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Effect of Amendments on Soil Charge Characteristics in Sub-Optimal Dryland of Aceh Besar, Indonesia

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ABSTRACT

Soil colloids play a critical role in controlling chemical behavior, particularly in tropical sub-optimal drylands dominated by variable-charge soils. However, information on the comparative effects of organic and inorganic amendments on soil charge characteristics across different soil orders remains limited. This study aimed to evaluate the effects of compost, biochar, $CaCO_3$, and Superphosphate fertilizer (SP-36) on the charge characteristics of tropical dryland soils. Nine amendment combinations were applied to topsoil (0–20 cm) from Andisols (Saree), Inceptisols (Cucum), and Ultisols (Jantho), followed by incubation for 60 days at 25–27 °C under field capacity conditions. Soil charge parameters were analyzed before and after incubation. Results showed that amendment type and rate significantly affected soil charge characteristics, with responses varying among soil orders. Organic amendments (15–30 t ha^{-1}) and SP-36 (2–4 t ha^{-1}) decreased pH€ and significantly increased cation exchange capacity (CEC) and net negative charge, indicating improved soil reactivity. In contrast, $CaCO_3$ increased pH_o and reduced negative charge. These findings support the strategic use of organic amendments to enhance soil fertility and sustainability.

Keywords: Land evaluation, land suitability, peat land, Sorghum (*Sorghum bicolor* L)

INTRODUCTION

Suboptimal land (marginal lands) refers to land with inherently low productivity due to various limiting factors that hinder crop production, particularly food crops (Csikós and Tóth, 2023). In Indonesia, suboptimal drylands occur across both dry and humid climatic zones, with the largest proportion located in humid tropical environments, commonly referred to as tropical drylands. These lands represent an important potential resource for agricultural expansion; however, many have undergone significant degradation and are currently classified as critical land, covering more than 18 million hectares (Pitaloka, 2020; Arista et al., 2023). Improving the quality and productivity of these lands has therefore become a key priority for sustainable agricultural development and food security in tropical regions (Samijan et al., 2023; Sufardi, 2024; Sufardi and Helmi, 2025).

In Aceh Besar District, Indonesia, spatial analysis indicates that suboptimal dryland covers approximately 239,387.91 hectares (Umar et al., 2021). Nevertheless, only part of this area can be used for agriculture because large portions are in forests and conservation areas. Previous studies reported that the soils of this region consist of several soil orders, including Ultisols, Oxisols, Inceptisols, Entisols, and Andisols, with Mollisols occurring in limited areas (Sufardi et al., 2020). These soils are generally characterized by low clay activity due to mineralogical compositions dominated by Fe- and Al-hydroxide-oxides (Fitri et al., 2020; Cao et al., 2024; Quantin and Becquer, 2025). As a consequence, the soils typically exhibit low negative surface charge, low cation exchange capacity (CEC), and relatively high zero point of charge (pH_o) values, which are often higher than the actual soil pH (Kautsar et al., 2018; Sufardi et al., 2019; Sufardi et al., 2020).

Many soils in tropical suboptimal drylands are classified as variable-charge soils. In these soils, the surface charge of soil colloids originates from hydroxyl groups associated with clay minerals, phyllosilicates, allophane–imogolite complexes, hydrous oxides, and soil organic matter (Sparks et al., 2022). Unlike in permanent-charge soils, the magnitude and even the sign of the surface charge in variable-charge soils can change with soil pH and electrolyte concentration (Alemayehu and Teshome, 2021). These charge characteristics strongly influence soil chemical processes, including nutrient retention, ion exchange, and the adsorption behavior of cations and anions (Khanri et al., 2025).

Suboptimal drylands generally have low soil fertility due to unfavorable physicochemical properties. These soils typically contain low organic matter, limited availability of essential nutrients such as phosphorus and potassium, low CEC, and acidic soil reactions (McLeod et al., 2020; Sufardi et al., 2022; Abdullah et al., 2025; Sufardi et al., 2025). The low fertility status of these soils is closely related to the charge characteristics of soil colloids (Uehara and Gillman, 1985; Yu et al., 2025; Violante and Gianfreda, 2023). In variable-charge soils, the relatively high zero point of charge significantly affects nutrient dynamics, particularly the adsorption of anions such as phosphate on soil colloid surfaces (Nguyen et al., 2020; Penn and Camberato, 2019). Consequently, improving soil charge characteristics is essential for enhancing nutrient availability and soil fertility in tropical dryland ecosystems (Sufardi, 2024; Usman, 2024).

One common approach to improving the physicochemical properties of such soils is the application of soil amendments. Amendments are used to reduce soil acidity, increase negative surface charge, enhance CEC, and modify the zero point of charge of soil colloids. However, previous studies have shown that different types of amendments may produce contrasting effects on the charge characteristics of variable-charge soils (Wen et al., 2020; Sufardi et al., 2024). For example, the application of lime ($CaCO_3$) to acidic tropical soils can increase soil pH and CEC while reducing exchangeable Al (Guddisa et al., 2018; Xia et al., 2020). Liming with $CaCO_3$ is widely used to ameliorate acidic soils by increasing soil pH, neutralizing exchangeable Al, and increasing base saturation. The increase in soil pH promotes the development of pH-dependent negative charges on soil colloids, thereby enhancing the cation exchange capacity (CEC), particularly in highly weathered soils dominated by variable-charge minerals (Makaza et al., 2026; Moreira et al., 2026). On the other hand, liming may also increase the soil pH_o value because $CaCO_3$ itself has a relatively high zero point of charge (El-Aswad et al., 2023).

