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Enhancing saline soil fertility through biochar and organic manure combinations: An incubation study

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ABSTRACT

Indonesia has vast saline land that remains underutilized due to low productivity, making it unsuitable for agriculture. The efforts to mitigate the negative impact of salinity on plant growth and yield have focused on organic soil amendments to enhance fertility and productivity. This study evaluated the effects of organic manure and biochar on saline soil properties and identified the optimal biochar-to-manure ratio over a 91-day incubation. The experiment was conducted using a completely randomized design (CRD) with nine treatments, each replicated three times. The treatments included soil-only (SO), chicken manure (CM), three ratios of chicken manure and biochar (1:1, 1:2, and 1:3), goat manure (GM), as well as three ratios of goat manure and biochar (1:1, 1:2, and 1:3). Key parameters measured were organic carbon (C), pH, electrical conductivity (EC), available phosphorus (P), total nitrogen (N), cation exchange capacity (CEC), and exchangeable cations. The findings show that the addition of biochar, particularly at higher ratios, significantly enhanced organic C, CEC, available P, and total N while stabilizing soil pH and reducing EC and exchangeable sodium percentage (ESP). The combination of chicken manure and biochar at a 1:3 ratio yielded the most substantial improvements across most parameters. These results underscore the potential of tailored combinations of organic manure and biochar to optimize soil fertility and support sustainable agricultural practices.

Keywords: biochar, organic manure, CEC, soil chemical properties, saline soil.

INTRODUCTION

Salinity is a major agricultural challenge worldwide, limiting crop productivity and soil health. In Indonesia, saline soils, covering approximately 440,300 hectares, remain largely underutilized due to their low fertility and poor suitability for conventional farming (Karolinoerita and Annisa, 2020). This issue is exacerbated by improper land use and excessive fertilizer application, particularly in coastal and irrigated areas. As Indonesia's population grows, developing sustainable strategies to enhance saline soil productivity is crucial for addressing food security.

Saline soils are characterized by high concentrations of salts, such as sodium (Na), calcium (Ca), and magnesium (Mg), which reduce nutrient availability, impair soil structure, as well as hinder water infiltration and microbial activity (Awad-Allah et al., 2020; Rahman, 2023). High osmotic pressure also restricts plant water uptake, further stressing crop development (Atteya et al., 2022; Feng et al., 2021). Thus, effective approaches to reclaim saline soils are essential, particularly in semi-arid and coastal regions that support a large portion of the global population.

One promising solution is the incorporation of organic amendments, such as manure and biochar, which improve soil aggregation, increase hydraulic conductivity, and enhance CEC (Bhat et al., 2022; Hewage et al., 2023). Biochar, a product of pyrolyzed organic residues, offers a versatile option for improving soil properties. Indonesia's agricultural sector generates ample biomass for biochar production, with an estimated 6.8 million tons of biomass potential annually (Nurida et al., 2015). Additionally, biochar helps mitigate greenhouse gas emissions, contributing to climate change mitigation alongside its soil-enhancing benefits (Long et al., 2021; Schmidt et al., 2021; Shiyal et al., 2022).

The integration of biochar and organic manure provides synergistic benefits for soil amelioration. Biochar enhances soil pH, nutrient retention, as well as reduces salinity by lowering EC and stabilizing soil organic carbon (Nguyen and Nguyen, 2023; Yue et al., 2023). Its high porosity and CEC allow it to retain nutrients and minimize leaching (Zhang et al., 2021). Recent studies also emphasize its effectiveness in improving soil physical properties such as bulk density and water retention, which support plant growth under saline conditions (Khanam et al., 2022; Zonayet et al., 2023).

Despite these benefits, optimal combinations of organic amendments for specific soil and climate conditions remain underexplored. This study aimed to bridge this gap by evaluating the effects of combining biochar with organic manure on the chemical properties of saline soils during a 91-day incubation period. By identifying effective treatments, this research contributes to sustainable agricultural practices for reclaiming saline soils and enhancing food security.

MATERIAL AND METHOD

Soil sampling and characterization

Soil samples were collected from a depth of 0–25 cm in Tugu District, Semarang City, East Java, Indonesia. The sampling location is situated in a region with an average annual rainfall of 2.790 mm, air temperatures ranging from 23 °C to 34 °C, and an average annual air humidity of 77%.

The geographical coordinates of the sampling site are shown in Figure 1. Soil samples were taken from multiple points within the area and combined to create a composite sample. The composite samples were transported to the laboratory, air-dried at room temperature, and sieved through a 2 mm stainless steel mesh to remove debris and coarse particles.

