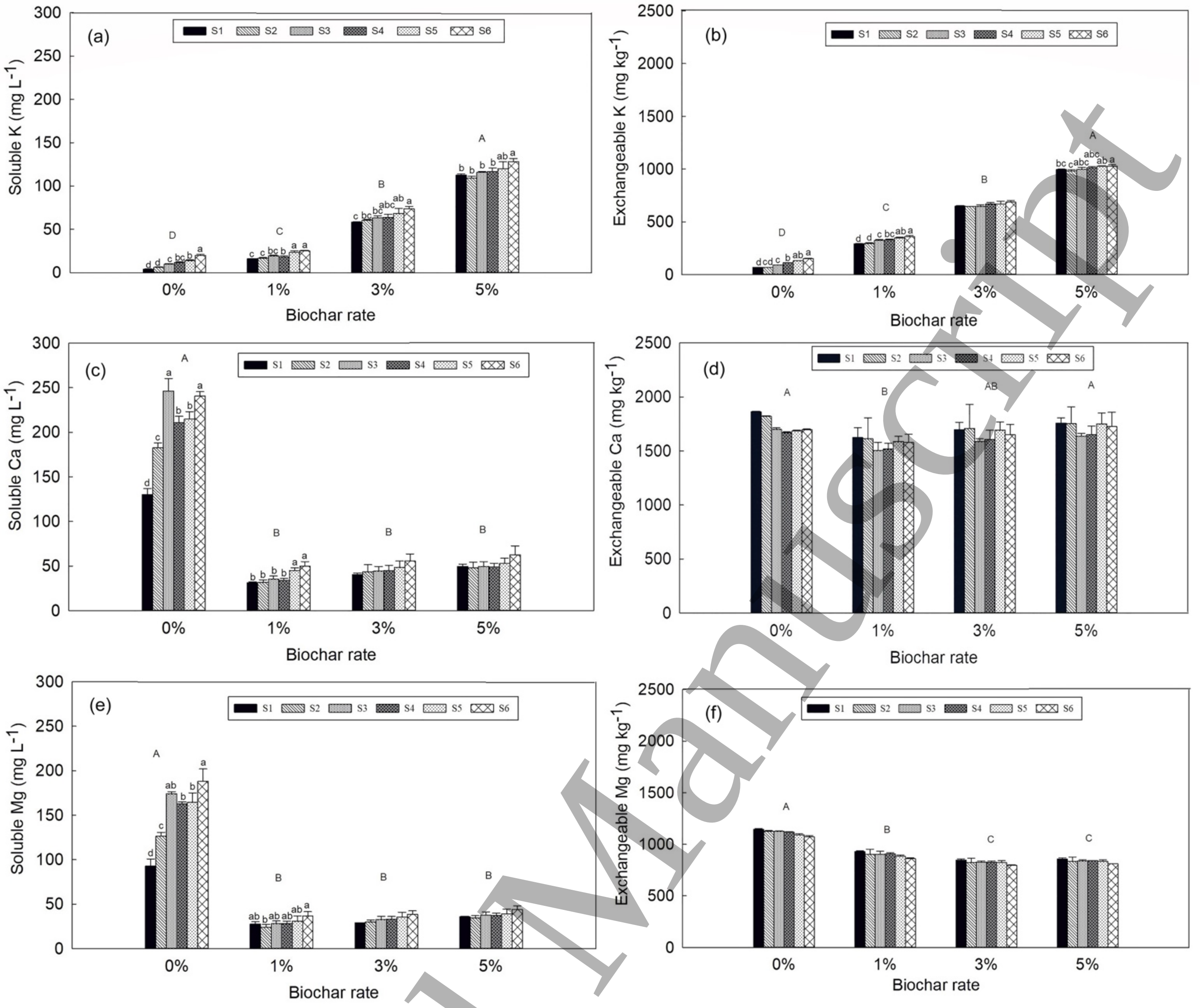


Figure 8. The various levels of rice straw biochar application effects on soluble K^+, Ca^{2+}, and Mg^{2+} (a, c, e) exchangeable K^+, Ca^{2+}, and Mg^{2+} (b, d, f) in salt-affected soils. The different uppercase letters denoted significant differences between biochar applications. The different lowercase letters indicated significant differences between soils in each biochar application rate at $P< 0.05$. Error bar = standard error.