Organic amendments are also widely used to improve soil physicochemical properties. Organic materials can increase the density of negative surface charges on soil colloids, thereby enhancing nutrient retention, although their effect on increasing soil pH is generally limited (Li et al., 2021; Lin et al., 2025). Theoretically, the magnitude of variable charge is influenced by several factors, including soil pH, electrolyte concentration, ionic valence, temperature, and the inherent pH_o status of the soil (Van Ranst et al., 2017; Patel, 2025). Despite the recognized importance of soil amendments in improving soil quality, comparative information on how different organic and inorganic amendments influence soil charge characteristics across various soil orders in tropical suboptimal drylands remains limited.

Although numerous studies have investigated the role of soil amendments in improving the chemical properties of tropical soils, most have focused on changes in soil pH, nutrient availability, and crop productivity. Comparatively little attention has been given to how different types of amendments influence the surface charge characteristics of soil colloids, particularly in variable-charge soils that dominate tropical suboptimal drylands. Furthermore, previous studies generally examined individual soil types or single amendments, while comparative studies across different soil orders within the same agro-ecological region remain limited. This limitation impedes a comprehensive understanding of how organic and inorganic amendments modify the electrochemical behavior of soil colloids and, in turn, influence soil fertility. Therefore, investigating how soil charge characteristics respond to different amendments across multiple soil orders is essential for developing more effective soil management strategies in tropical suboptimal drylands.

This study offers new insights into the role of organic and inorganic amendments in regulating soil surface charge properties in tropical dryland soils, which is essential for developing sustainable soil management strategies in suboptimal agricultural lands. Therefore, this study aims to evaluate the effects of several soil amendments on the charge characteristics of soils in the suboptimal drylands of Aceh Besar, Indonesia.

MATERIALS AND METHODS

The research was conducted under laboratory conditions using topsoil (0–20 cm) collected from three soil orders in sub-optimal dryland areas of Aceh Besar Regency, Aceh, Indonesia. The soils consisted of Andisols (Eutric Hydrudands) from Saree (05°272 03.23 N; 95°432 45.23 E), Inceptisols (Oxyaquic Dystrudepts) from Cucum Village (05°182 183 N; 95°322 483 E), and Ultisols (Typic Kandiudults) from Jantho (05°162 583 N; 95°372 51.83 E). Soil samples were collected from a depth of 0–20 cm. Before treatment application, the samples were air-dried for one week, ground, and sieved through a 0.5-mm mesh. The experiment was arranged in a completely randomized design (CRD) with two factors. The first factor was the type and rate of soil amendment with nine levels: control (without amendment), biochar at 15 t ha^{-1}, biochar at 30 t ha^{-1}, compost at 15 t ha^{-1}, compost at 30 t ha^{-1}, $CaCO_3$ at 2 t ha^{-1}, $CaCO_3$ at 4 t ha^{-1}, SP-36 at 2 t ha^{-1}, and SP-36 at 4 t ha^{-1}. The second factor consisted of three soil orders: Andisols (Saree), Inceptisols (Cucum), and Ultisols (Jantho). These two factors resulted in 27 treatment combinations with a total of 54 experimental units.

For the incubation experiment, 500 g of soil were placed into plastic bottles. Biochar, compost, $CaCO_3$ (lime), and phosphate fertilizer (SP-36) were then applied according to the designated treatments and thoroughly mixed with the soil. Distilled water was added to each bottle to adjust the soil moisture to field capacity. The samples were incubated for 60 days in a temperature-controlled room at 25–27 °C. After the incubation period, soil samples were removed from the bottles and air-dried for one week. The dried soils were then gently crushed and sieved through a 1.0-mm mesh. Subsequently, 100 g of soil from each sample was collected for laboratory analysis. To determine the initial soil charge characteristics, soil samples from each soil order were also analyzed before the incubation experiment.

The soil charge characteristics analyzed included pH_o , pH (H_2O), pH (KCl), ΔpH (KCl – H_2O), variable charge, cation exchange capacity (CEC), and exchangeable cations (Ca, Mg, K, Na, Al, and H). The zero point of charge (pH_o) was determined using the ion adsorption and potentiometric titration method with $CaCl_2$, following the procedure of Uehara and Gillman (1985). Soil pH in H_2O and KCl was measured using a pH meter. The variable charge was calculated as the difference between the CEC determined by the 1 *N* NH_4OAc extraction at pH 7 and the effective CEC, which was obtained from the sum of exchangeable base cations and exchangeable acidity (Al + H) extracted with 1 M KCl.