The physical and chemical properties of the soil were analyzed using standard laboratory methods. Soil pH and EC were measured in a 1:5 soil-to-water suspension using a calibrated pH meter and EC meter, respectively (McLean, 1982). The organic carbon content was determined using the method described by Walkley and Black (1934) and total N was analyzed by means of the Kjeldahl method, following the protocol outlined

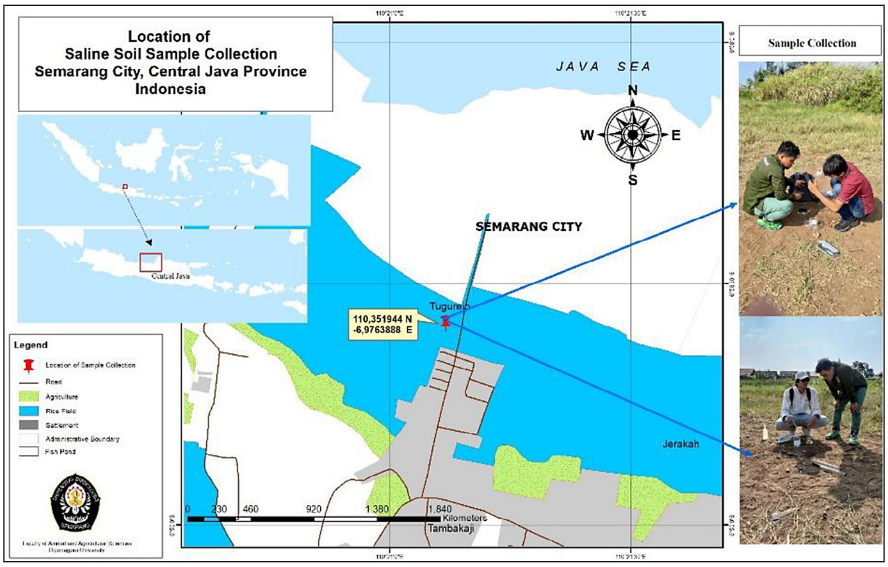

Figure 1. Location of saline soil sample collection

by the Association of Official Agricultural Chemists (AOAC, 1995). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and CEC were determined using ammonium acetate (NH_4Oac) extraction at pH 7.0, following the method described by BPT (Balai Penelitian Tanah, 2005). Available P was analyzed using the Olsen method (Olsen et al., 1954). The physical and chemical characteristics of the soil are summarized in Table 1.

Table 1. Soil chemical properties before the experiment

Parameters	Value
Physical properties	
Texture	
Sand (%)	35.8
Silt (%)	44.4
Clay (%)	19.8
Chemical properties	
pH (H_2O)	7.76
EC (mS/cm)	6.05
C (%)	0.50
N (%)	0.07
C/N	7.14
CEC (cmol/kg)	25.43
Available P (mg/100 g)	20.34
Exchangeable base (cmol/kg)	
Ca	19.85
Mg	8.7
K	0.73
Na	0.26

Analysis of the chemical characteristics of technological components

The biochar, chicken manure, and goat manure used in this study are characterized in Table 2. The biochar was produced by the slow pyrolysis of rice husk at 500 °C for 2 hours. The rice husk biochar used in this study was selected based on both its availability and its known agronomic potential. Rice husk is an abundant agricultural byproduct in Indonesia, particularly in the study area, making it a readily available and cost-effective feedstock for biochar production. The chicken manure and goat manure were sourced from the Faculty of Animal and Agricultural Sciences, Universitas Diponegoro. Both were crushed and sieved to < 2 mm to ensure consistency and uniformity in application.

Soil treatments and incubation

The experiment was designed using a completely randomized design (CRD) with nine treatments: SO (soil only), CM (chicken manure only), GM (goat manure only), and three different ratios of biochar combined with chicken manure (CM:B 1:1, 1:2, 1:3) or goat manure (GM:B 1:1, 1:2, 1:3). Each treatment was replicated three times, resulting in a total of 27 experimental units. The selection of amendment dosages in this study was guided by a previous experiment (Fauzan et al., 2021), which investigated combinations of chicken manure and steel slag to mitigate the greenhouse gas emissions in rice cultivation. In that study, the treatments involving fixed amounts of chicken manure with increasing ratios of steel slag (1:1, 1:1.5, and 1:2.5) were shown to be effective for improving soil chemical properties and reducing emissions. Building upon this experimental framework, the present study adapted a similar dosage design using chicken and goat manure in combination with rice husk biochar, replacing steel slag with a more sustainable, carbon-rich organic amendment.

Treatments were prepared by adding chicken or goat manure to the soil at a rate of 2.5% by weight, while biochar was added at rates of

Table 2. Biochar, chicken manure, and goat manure chemical characteristics for the incubation experiment

Parameters	Biochar	Chicken manure	Goat manure
pH	9.88	8.68	8.08
EC (mS/cm)	0.92	7.35	11.42
C (%)	7.60	28.04	10.14
N (%)	0.54	1.92	0.95
C/N	14.07	14.60	10.67
CEC (cmol/kg)	30.55	-	-
Total P (%)	0.02	0.06	0.15
Total K (%)	0.74	3.00	3.71

2.5%, 5%, and 7.5% by weight, depending on the treatment. For instance, in the CM:B (1:1) treatment, chicken manure and biochar were added in equal proportions, each constituting 2.5% of the soil weight. In the CM:B (1:2) and CM:B (1:3) treatments, biochar was added at higher rates of 5% and 7.5%, respectively, while the manure remained constant at 2.5%. The treated soil samples were placed in plastic containers and incubated for 91 days under field capacity moisture conditions and controlled laboratory conditions (25 ± 1 °C). The soil used for the experiment was pretreated by air-drying and sieving to < 2 mm before mixing with the amendments.

Soil samples were collected from each treatment at 91 days after incubation (DAI). These samples were air-dried, sieved to < 2 mm, and analyzed for organic carbon, pH, EC, available P, total N, CEC and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+). The exchangeable sodium percentage (ESP) was calculated following the method described by Cera et al., (2024).