4. Discussion

4.1 Soil acidity

The soil pH was significantly different among S1 to S6 only in the control, which might be due to the higher levels of seawater application (figure 3). Although soil pH values were not statistically different among 0%, 1%, and 3% application rates, the biochar application above 1% reduced the soil acidity of salt-affected soils. A previous study stated that the biochar amendment improved soil quality by increasing the soil pH (Dai *et al* 2017). The main reason for the increased pH of the salt-affected soil is the difference between the biochar pH and salt-affected soil pH (Nath *et al* 2022). The pH of the rice straw biochar (pH > 7.98) (table 2) was higher than the soil pH (pH < 5.5). This result was similar to Sun *et al* (2021), who found that as the biochar application rate increased, the soil pH increased (figure 3). Thus, the initial pH of biochar may be an important factor of pH in saline soil (Tan *et al* 2021). The soil pH increase after biochar application was due to the release of base cations, such as K^+, Mg^{2+}, and Ca^{2+} (table 2), potentially replacing exchangeable acidity on the soil surface (Omara *et al* 2023) and reducing soil acidity. Therefore, 1% biochar application is a suitable dose for the pH (pH > 5.2), which is a safe level for rice because the rice is commonly grown under submerged soil. After a few weeks of soil submergence, the acidic soil pH will be increased to nearly neutral in a paddy soil (Ding *et al* 2019).

4.2 Soil salinity

The highest ECe value was found in 5%, followed by 3 %, 1%, and 0% biochar applications (figure 4). A study reported that a biochar application increased the EC of salt-affected soils (Zheng *et al* 2022). All salt-affected soils had higher ECe after biochar applications, so that the soils became moderate or high saline soils except S1 at 0% (1.91 dS m^{-1}) and 1% application (3.96 dS m^{-1}) (figure 4). Therefore, the high rate of biochar application caused higher salinity (ECe), which is greater than the critical value (4 dS m^{-1}) (Foronda and Colinet 2023) in soil because the biochar had a large amount of base ions (Li *et al* 2018), such as K^+ in this study (table 2), which is beneficial for rice growth in salt-affected soil. Therefore, assessing the proper biochar application rate is important to improve soil properties because an excessive application can increase soil salinity (Figure 4), leading to harmful effects on plants (Qi *et al* 2024).

4.3 Soil sodicity

The highest values of SAR and ESP occurred in S6, whereas the smallest value occurred in S1, which was the effect of seawater application levels. High-salinity soils had higher SAR and ESP than soils with low salinity content in S1 (non-saline control). The SAR and ESP values were significantly reduced by biochar application (figure 5(a) and 5(b)). This might be due to a decrease in the base cations ($Ca^{2+,}$ Mg^{2+}, and Na^+) in soil solution after biochar application. In a similar study by Anwari *et al* (2020), the SAR and ESP were decreased with the increasing level of biochar application due to the reduction in soluble and exchangeable Na^+ in all salt-affected soils, similar to this study (figure 5(a) and 5(b)). SAR values decreased below the critical value of 13 (Foronda and Colinet 2023) with different biochar applications (figure 5(a)). In addition, the biochar application reduced ESP values (figure 5(b)) below the threshold value of 15% (Foronda and Colinet 2023). The SAR and ESP values in biochar applications of 1%, 3%, and 5% were not significantly different from each other. Thus, a 1% biochar application rate can be used to reduce sodicity in salt-affected soils. This might be due to the biochar (1%) application having the ability to absorb and retain exchangeable cations like Na due to high total porosity and surface area (Amesalu *et al* 2020). Yang *et al* (2021) reported that the application of 1% rice straw biochar, which was synthesized at 450 °C, enhanced the total porosity and microporosity in Ultisol and Alfisoil soils. Rekaby *et al* (2021) also reported that the biochar application was an effective way to reduce soil salinity by improving soil properties by removing Na^+. Consequently, the soil physical properties were improved by increasing soil aggregation by the increase in the soil organic carbon content and the decline in ESP (Saifullah *et al* 2018).