The data were analyzed using analysis of variance (ANOVA), and treatment means were compared using the least significant difference (LSD) test at $P < 0.05$ (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

The initial Soil Characteristics

Table 1 shows that the Andisol from Saree is characterized by low pH (H_2O and KCl) and very low available P, but contains high organic C, moderate total N, and very high potential P_2O_5 and K_2O_5. These results indicate that the main constraints of this soil are acidic pH and low available P. In the Inceptisol from Cucum Village, the major limitations include slightly acidic pH, very low available P, low organic C and total N, and low K, O content. Similarly, the Ultisol from Jantho exhibits slightly acidic pH and very low levels of available P, organic C, and total N. Based on these chemical

Table 1. Chemical characteristics of the topsoil of Andisol, Inceptisol, and Ultisol before the experiment.

Soil chemical characteristics	Andisols Saree	Inceptisols Cucum	Ultisols Jantho
pH H_2O (1:2.5)	5.56^{A}	6.45^{SA}	5.97^{SA}
pH KCl (1:2.5)	4.35^{HA}	4.73^{A}	4.01^{HA}
ZPC = pH_o	5.91^{H}	4.48^{M}	5.58^{H}
CEC (cmol kg^{-1})	31.60^{H}	21.20^{M}	20.40^{M}
Available P (mg kg^{-1})	2.30^{VL}	0.50^{VL}	2.85^{VL}
Organic C (g kg^{-1})	39.5^{H}	0.64^{VL}	0.53^{VL}
Total N (g kg^{-1})	2.52^{M}	0.51^{VL}	0.45^{VL}
Total P_2O_5 (mg 100 g^{-1})	83.12^{VH}	77.35^{VH}	221.21^{VH}
Total K_2O (mg 100 g^{-1})	65.98^{VH}	38.25^{L}	28.14^{L}
Base saturation (%)	43.52^{H}	36.74^{M}	25.78^{L}

HA (highly acid), A (acid), SA (slightly acid), VL (very low), M (medium), H (high), VH (very high) properties, the Inceptisol (Cucum) and Ultisol (Jantho) are classified as having low soil fertility status due to low soil pH, low organic C, and low base saturation, despite their relatively high potential P_2O_5 content. Another characteristic of these sub-optimal dryland soils is the relatively high zero point of charge (pH_o), which exceeds the soil pH measured in H_2O. This condition indicates that the three soil orders used in this study are dominated by variable-charge soils, as reported by Wen et al. (2020).

Effects of Soil Amendments on Charge Characteristics

pH H_2O, pH KCl, and ΔpH

The incubation experiment demonstrated that the application of different types and rates of amendments significantly influenced soil pH (H_2O and KCl) in sub-optimal dryland soils of Aceh Besar Regency, Aceh, Indonesia (Table 2). However, the magnitude of pH change varied among soil orders. In the Andisol from Saree, most amendments did not significantly change soil pH. A slight increase in pH was observed only with the application of compost at 30 t ha^{-1} and $CaCO_3$ at 2–4 t ha^{-1}. The limited change in pH may be related to the high buffering capacity of Andisols, which are dominated by amorphous minerals and organic matter that tend to stabilize soil acidity (Parada et al., 2024; Fajarini et al., 2025). Without amendment, the soil pH was acidic (5.41), whereas the addition of compost and $CaCO_3$ slightly increased it to 5.82, still classified as slightly acidic. The liming effect of $CaCO_3$ occurs through the neutralization of exchangeable acidity and the precipitation of Al^{3+}, thereby increasing soil pH (Zhang et al., 2023; Abdi, 2024).

In the Inceptisol from Cucum Village, an increase in soil pH was observed only with $CaCO_3$ application at rates of 2–4 t ha^{-1}, indicating that liming was the most effective treatment for reducing soil acidity. In contrast, compost and biochar did not significantly affect soil pH. The application of SP-36 at 2–4 t ha^{-1} tended to decrease soil pH from slightly acidic to acidic conditions, which may be associated with the release of acidity during phosphate fertilizer reactions in the soil.

Similarly, in the Ultisol from Jantho, soil pH increased with the application of compost and $CaCO_3$, whereas biochar had no significant effect. The increase in pH with compost application may be related to the release of basic cations during organic matter decomposition, which can partially neutralize soil acidity. Conversely, the application of SP-36 tended to reduce soil pH, indicating its potential acidifying effect in highly weathered soils. These results suggest that liming and organic amendments are more effective at reducing soil acidity in variable-charge soils than biochar or phosphate fertilizer alone.

The incubation experiment indicated that lime ($CaCO_3$) and compost amendments were effective in increasing soil pH (H_2O). In contrast, biochar and phosphate fertilizer (SP-36) were less effective in improving soil acidity in sub-optimal dryland soils of Aceh Besar Regency, Aceh, Indonesia. Compost has high potential to restore soil fertility because it is an important source of organic matter. During incubation, the decomposition of organic materials releases basic cations and organic ligands that can neutralize acidic cations such as H^+ and Al^{3+}, thereby increasing soil pH, as reported by Zhang et al. (2023). Similarly, the application of $CaCO_3$

Table 2. pH H_2O, pH KCl, and ΔpH of three soil orders on various amendment treatments in Aceh Besar dryland