Statistical analysis

Analysis of variance (ANOVA) was employed to assess the significance of the treatments, utilizing a significance level of 5%. The variables that exhibited significant differences were further analyzed using Duncan's Multiple Range Test (DMRT) with the aid of SPSS Statistics version 22.

RESULTS AND DISCUSSION

Organic C

Significant variations in the organic C content were observed across the treatments during the incubation period ($p < 0.05$) (Figure 2). The highest organic C was observed in the CM:B (1:3) treatment (1.21%), but was not statistically significant relative to CM (1.09%), CM:B (1:2) (1.07%), GM:B (1:2) (0.91%) and GM:B (1:3) (0.99%). The treatments involving CM and its combinations with biochar (CM:B) generally enhanced soil organic carbon compared to those amended with GM and its combinations (GM:B). The lowest value (0.51%) was recorded in SO and was statistically significant relative to other treatments, except GM (0.74%) and GM:B (1:1) (0.78%). The incorporation of biochar, particularly at higher ratios with chicken manure, significantly improves soil organic carbon content.

The carbon derived from decomposing organic matter in manure serves as a continuous source of organic carbon, thereby improving soil carbon levels over time (Mulugeta and Getahun, 2020). Soil organic carbon plays a critical role as an energy source for soil microbial communities, facilitating organic matter decomposition and nutrient mineralization essential for maintaining soil fertility (Sofyan et al., 2025). In addition to directly contributing carbon, biochar enhances the soil physical properties that indirectly promote soil

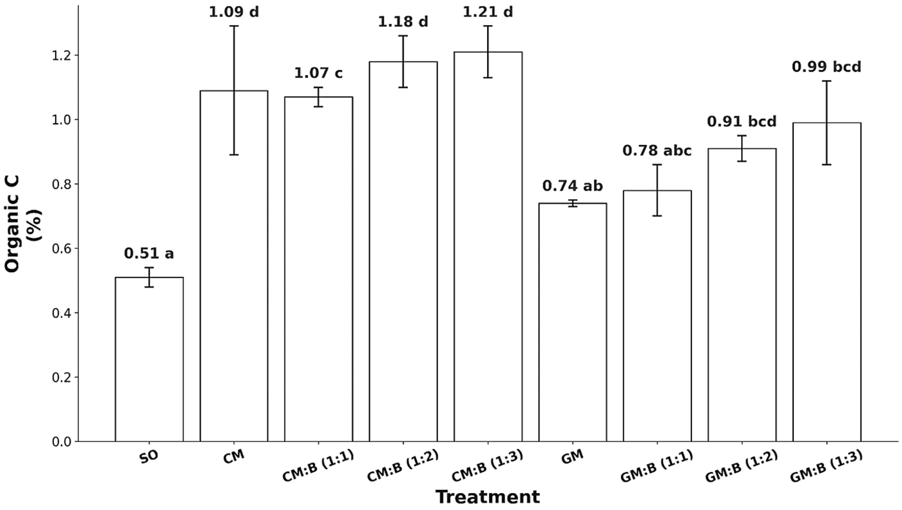

Figure 2. The organic C values of all treatments after incubation are presented as means; SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the $p < 0.05$ level

organic carbon sequestration. For example, its porous structure and high surface area foster soil aggregation, which protects organic matter within micro-aggregates from rapid microbial decomposition (Hua et al., 2013; Mitra et al., 2015). The combination of chicken manure and biochar, particularly at higher application rates, demonstrates a pronounced synergistic effect. The recalcitrance to degradation characterizing biochar and its strong adsorption capacity are key mechanisms for stabilizing organic carbon and minimizing its loss from the soil (Das et al., 2021; Kumar et al., 2024; Rabbi et al., 2021).

Importantly, the carbon in biochar is predominantly composed of stable, aromatic compounds that are highly recalcitrant and not readily available for microbial utilization. During pyrolysis, the thermal conversion of biomass results in the formation of fused aromatic ring structures with strong carbon–carbon bonds, which contribute to their chemical stability and resistance to biological degradation (Harvey et al., 2012). These aromatic clusters are characterized by extensive conjugation, limiting enzymatic accessibility and oxidation typically required for microbial metabolism, thereby reducing the bioavailability of this carbon fraction to soil microorganisms (Kolton et al., 2016).

These findings are consistent with earlier studies, such as those by Shi et al., (2020), which demonstrated that biochar applications significantly enhance soil organic matter, a crucial factor for maintaining soil fertility and structure. Biochar-amended treatments consistently outperformed those without biochar, highlighting its effectiveness in improving soil organic carbon retention. Notably, the CM:B (1:3) treatment exhibited superior performance, achieving the highest organic carbon content (1.21%), reinforcing biochar's important role in improving long-term soil health and fertility through enhanced carbon retention.

pH

The pH values of the treatments exhibited significant variation throughout the incubation period ($p < 0.05$) (Figure 3). All treatments-maintained soil pH within a neutral to slightly alkaline range (7.36–7.54). The lowest pH value was recorded in the SO treatment at 7.36, which was not statistically significant relative to several manure-amended treatments. In contrast, the CM and GM treatments, with or without biochar addition, maintained slightly higher pH values between 7.44 and 7.54. Specifically, the CM and GM treatments without biochar both recorded a pH of 7.54, statistically higher than SO, but not significantly different from each other or from the biochar-amended groups.