4.4 Toxicity elements

4.4.1 Soluble chloride

The highest soluble $Cl^–$ occurred in S6, whereas the smallest values occurred in S1 among salt-affected soils in all biochar applications since the soils with higher salinity had more soluble $Cl^–$ than S1 (non-saline control). The biochar applications reduced the soluble $Cl^–$ content of all salt-affected soils compared with the control. Studies also reported that the soluble $Cl^–$ content was significantly decreased by biochar application in the soil under salt stress (Huang *et al* 2022) and coastal saline-alkali soil (Zhang *et al* 2022). In this study, the soluble $Cl^–$ in salt-affected soils at 1%, 3%, and 5% biochar application rates were below 673 mg L^{-1} (figure 6), which was the safe level for most of the plants without any injuries (Bryson and Mills 2014). This might be that functional groups, such as C-H, C-O, and C=C stretching (table 3), of biochar held a partial positive charge that adsorbed various salt ions like $Cl^–$ in the soil; therefore, it mitigated soil salinity (Mao *et al* 2022). Although soluble $Cl^–$ content was not statistically different among biochar application rates of 1%, 3%, and 5%, the lowest value resulted in 1% application (figure 6). This might be due to adsorption mechanisms involving surface complexation and electrostatic attractions (Qiu *et al* 2022). Calcium and magnesium ions from the soil can act as bridges between the negatively charged biochar surface and Cl^- ion, leading to the high adsorption of chloride near the biochar surface (Joseph *et al* 2010). Thus, the biochar could reduce the Cl- concentration by adsorption (Tang *et al* 2023). Hence, the application of 1% biochar reduced soluble $Cl^–$ which caused salinity in salt-affected soils in this study, and it will alter some physicochemical properties of soil, which can positively affect plant growth (Yuan *et al* 2019) and yield and quality of crops, especially in saline-alkali soils (Zhang *et al* 2023).

4.4.2 Soluble and exchangeable sodium

The biochar application rate of 1% significantly decreased soluble and exchangeable Na^+ ions compared with the control (figure 7(a) and 7(b)), which might suggest that the biochar can bind Na^+ in the soil solution, reducing the soluble and total Na^+ over time (Prasertsuk and Wijitkosum 2021). Another study suggested that biochar could supply mineral nutrients such as K^+, Ca^{2+}, and Mg^{2+}. These ions replace Na^+ from the exchange sites of salt-affected acid soils (Gunarathne *et al* 2020). A possible mechanism might be that the K^+-rich biochar in this study (table 2) released and exchanged K^+ with Na^+ from the salt-affected soils. K^+ ions have a stronger affinity for the exchange site due to their lower hydration radius and higher charge density than Na+. Yang *et al* (2024) suggested that K^+ in biochar is the predominant mechanism that causes Na adsorption by ion-exchange interaction. A possible mechanism might be that the K^+-rich biochar in this study (table 1) exchanged K^+ with Na^+ from the salt-affected soils. The Na^+ sorption capacity of biochars may vary depending on their surface area, pore volume, and functional groups (Sudratt and Faiyue 2023). Our rice straw biochar had a strong capacity to adsorb and retain exchangeable cations due to the high surface area (figure 1) and negative surface charge (table 2). According to the FT-IR analysis of this biochar, the main functional groups were hydroxy and carboxy groups (O-H stretching and O-H bending) (table 3) on the biochar surface held negative charges that had a strong ability to adsorb cations like Na^+ from the soil (Amesalu *et al* 2020; Khan *et al* 2024; Murtaza *et al* 2024). The 1% biochar application reduced exchangeable Na^+ due to the high porosity and surface area of the study biochar, which might improve soil structure and water and nutrient retention in salt-affected soil. A high amount of exchangeable Na^+ can break down soil materials and reduce soil aeration and hydraulic conductivity, limiting crop growth and production (Anwari *et al* 2020). Therefore, biochar application (1%) is advantageous in salt-affected soils, as it improves the physicochemical properties of the soil by reducing the salinity or sodicity through the adsorption of Na^+ (Zaib *et al* 2022). Abdeen et al (2023) reported that the biochar application reduced the Na^+ in the soil solution due to its high adsorption capacity. Therefore, it decreased the harmful effects of Na^+ in the soil and prevented Na^+ uptake by plants.

4.5 Soluble and exchangeable potassium, calcium, and magnesium

The highest values of soluble and exchangeable K^+ were found in 5%, followed by 3%, 1%, and 0%. Similar to increased soluble and exchangeable K^+ in salt-affected soils in this study (figure 8(a) and 8(b)), Wang *et al* (2019) reported that biochar application increased available K^+. The possible mechanism might be the ion competition between K^+ and other cations from the exchange sites of biochar, and K^+ was also readily soluble in water. Therefore, K^+-rich biochar in this study (table 2) may significantly increase K^+ content in saline soils and in the extracts, which is an essential nutrient for plant growth (Wang *et al* 2019).