Amendments	Andisols Saree			Inceptisols Cucum			Ultisols Jantho		
application	pH H_2O	pH KCl	ΔpH	pH H_2O	pH KCl	ΔpH	pH H_2O	pH KCl	ΔpH
Control	5.41 a	4.41 a	-1.00	6.39 b	5.27 bc	-1.12	5.61 b	4.08 ab	-1.53
Biochar 15 t ha^{-1}	5.45 a	4.43 a	-1.02	6.54 b	4.28 a	-2.26	5.67 b	4.16 ab	-1.51
Biochar 30 t ha^{-1}	5.49 a	4.44 a	-1.05	6.66 b	4.30 a	-2.36	5.71 b	3.82 a	-1.89
Compost 15 t ha^{-1}	5.54 a	4.54 a	-1.00	6.43 b	4.67 ab	-1.76	6.43 c	4.53 c	-1.90
Compost 30 t ha^{-1}	5.82 b	4.93 b	-0.89	6.58 b	4.98 b	-1.60	6.50 c	4.33 bc	-2.17
$CaCO_3$ 2 t ha^{-1}	5.74 b	4.69 b	-1.05	6.95 bc	4.97 b	-1.98	6.26 c	4.81 cd	-1.45
$CaCO_3$ 4 t ha^{-1}	5.78 b	4.79 b	-0.99	7.35 c	5.36 c	-1.99	6.35 c	5.02 d	-1.33
SP-36 2 t ha^{-1}	5.42 a	4.36 a	-1.06	5.81 a	4.29 a	-1.52	5.15 a	4.01 a	-1.14
SP-36 4 t ha^{-1}	5.39 a	4.32 a	-1.07	5.63 a	4.29 a	-1.34	4.92 a	3.93 a	-0.99

Values followed by the same letter in each column are not significantly different (LSD 0.05) increased soil pH through the dissociation of $CaCO_3$ into Ca^{2+} and CO_3^{2-} ions. The carbonate ions react with H^+ and Al^{3+} in the soil solution, leading to the precipitation of Al compounds and a reduction in exchangeable acidity, which ultimately increases soil pH (Panda et al., 2025; Makaza et al., 2026).

In contrast, applying biochar at rates of 15–30 t ha^{-1} did not significantly increase soil pH in this study. It may be related to the characteristics of the biochar used, which contains a high proportion of stable carbon and functions primarily as an adsorbent rather than as a liming material, as suggested by Tang (2025). However, other studies have reported that biochar can increase soil pH depending on the application rate and feedstock characteristics (Juriga et al., 2022). Biochar may help neutralize soil pH and improve soil chemical properties, particularly in acidic soils, while also serving as a stable carbon source due to its resistance to microbial decomposition (Yang et al., 2025).

The application of SP-36 at rates of 2–4 t ha^{-1} tended to decrease soil pH. This effect may be associated with the presence of sulfate in the fertilizer and the formation of phosphoric acid during phosphate reactions in the soil solution. Nevertheless, other studies have shown that phosphate application can also increase soil pH under certain conditions (Zhao et al., 2021). This occurs when phosphate anions are adsorbed onto positively charged soil colloids, thereby reducing proton activity and consequently increasing soil pH (Zhang et al., 2023; Sufardi et al., 2024).

Table 2 also shows that the types and rates of amendments affected soil pH (KCl), although the magnitude of this effect varied among soil orders. In the Andisol from Saree, the application of compost at 30 t ha^{-1} increased pH (KCl) compared with the control treatment without amendment. In the Inceptisol from Cucum Village, the application of $CaCO_3$ at rates of 2–4 t ha^{-1} increased soil pH (KCl) relative to the control. Similar findings were reported by Ameyu (2019), who showed that the application of $CaCO_3$ combined with humic substances increased soil pH above 6.5 and reduced exchangeable Al through $CaCO_3$ precipitation and chelation by the functional groups of humic compounds.

The increase in soil pH following $CaCO_3$ application is mainly attributed to the neutralization of soil acidity through the replacement of H^+ ions by Ca^{2+} on the exchange complex, as reported by Mosharrof et al. (2021). In the Ultisol from Jantho, the application of $CaCO_3$ at 4 t ha^{-1} also increased soil pH (KCl) compared with the control. Liming can produce hydroxyl ions (OH^-) in the soil solution, which reduce exchangeable Al by forming insoluble $Al(OH)_3$ precipitates, thereby decreasing soil acidity (Guddisa et al., 2018; Panda et al., 2025; Makaza et al., 2026).

The application of amendments to variable-charge soils in the sub-optimal drylands of Aceh Besar Regency also influenced changes in ΔpH (pH KCl - pH H_2O). However, the effect was not significant in the Andisol from Saree (Table 2). In the Inceptisol from Cucum, the application of biochar, compost, $CaCO_3$, and phosphate fertilizer (SP-36) increased ΔpH values compared with the control treatment. In contrast, in the Ultisol from Jantho, only biochar and compost increased ÄpH values.

An increase in ΔpH indicates a greater development of negative charge on soil colloids (Wen et al., 2020), which can improve soil chemical properties and nutrient retention. The increase in negative surface charge following amendment application depends not only on the type and rate of amendment but also on soil mineralogical composition, which differs among soil orders (Sufardi et al., 2019; Belghazdis and Hachem, 2022).