Biochar application, either with chicken manure (CM:B) or goat manure (GM:B), did not significantly alter soil pH compared to the manure-only treatments. For instance, CM:B (1:1) and CM:B (1:2) recorded pH values of 7.52 and 7.45, respectively, which were statistically similar to

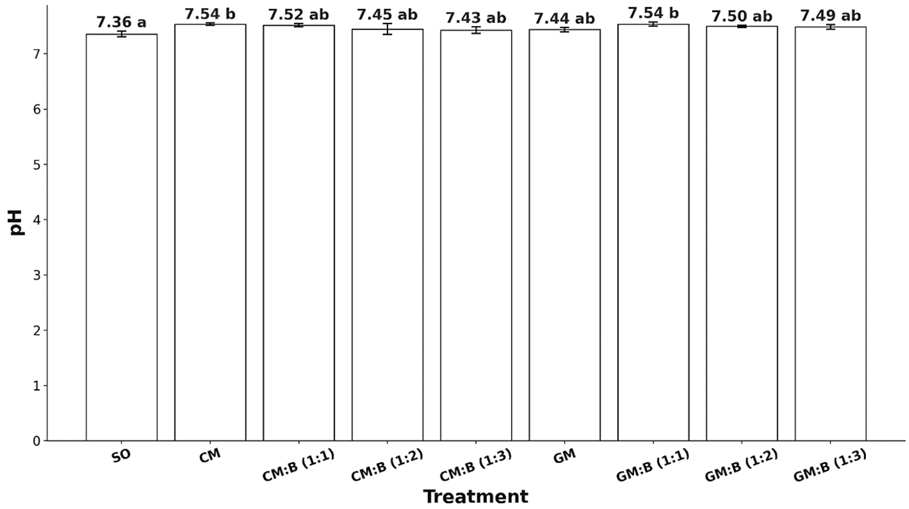

Figure 3. The pH values of all treatments after incubation are presented as means. SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the $p < 0.05$ level

CM and GM treatments. Likewise, GM:B (1:1), GM:B (1:2), and GM:B (1:3) exhibited pH values of 7.54, 7.50, and 7.49, respectively, without statistically significant differences among them.

The highest pH values were recorded in GM:B (1:1) and CM (7.54), which were statistically significant relative to SO (7.36). The increases, although numerically small (~2.5%), were statistically significant ($p < 0.05$), suggesting that organic amendments, especially goat manure and chicken manure alone, can buffer soil pH. The liming effect of biochar may also contribute to this moderation, especially in CM:B and GM:B treatments. This suggests that although biochar initially contributes to a slight acidity, its long-term effects appear to promote pH stabilization or even improvement, a finding consistent with Schmidt et al., (2021).

The neutral to slightly alkaline pH maintained across treatments is beneficial for nutrient availability, microbial activity, and overall soil health. The alkaline nature of biochar often raises concerns about potential over-alkalization, but in this study, the pH moderation effect appears balanced, particularly when combined with organic materials. These findings align with previous studies (Gunarathne et al., 2020), which reported that organic amendments can buffer soil pH fluctuations when applied with biochar, stabilizing soil chemical environments and promoting sustainable soil management practices. Organic amendments contribute to stabilizing soil pH by gradually releasing nutrients, without leading to significant soil acidification (Šimanský et al., 2021; Ai et al., 2023).

EC

The EC of the treatments varied significantly throughout the incubation period ($p < 0.05$) (Figure 4), reflecting the effects of different soil amendments on salinity. The EC of the soil varied modestly, ranging from 5.71 to 6.82 mS/cm. GM:B (1:2) had the highest EC and was statistically significant relative to GM:B (1:3). GM:B (1:3) had the lowest, and was statistically significant relative to GM:B (1:2) (6.82). Treatments such as CM, CM:B (1:1), and CM:B (1:2) exhibited intermediate values with no significant differences among them. The reduced EC in GM:B (1:3) suggests that a higher proportion of biochar can mitigate salt accumulation, potentially by improving cation exchange or reducing ionic mobility. This trend emphasizes that both the type of manure and the biochar ratio influence soil salinity dynamics. The GM:B (1:3) treatment demonstrated a 12.29% reduction in EC compared to the SO treatment, underlining the potential of biochar to reduce soil salinity. The application of biochar leads to improved soil structure, increased water retention, and enhanced leaching of excess salts (Xiao and Meng, 2020; Li et al., 2022).