This study showed that biochar application decreased soluble and exchangeable Ca^{2+} and Mg^{2+} in salt-affected soils. This might be due to the basic ions such as K^+, Ca^{2+}, Mg^{2+}, and Na^+ in biochar could alter the solute composition through the process of dissolution and ion exchange (Wang *et al* 2019). Similar to the study by Miranda *et al* (2017), soluble and exchangeable Ca^{2+} and Mg^{2+} decreased in soils after biochar application (figures 8(c)-(f)). This might be due to the biochar having a high adsorption capacity for these ions due to the high CEC (table 2) and high surface area (figure 1(a)) (Gunarathne *et al* 2020). According to the previous study, biochar decreased the soluble salt contents in the soil solution, and it had a cationic sorption capacity due to its porose structure, high specific surface area and surface negative charges (Gondek *et al* 2020; Premalatha *et al* 2023). Therefore, biochar reduced the losses of ions because of its high sorption capacity. The other mechanism might be that functional groups on the surface of biochar, such as the O-H (alcohol) and S=O (sulfone) stretching groups and O-H bending group (carboxylic acid), held negative charges on the biochar surface (table 3) and could strongly adsorb cations such as Ca^{2+}, Mg^{2+}. Jiang *et al* (2025) suggested that Ca and Mg bond to biochar mainly by complexation with organic functional groups such as carboxyl or hydroxyl groups. Additionally, calcium and magnesium ions can form a cation bridge between the negatively charged biochar surface and anionic ions such as Cl^- or SO_4^{2-} from the soil, which can be decreased in the the soluble and exchangeable form of Ca^{2+} and Mg^{2+} (Joseph *et al* 2010). These tightly bound cations can be released slowly, and the biochar may contribute to soil fertility (Haowei *et al* 2019), which depends on the biochar type, aging time, and adsorption strength (Dahlawi *et al* 2018). This study showed that the amount of Ca^{2+} and Mg^{2+} declined with biochar application since the 1% application rate.

This study showed increased amounts of soluble and exchangeable K^+ contents and decreased amounts of Ca^{2+} and Mg^{2+} after biochar application (figures 8(a)-(f)). The K^+ forms weak complexes that are easily exchangeable. Therefore, K^+ did not strongly compete with Ca^{2+} and Mg^{2+} for the binding sites of the biochar (Rengel *et al* 2022). Thus, the K^+ contents increased after the biochar application in salt-affected soils at an increasing biochar application rate, which exceeded the optimum range for the rice crops. The higher amount of K^+ above this optimum level in the soil might induce antagonistic effects. The excess K^+ could suppress Ca^{2+} and Mg^{2+} uptakes by rice plants (Bryson and Mills 2014), leading to Ca^{2+} and Mg^{2+} deficiency problems in rice crops. In order to avoid the problem, the application of 1% biochar is appropriate for rice growth and development in salt-affected soils. The previous study stated that although the increasing biochar application rates improved soil chemical properties, such as nutrient contents and retention, the excessive application rate declined soil quality. The biochar application rate was closely related to the effects of biochar on soil physical, chemical, and biological properties (Qi *et al* 2024). The other study also suggested that an increase in available K^+ content due to biochar application was one of the significant benefits on crop yields (Miranda *et al* 2017). Typically, high Na^+ in salt-affected soil competes with K^+ for nutrient uptakes by plants, which induces K deficiency (Bryson and Mills 2014). Increasing soluble and exchangeable K^+ may prevent Na^+ uptake by plants in salt-affected soil.

5. Conclusions

The different rates of biochar applications, such as 1%, 3%, and 5%, influenced soil chemical characteristics in salt-affected acid soils. The biochar application significantly increased soil pH and ECe with an increasing rate of application compared with the control in salt-affected soils. Significant decreases in SAR and ESP below the critical level of sodicity were observed above the biochar application rate of 1% compared with the control in salt-affected soils. Toxicity elements, such as soluble Cl^{-} and soluble and exchangeable Na^{+}, were significantly reduced after biochar application rate above 1%. Biochar application led to significant increases in soluble and exchangeable K^{+} and declines in soluble and exchangeable Ca^{2+} and Mg^{2+} compared with the control after the biochar application rate above 1%. This study suggested that the 1% rate of biochar application was suitable for reducing soil acidity to the safe level for rice crops and sodicity by alleviating the contents of soluble Cl^{-}, soluble and exchangeable Na^{+} that declined SAR and ESP in salt-affected soils. Moreover, it also increased available K^{+}, which was essential for rice plant growth and development in salt-affected soils. This study concludes that biochar may be used as a soil amendment to diminish soil acidity, toxicity, and sodicity that negatively influence rice growth and yield in salt-affected soils. Therefore, field experiments need to be conducted to study these effects on rice growth and yield in salt-affected acid soil.

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