The changes in soil pH following amendment application were closely related to variations in ΔpH, cation exchange capacity (CEC), and the development of variable surface charge. In variable-charge soils, the magnitude and sign of surface charge depend strongly on soil pH relative to the zero point of charge (pH_o). When soil pH exceeds pH_o , negative charges on soil colloids increase, leading to greater CEC and enhanced nutrient retention. Conversely, when soil pH is lower than pH€ , positively charged sites tend to dominate the colloidal surfaces. The increase in soil pH observed after the application of compost and $CaCO_3$ likely promoted the development of negative surface charges, as indicated by the increase in ΔpH values. This condition enhances the dissociation of functional groups on soil organic matter and variable-charge minerals such as Fe and Al oxides, thereby increasing the number of negatively charged sites available for cation adsorption. As a result, the soil's capacity to retain essential nutrient cations also increases.

The application of biochar, compost, and phosphate fertilizer (SP-36) tended to increase soil pH, thereby increasing ΔpH values (pH KCl - pH H_2O) and promoting the development of more negative surface charges on soil colloids. However, the effect of $CaCO_3$ amendment on soil charge was less consistent. At higher application rates, $CaCO_3$ may increase the concentration of Ca^{2+} in the soil solution, thereby enhancing cation adsorption and partially increasing the positive charge on soil colloid surfaces.

The development of negative charge on soil colloids plays an important role in maintaining soil fertility because negatively charged sites can adsorb and retain nutrient cations, thereby reducing nutrient losses through leaching (Mosharrof et al., 2021). This phenomenon is commonly observed in highly weathered soils with variable-charge characteristics in tropical and subtropical regions, where soil surface charge is strongly influenced by soil pH and mineral composition (Van Ranst et al., 2017; Cao et al., 2024).

Furthermore, the relationship between soil pH and the zero point of charge (pH_o) is an important indicator of soil charge behavior. The difference between pH€ and soil pH (pH_o - pH H_2O) reflects the dominance of positive or negative charges on soil colloids. When soil pH approaches or exceeds pH_o, negative charges tend to dominate, whereas when soil pH is lower than pH_o, positive charges become more dominant. Therefore, amendments that increase soil pH can shift the balance toward greater negative surface charge in variable-charge soils.

Overall, the results demonstrate that soil amendments play an important role in modifying the surface charge characteristics of variable-charge soils. The increase in soil pH following the application of compost and $CaCO_3$ shifted the balance between positive and negative charges on soil colloids, as reflected by changes in ÄpH and the relationship between soil pH and the zero point of charge (pH_o). When soil pH approaches or exceeds pH_o, the number of negative surface charges increases due to the dissociation of functional groups on soil organic matter and oxide minerals, thereby enhancing cation exchange capacity (CEC) and nutrient retention.

pH H_2O and pH_o

The effects of amendment materials on the charge characteristics of sub-optimal dryland soils in Aceh Besar, as indicated by the parameters pH H_2O, pH_o and the difference between pH_o and pH H_2O, are presented in Figures 1 and 2. Figure 1 shows that amendments of different types and application rates influenced the pH_o of variable-charge soils, with the magnitude of the effect depending on both amendment type and soil order. In general, the application of amendments is expected to reduce soil pH_o. The results of this experiment indicate that organic amendments, namely biochar and compost, as well as phosphate fertilizer (SP-36), were effective in decreasing soil pH_o, whereas $CaCO_3$ application increased soil pH_o. In Andisols from Saree, the application of biochar, compost, and SP-36 at specific rates reduced pH_o from 4.01 to 3.06, and similar trends were observed in Inceptisols from Cucum and Ultisols from Jantho.

In contrast, the application of $CaCO_3$ increased pH€ from 4.05 to 6.00. These results demonstrate that organic and phosphate amendments can improve the charge characteristics of soil colloids by reducing soil pH_o. When the actual soil pH is lower than pH_o, soil colloids are predominantly positively charged (Wen et al., 2020; Yu et al., 2025).

Conversely, when soil pH exceeds pH_o, soil colloids become negatively charged (Lal, 2017). Most soils in humid tropical regions generally have relatively high pH_o values. Consequently, anions in the soil solution, such as phosphate, molybdate, and