The porous structure of biochar plays an important role in alleviating soil salinity. By trapping salts

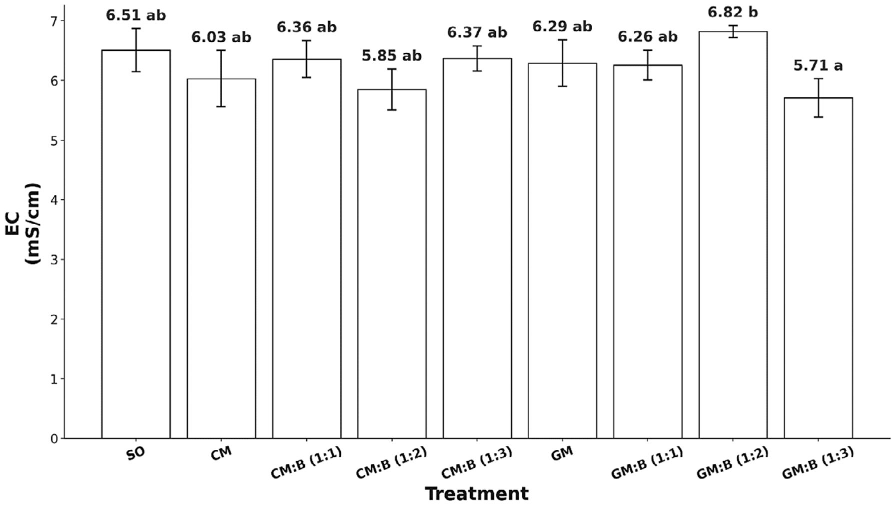

Figure 4. The EC values of all treatments after incubation are presented as means; SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the p < 0.05 level

and reducing the ionic concentration in the soil, biochar contributes to improved soil conditions. This is in line with the work of El-Sayed et al., (2021), who demonstrated that the structure of biochar significantly aids in salinity reduction. Furthermore, Gu et al., (2023) highlighted that the impact of biochar extends beyond EC, also improving soil pH and enhancing its suitability for crop growth.

Available P

The concentrations of available P varied significantly across treatments throughout the incubation period ($p < 0.05$) (Figure 5). The CM:B (1:3) treatment showed the highest concentration of available P (197.41 ppm), almost four times higher than the SO, but was not statistically significant relative to GM:B (1:3) (181.27). In contrast, the SO treatment consistently recorded the lowest levels, and was statistically significant relative to other treatments, reaching only 51.38 ppm. CM and GM treatments alone (without biochar) resulted in relatively lower P values (84.41 ppm and 82.97 ppm) and were not statistically significant from each other, indicating the critical role of biochar in enhancing phosphorus availability. These findings reinforce the critical role of biochar in reducing P fixation and enhancing nutrient retention.

Organic amendments, particularly CM and GM, played a significant role in enhancing soil phosphorus availability. The addition of biochar further enhanced this effect, with higher biochar ratios leading to even greater increases in available P. This aligns with the findings by Luan et al., (2023) and Yue et al., (2023), who demonstrated that biochar improves phosphorus availability by facilitating its adsorption onto biochar surfaces and by fostering the conditions conducive to microbial activity that solubilizes phosphorus. These trends are consistent with Mendes et al., (2015), who reported that biochar not only enhances phosphorus availability by improving soil structure but also promotes microbial activity, further aiding phosphorus solubilization. The treatments with higher biochar ratios, such as CM:B (1:3) and GM:B (1:3), demonstrated the most pronounced increases in available P, a result that is supported by the research indicating that biochar alters soil pH and reduces phosphorus adsorption (Amin, 2023; Fogat et al., 2023).

Integrating biochar with organic fertilizers has been shown to optimize phosphorus availability, enhance nutrient cycling, and improve soil fertility over time (Liu et al., 2022). The combination of biochar and organic fertilizers represents a sustainable strategy for improving phosphorus availability in soils, thereby supporting enhanced soil fertility and agricultural productivity.

Total N

Throughout the incubation period, significant variations in total N levels were observed among the treatments ($p < 0.05$) (Figure 6). The highest

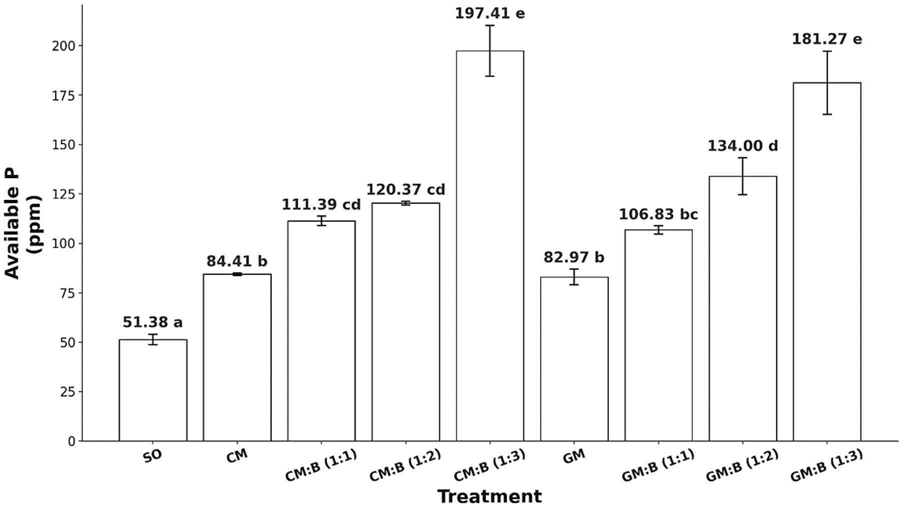

Figure 5. The available P values of all treatments after incubation are presented as means; SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the $p < 0.05$ level

nitrogen value was found in CM:B (1:3) (0.13%) and was statistically significant relative to other treatments. This represented a 160% increase compared to the control and GM (both 0.05%). CM:B (1:1) and CM:B (1:2) also had significantly higher nitrogen contents (0.10% and 0.11%, respectively). Among goat manure treatments, only GM:B (1:3) reached a comparable level (0.10%) to the chicken manure treatments, but remained statistically different from CM:B (1:3). This indicates that while goat manure with high biochar ratios can moderately improve nitrogen levels, chicken manure remains more effective for enhancing soil nitrogen retention.