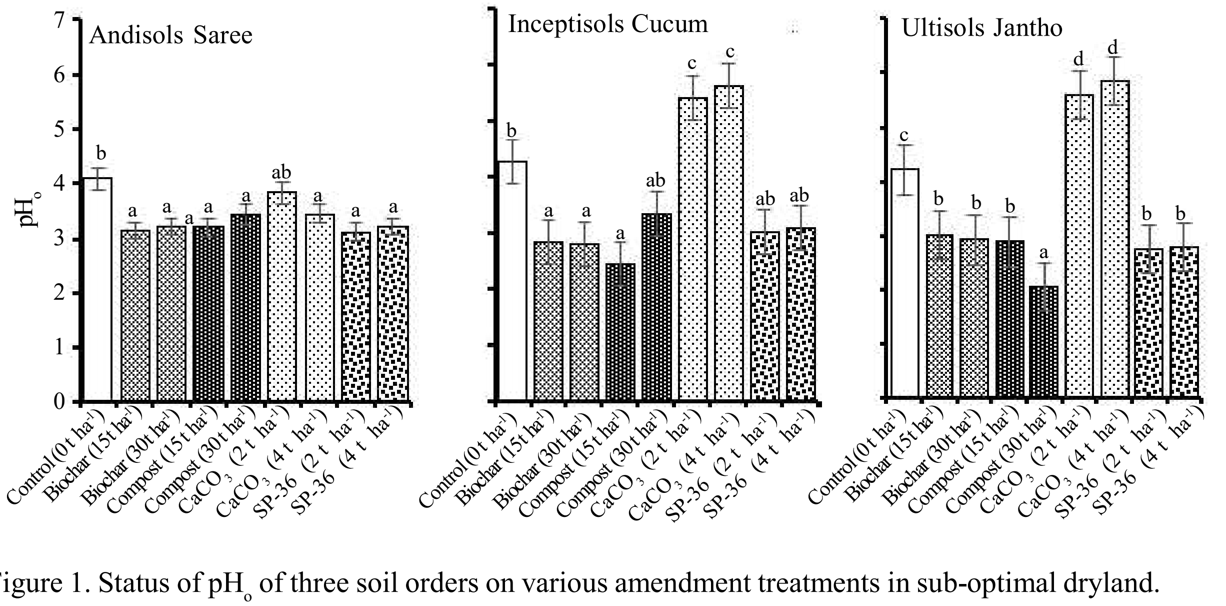

Figure 1. Status of pH_o of three soil orders on various amendment treatments in sub-optimal dryland.

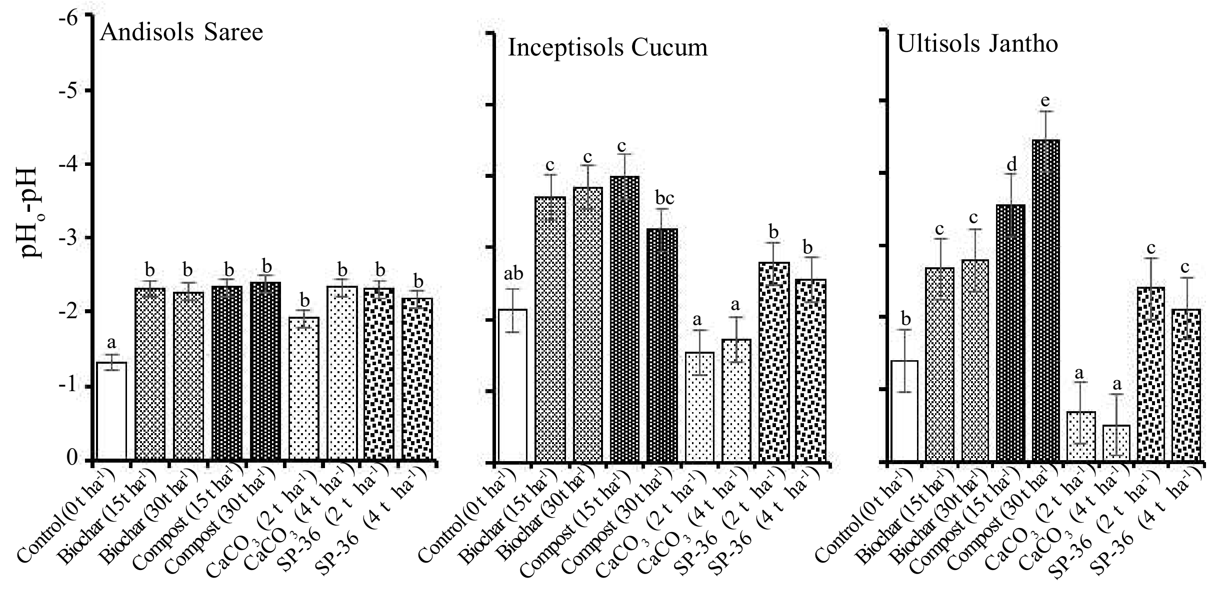

Figure 2. The value of pH_o-pH H_2O of three soil orders on various amendment treatments in sub-optimal dryland.

sulfate, tend to be strongly adsorbed onto soil particle surfaces, thereby reducing their availability in the soil solution (Barrow and Hartemink, 2023). The increase in soil pH_o following lime application can be attributed to carbonate anions derived from $CaCO_3$, which inherently have a high pH_o and thus increase soil pH_o upon application (Guddisa et al., 2018). Furthermore, Ca^{2+} cations released from lime may be adsorbed onto the inner layer of the colloidal surface, altering the surface charge of soil colloids and increasing the point of zero charge.

The results of this experiment also showed that a decrease in soil pH_o following amendment application, particularly with organic materials, was accompanied by an increase in soil negative charge. As shown in Figure 2, except for the Andisols from Saree, organic amendments (biochar and compost) applied at rates of 10–20 t ha^{-1} increased the pH_o - pH H_2O value, indicating an increase in the net negative charge of the soil. Among the tested amendments, compost produced the greatest increase in negative charge, followed by biochar and phosphate fertilizer. The highest negative charge, expressed as the difference between pH_o and pH H_2O, was obtained with the application of compost at 20 t ha^{-1}. Under this treatment, the negative charge increased from “1.00 to “4.00, representing a fourfold increase. This increase in negative charge is associated with the inherently low pH_o of organic matter and phosphate compounds (Koishi et al., 2020). Organic matter contains humic and fulvic substances that help neutralize positive charges on soil colloids (Li et al., 2021). In contrast, although $CaCO_3$ application increases soil pH, it simultaneously increases soil pH_o, resulting in a tendency toward a more positive net colloidal charge, particularly at higher application rates, as indicated by the relatively small difference between pH_o and pH H_2O (Tang et al., 2025; Zhang et al., 2025).