The application of organic amendments, especially when combined with biochar, contributes to improved nitrogen retention in soils. The high surface area and porosity of biochar enable it to adsorb and retain nitrogen, minimizing losses through leaching and volatilization, while gradually releasing nitrogen into the soil. This ensures a consistent supply of nitrogen over time, even in saline or nutrient-limited environments (Nehela et al., 2021). Furthermore, the ability of biochar to enhance microbial activity plays a crucial role in nitrogen cycling. Soil microbes contribute to nitrogen mineralization through the decomposition of organic matter, while biochar stabilizes organic nitrogen, preventing immobilization (Luan et al., 2021). The enhanced nitrogen retention observed in the CM:B (1:3) treatment aligns with the findings of Widowati et al., (2024), who demonstrated that biochar can increase nitrogen availability by up to 70% in amended soils. Additionally, biochar facilitates the formation of humic substances, which are essential for improving nitrogen stabilization and slowing the decomposition of organic nitrogen (Liao et al., 2024). In contrast, the gradual reduction in total N in the non-biochar treatments, such as SO, can be attributed to natural mineralization and immobilization processes carried out by microorganisms. Biochar effectively offsets these losses by retaining and slowly releasing nitrogen, especially when combined with organic amendments like chicken and goat manure. These findings also support recent research by Qian et al., (2023), which demonstrated that biochar enhances nitrogen retention by improving soil structure, increasing CEC, and promoting the retention of ammonium ions. Overall, the results highlight the significant role of biochar, particularly in higher ratios like CM:B (1:3), in mitigating nitrogen losses and improving nitrogen retention.

CEC

Significant variations in CEC were observed across treatments ($p < 0.05$) at the end of the incubation period (Figure 7). The biochar-amended treatments, particularly CM:B (1:3) and GM:B (1:3), exhibited the highest CEC values, reaching

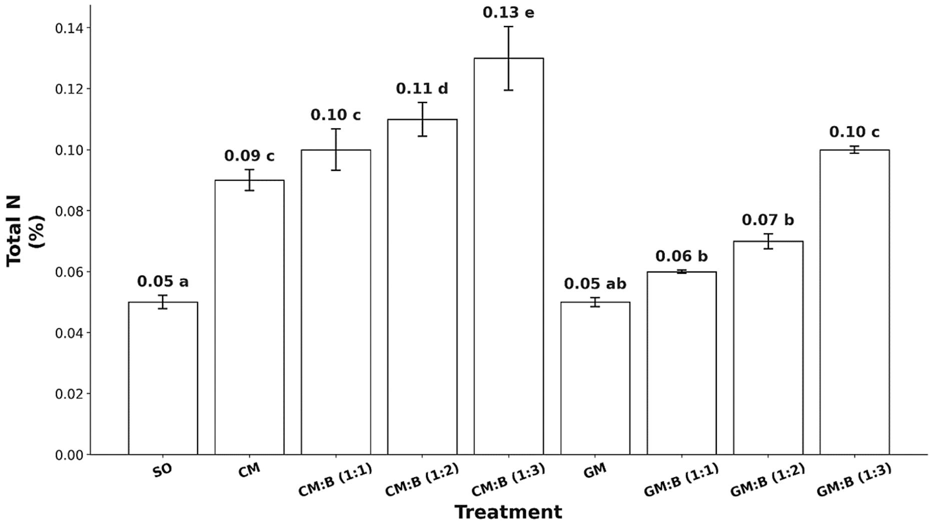

Figure 6. The Total N values of all treatments after incubation are presented as means; SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the $p < 0.05$ level

31.78 cmol/kg and 30.55 cmol/kg, respectively, highlighting the synergistic effect of biochar with organic amendments like chicken and goat manure in improving soil fertility. The SO treatment had the lowest CEC value at 25.23 cmol/kg, which was significantly lower relative to other treatments except CM (27.19 cmol/kg). The application of organic amendments has been shown to improve the capacity of soil to retain cations, contributing to enhanced CEC. These findings align with previous studies Abdelhameed et al., (2024) that demonstrate the positive impact of organic amendments on CEC.

The application of CM slightly increased CEC to 27.19 cmol/kg, while GM showed a similar trend with 27.61 cmol/kg. These values were not statistically significant from each other, indicating that while both manure sources contribute to improved CEC, their effects were relatively modest when applied without biochar. A notable improvement was observed with the incorporation of biochar. Among the chicken manure and biochar combination treatments (CM:B), CEC increased progressively with higher biochar ratios. These results are consistent with the studies by Wijitkosum and Jiwnok (2019) and Sy et al., (2022), who emphasized the role of biochar in adsorbing cations and improving soil aeration, both of which are key to increasing CEC.

CM:B (1:1) and CM:B (1:2) showed intermediate values of 27.70 and 29.65 cmol/kg, respectively. However, the most pronounced effect was observed in CM:B (1:3), which recorded the highest CEC at 31.78 cmol/kg. This value was significantly higher than all other treatments except CM:B (1:2) (29.65 cmol/kg) and GM:B (1:3) (30.55 cmol/kg), and reflects a 25.9% increase compared to SO. Similarly, goat manure combined with biochar treatments (GM:B) also enhanced CEC values relative to goat manure alone. While both types of manure benefited from biochar addition, chicken manure combined with higher biochar ratios had a more substantial effect on improving soil CEC. These effects are attributed to the high surface area, porosity, and negative charge of biochar, which enhance cation retention and improve nutrient availability (Crane-Droesch et al., 2013; Kharel et al., 2019). Although goat manure showed a marginally higher CEC than chicken manure in the non-biochar treatments, both manures, when combined with biochar, demonstrated comparable improvements in CEC. This indicates that the impact of biochar is consistent across different organic amendments.

Exchangeable cations and ESP

Significant variations in exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) and ESP were observed across treatments after the incubation period ($p < 0.05$) (Table 3). Exchangeable Ca^{2+}

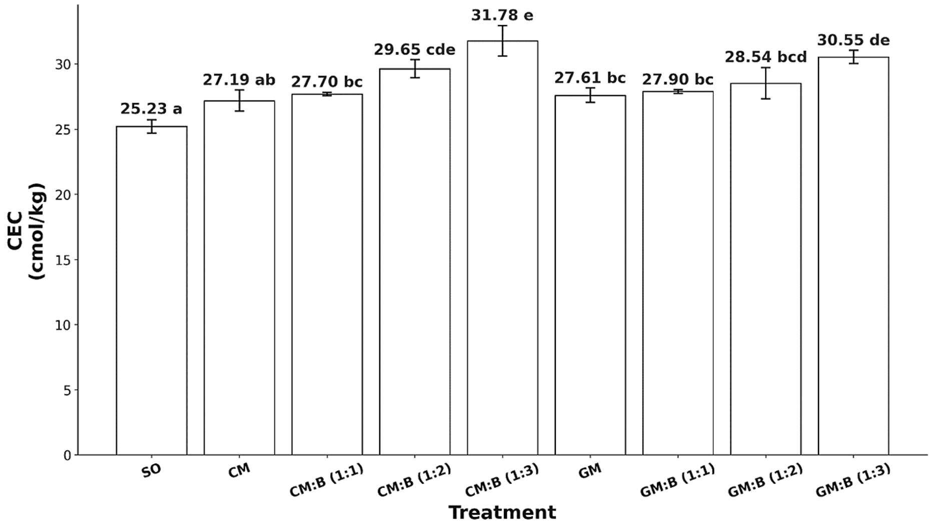

Figure 7. The CEC values of all treatments after incubation are presented as means; SO denotes the control treatment with soil only, CM refers to chicken manure, and GM represents goat manure. The notations CM:B and GM:B indicate the respective weight ratios of chicken manure and goat manure mixed with biochar. Different lowercase letters within the same column indicate statistically significant differences among treatments at the $p < 0.05$ level

Table 3. Exchangeable cations after the end of incubation

Treatments	(cmol/kg)				ESP (%)
	Ca^{2+}	Mg^{2+}	K^+	Na^+	
SO	14.47 a	7.86 a	0.66 a	0.20 d	0.78 d
CM	17.21 ab	9.91 bc	1.65 b	0.16 c	0.59 c
CM:B (1:1)	15.29 ab	8.71 ab	2.03 cd	0.16 c	0.59 c
CM:B (1:2)	15.17 a	8.66 ab	2.11 d	0.13 b	0.43 b
CM:B (1:3)	18.62 b	10.47 c	2.25 de	0.11 ab	0.35 a
GM	17.06 ab	9.883 bc	1.72 bc	0.12 b	0.45 b
GM:B (1:1)	16.92 ab	9.89 bc	2.10 d	0.12 ab	0.42 b
GM:B (1:2)	16.35 ab	9.29 bc	2.32 de	0.10 ab	0.36 ab
GM:B (1:3)	18.55 b	10.40 c	2.58 e	0.09 a	0.28 a

Note: SO denotes soil only, CM refers to chicken manure, and GM signifies goat manure. The notation CM:B indicates the weight ratio between chicken manure and biochar, while GM:B represents the weight ratio between goat manure and biochar. All values are presented as means. Different letters within the same column among the treatments indicate a statistically significant difference ($p < 0.05$).

levels ranged from 14.47 to 18.62 cmol/kg. The lowest value was found in SO, while the highest was observed in CM:B (1:3), representing an increase of 28.7%. This treatment was statistically significant relative to SO and most GM-based treatments. Notably, both CM and GM increased the exchangeable Ca^{2+} levels compared to SO, but the combinations with biochar—particularly CM:B (1:3) and GM:B (1:3)—resulted in the most pronounced increases. These two treatments were statistically similar to each other but statistically significant relative to SO, indicating that both manure types benefit from biochar incorporation, especially at higher ratios.