Overall, these findings highlight that organic amendments, particularly compost and biochar, play a crucial role in modifying the charge characteristics of variable-charge soils by reducing pH_o and increasing net negative surface charge, thereby improving nutrient retention in sub-optimal tropical drylands.

CEC and ECEC

This experiment also demonstrated that the application of amendments influenced both the cation exchange capacity (CEC) and the effective cation exchange capacity (ECEC) of the soils. As shown in Figure 3, different amendment types and application rates affected CEC, although the magnitude of the effect varied across amendment types and soil orders. The application of biochar, compost, and phosphate fertilizer increased potential CEC, particularly in the Inceptisols of Cucum and Ultisols of Jantho. In contrast, the effect was relatively small in the Andisols of Saree, which inherently possess high CEC and strong buffering capacity due to the presence of allophane minerals (Sufardi et al., 2020; Belghazdis and Hachem, 2022). Conversely, the application of $CaCO_3$ at rates of 2–

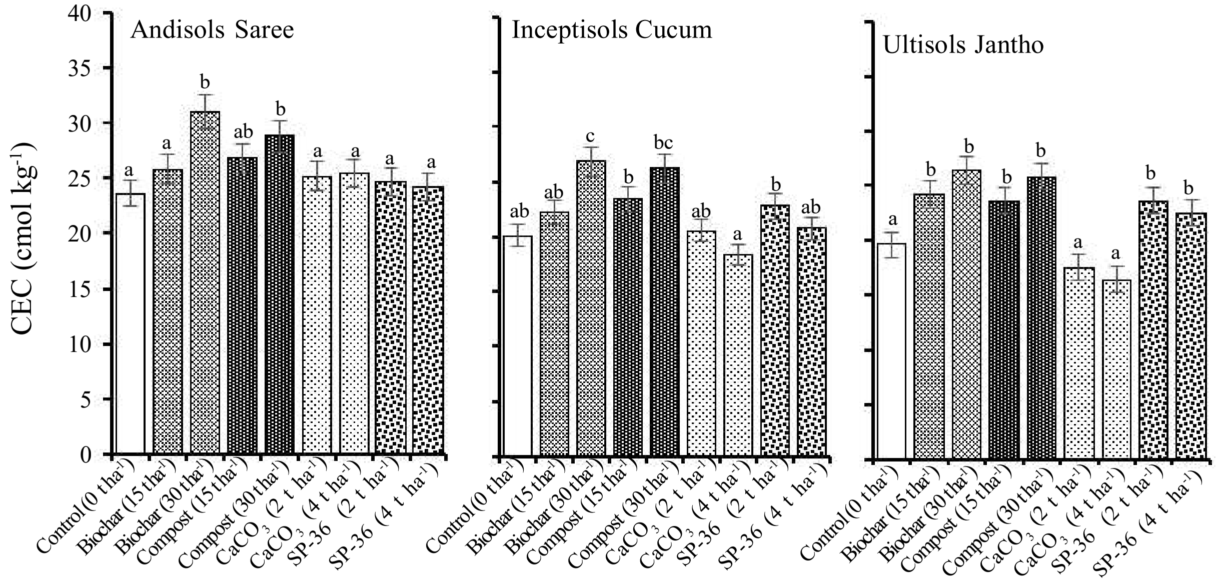

Figure 3. The values of soil CEC of three soil orders on various amendment treatments in sub-optimal dryland.

4 t ha^{-1} tended to reduce soil CEC. The increase in CEC following amendment application is associated with the increase in negative surface charge of soil colloids, as soil CEC is positively correlated with the magnitude of colloidal charge (Khadim et al., 2023). Compost, in particular, contributes additional negative charges derived from carboxyl (COO^-) and hydroxyl (OH^-) functional groups, which enhance the soil's ability to retain cations in the soil solution (Senesi and Loffredo, 2018; Boukhatem et al., 2025). The improvement of CEC in Inceptisols of Cucum and Ultisols of Jantho is particularly important because these soils have relatively low organic matter content. In addition, $CaCO_3$ application can increase the concentration of Ca^{2+} ions in the soil solution, which occupy exchange sites on the soil exchange complex and help neutralize excess Al^{3+} and H^+ ions (Iqbal, 2012). Overall, these results

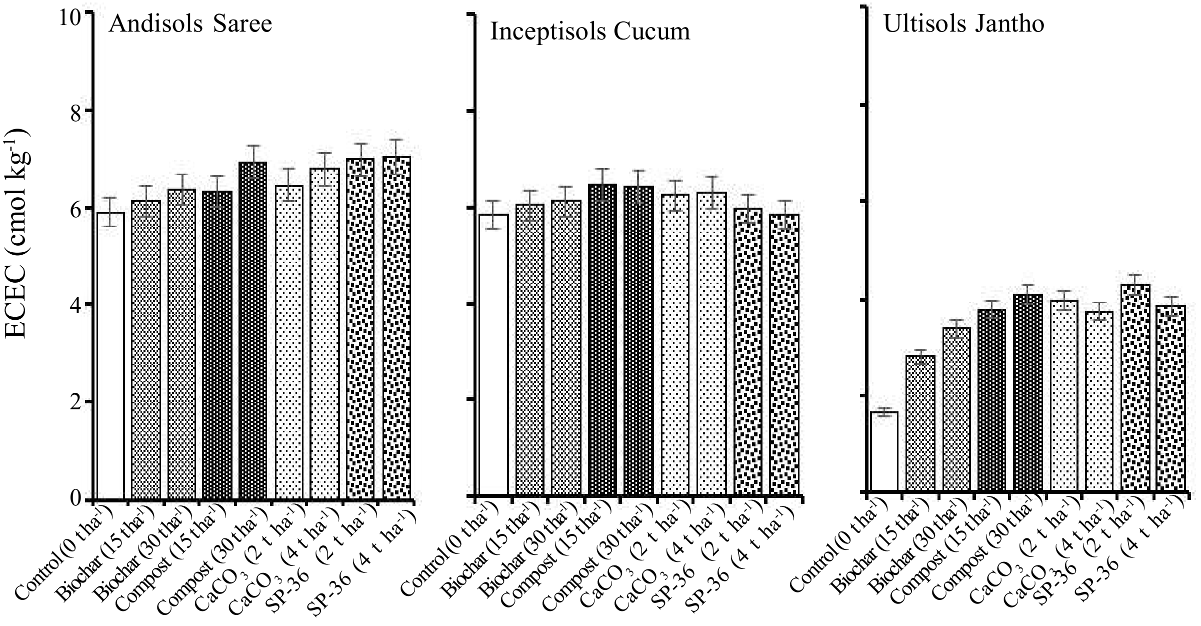

Figure 4. The values of soil ECEC of three soil orders on various amendment treatments in sub-optimal dryland.

indicate that organic amendments are more effective than lime in enhancing soil CEC by increasing the negative surface charge in variable-charge soils.

Effective cation exchange capacity (ECEC) also increased following the incubation experiment after the application of amendment materials (Figure 4). ECEC represents the sum of exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) and acidic cations (Al^{3+} and H^{+}) present on the soil exchange complex. The results showed that the three soil orders—Andisols from Saree, Inceptisols from Cucum, and Ultisols from Jantho—exhibited the highest ECEC values when compost was applied at a rate of 30 t ha^{-1}. In contrast, the lowest ECEC values were observed in the control treatment without amendments. The ECEC values of the studied soils remained relatively low, indicating that the sub-optimal dryland soils of Aceh Besar are classified as variable-charge soils with low-activity clay (LAC), characterized by ECEC values of less than 12 cmol kg^{-1}. As shown in Figure 4, the ECEC values ranged from 5.91–7.05 cmol kg^{-1} in the Andisols of Saree, 5.08–6.47 cmol kg^{-1} in the Inceptisols of Cucum, and 1.65–4.28 cmol kg^{-1} in the Ultisols of Jantho.

Soils dominated by low-activity clays are typically composed of kaolinite and hydroxides of Al and Fe, which commonly exhibit positive surface charges under acidic soil conditions and consequently result in relatively low CEC values (Li et al., 2021). In such soils, the negative charge contributing to soil CEC mainly originates from the dissociation of hydrogen ions from hydroxyl (OH) groups associated with Si and Al oxides, as well as from a small proportion of broken crystal edges. However, the charge generated from these processes contributes only a limited amount to the overall soil CEC (Ameyu, 2019; Adetunji and Blanco-Canqui, 2026). Overall, these results indicate that the low ECEC observed in the studied soils is closely related to the dominance of low-activity clay minerals typical of highly weathered tropical soils.

Overall, the results demonstrate that organic amendments, particularly compost and biochar, enhance the electrochemical properties of variable-charge soils by increasing negative surface charge and improving CEC and ECEC. This improvement provides an effective strategy to enhance nutrient retention and fertility in suboptimal tropical dryland soils.

CONCLUSIONS

The results demonstrate that organic amendments significantly improve the charge characteristics and physicochemical properties of variable-charge soils in the sub-optimal drylands of Aceh Besar, including Andisols, Inceptisols, and Ultisols. Application of compost and biochar (15–30 t ha^{-1}) combined with phosphate fertilizer (SP-36) enhanced soil pH, increased effective cation exchange capacity (ECEC), and promoted greater development of negative surface charge. These amendments also reduced soil pH_o , indicating improved charge balance in variable-charge systems. In contrast, the application of $CaCO_3$(2–4 t ha^{-1}) increased soil pH and CEC but tended to raise pH€ and reduce negative surface charge. Overall, organic amendments were more effective than $CaCO_3$ in improving the electrochemical properties of tropical variable-charge soils, suggesting their important role in enhancing soil fertility and sustainable management of sub-optimal drylands.

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