A similar trend was observed in exchangeable Mg^{2+} content which also enhanced by organic treatments, with values ranging from 7.86 cmol/kg in SO to 10.47 cmol/kg in CM:B (1:3), an increase of 33.2%. This treatment is statistically significant relative to SO and most other treatments. Goat manure combinations such as GM:B (1:3) and GM:B (1:1) also showed high exchangeable Mg^{2+} values (10.40 and 9.89 cmol/kg, respectively) and were statistically similar to CM:B (1:3), suggesting a comparable positive effect. Both CM:B and GM:B combinations resulted in greater calcium accumulation in the soil compared to treatments where manure was applied without any biochar incorporation.

Exchangeable K^+ exhibited an increasing trend with increasing biochar ratios. The highest exchangeable K^+ was observed in GM:B (1:3) (2.58 cmol/kg), which was significantly higher than all other treatments except CM:B (1:3) (2.25 cmol/kg) and GM:B (1:2) (2.32 cmol/kg). This suggests that the GM:B (1:3) combination effectively preserved or enhanced potassium levels, likely due to the high inherent K content in goat manure (Table 2) and the cation-retention properties of biochar. The lowest value occurred in SO (0.66 cmol/kg) and was statistically significant relative to other treatments.

Exchangeable Na^+ followed a similar decreasing pattern, with the SO showing the highest exchangeable Na^+ concentration (0.20 cmol/kg) and statistically significant relative to other treatments. GM:B (1:3) exhibited the lowest (0.09 cmol/kg) but was not statistically significant relative to CM:B (1:3) (0.11 cmol/kg), GM:B (1:1) (0.12 cmol/kg), GM:B (1:2) (0.10 cmol/kg), a reduction of 55%. The addition of biochar—especially at higher ratios—consistently reduced the Na^+ content across both manure types. CM:B (1:3) also showed a notable decrease (0.11 cmol/kg).

ESP values followed the same trend as exchangeable Na^+. The SO had the highest ESP (0.78%), which was statistically significant relative to other treatments. The lowest ESP was found in GM:B (1:3) (0.28%) but was not statistically significant relative to CM:B (1:3) (0.35%) and GM:B (1:2) (0.36%). Treatments with higher biochar ratios (CM:B and GM:B at 1:3) consistently resulted in significantly lower ESP values, confirming the role of biochar in reducing sodicity. Lower ESP values in biochar-amended treatments appear closely linked to their higher calcium and magnesium concentrations—especially in CM:B (1:3) and GM:B (1:3), which showed the highest exchangeable Ca^{2+} and Mg^{2+} levels, both statistically different from SO and lower-ratio biochar combinations. These divalent cations effectively outcompete sodium on soil exchange sites, displacing it and preventing excessive sodium accumulation – thus explaining the concurrent drop in ESP. These reductions are agronomically beneficial, as high ESP can negatively affect soil structure and permeability. The effectiveness of organic amendments in mitigating soil sodicity is closely linked to their structural composition, particularly the concentrations of Ca^{2+}, Mg^{2+}, and K^+, as also emphasized by Jalali et al., (2020).

The application of organic amendments in combination with biochar demonstrated a positive effect on soil nutrient availability. The treatments with biochar showed notable increases in Ca^{2+}, Mg^{2+} and K^+ consistent with the findings by Liu et al., (2022), which highlighted ability of biochar to enhance soil nutrient retention through its high CEC. The application of organic amendments has been reported to effectively lower the ESP in saline soils. Akter and Khan, (2021) emphasized that organic amendments can enhance sodium leaching and reduce salinity stress by decreasing the ESP, contributing to improved soil health and crop productivity. This aligns with the findings by Gunarathne et al. (2020), who highlighted the synergistic potential of biochar and organic amendments in improving soil physicochemical properties, particularly by promoting lower ESP through increased salt-adsorbing capacity of the soil matrix. The soil in this study is not classified as sodic, as indicated by the consistently low exchangeable sodium concentrations observed across all treatments. Notably, biochar—particularly when applied in combination with organic amendments – substantially improves the nutrient profile of soil by increasing the availability of essential cations such as calcium and magnesium, while concurrently reducing sodium levels. Biochar reduces soil ESP by adsorbing exchangeable Na^+ through its high surface area and negative charge, while simultaneously increasing soil CEC, which promotes the replacement of Na^+ with beneficial cations such as Ca^{2+} and K^+ (An et al., 2023). Its inherently high surface area and porosity contribute to greater nutrient retention, improved soil structure, and enhanced long-term soil fertility management (Jílková, 2023; Luan et al., 2023).

CONCLUSIONS

This study demonstrated that the application of biochar and organic manures, particularly at higher biochar ratios, effectively improved the chemical properties of saline soils. Significant enhancements were observed in organic C, total N, available P, and CEC, alongside reductions in EC and ESP. Among all treatments, the combination of chicken manure and biochar at a 1:3 ratio yielded the most beneficial outcomes. While these findings are promising, several limitations should be acknowledged. The study was conducted under controlled laboratory conditions, which may not fully capture the complexity of field environments, including plant-soil-microbe interactions. Moreover, the biochar applied originated from a single feedstock (rice husk) and pyrolysis condition (500 °C), which may constrain the broader applicability of the results. The economic viability and scalability of biochar use in large-scale saline soil reclamation were also not assessed. Future research should investigate the field-scale performance of these amendments, assess their long-term impacts on soil health, and explore their interactions with plant productivity across diverse agroecological conditions.

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