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Mitigating Potassium Leaching from Muriate of Potash in a Tropical Peat Soil Using Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar

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Abstract: Using muriate of potash (MOP) as a source of potassium (K) is a cost-effective method for crop production in tropical peat soils. However, exchangeable K commonly leaches from tropical peat soils because of high rainfall and a lack of clay to retain this cation. Potassium retention as exchangeable K could inhibit K loss through leaching to increase K availability. Clinoptilolite zeolite (CZ), forest litter compost (FLC), and chicken litter biochar (CLB) can be used to retain K from MOP in tropical peat soils for crop use because of the high affinity of CZ, FLC, and CLB for K ions. These approaches can be used as innovative and sustainable alternatives for the frequently used lime ($CaCO_3$). However, information on using CZ, FLC, and CLB for MOP K retention is limited. Thus, CZ, FLC, and CLB were tested in a leaching study to determine their effects on MOP K retention in tropical peat soil. The use of CZ and FLC at rates of 100% and 75% of the recommended rate for pineapple cultivation (a commonly grown fruit crop in tropical peat soils in Malaysia) improved the K availability, pH, and CEC of the peat soil because of the high CEC of CZ and the humic substances (humic acids, fulvic acids, and humin) of FLC, which have a high affinity for K ions. The CLB did not improve K retention because of the competition between K, Ca, Mg, and Na ions, which are inherently high in this soil amendment. Instead of liming, which only replaces a few of the leached cations, such as calcium, the results of this study suggest an alternative method of retaining peat cations, such as K, that reduce peat acidity. This alternative method of retaining peat soil cations, especially K ions, is a practical and sustainable approach for improving peat soil productivity.

Keywords: acidic soils; organic soils; biochar; compost; organic amendments; potassium loss; zeolites; clay

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1. Introduction

Tropical peat soils are high in organic matter and provide nutrients for crops through their decomposition to produce, for example, ammonium nitrate, phosphate, and sulfur. However, tropical peat soils are not suitable for most plant growth and development because of their acidic nature [1]. For example, peat soils in Sarawak, Malaysia have low pH levels (3.5–4.0) [2]. As such, they are not able to retain significant amounts of macro-and micronutrients. Additionally, excessive rainfall and the porous nature of peat cause the leaching of plant nutrients, such as K ions. Furthermore, the leaching of most of these plant nutrients in peat soils is due to low levels or the absence of clay, which holds cations in deep peat soil. Clay has a large specific surface area with predominantly negatively charged exchange sites that adsorb and retain nutrients against leaching. These negative charges also react with H^+ and Al^{3+} ions to create a buffering condition against extreme pH changes. A lack of clay to glue peat soil particles in a manner that improves the water holding capacity and retention of positively charged plant nutrients is one of the reasons for the leaching of nutrients in peat soils. A lack of clay in tropical peat soils causes porosity. The porous nature of tropical peat soils makes them prone to the leaching of their nutrients, especially K ions. In addition, high rainfall and a weak attraction between K ions and organic matter accelerate K leaching [3]. These are among the reasons why it is difficult to build K in tropical peat soils for plant growth. Furthermore, K-bearing minerals are nearly absent in tropical peat soils.

After N and P, K is one of the essential nutrients that is used in large amounts by plants [4] because it is necessary for photosynthesis, protein synthesis, stomatal movement, and osmoregulation [5–7]. Potassium deficiency affects plant growth and development. One of the indicators of K deficiency is scorching of the leaf margins in older plant leaves [8]. The forms of potassium that exist in soils are unavailable K, available or fixed K, readily available or exchangeable K, and water-soluble K [9]. Nawaz et al. [10] reported that K leaching depends on the soil texture, pH, and the availability of K in soils. Although K leaching from the soil system does not have a serious negative impact on the environment as compared to N and P, K leaching can cause economic loss and waste agricultural inputs. Therefore, sustainable K management in agriculture is essential for promoting sustainable agriculture [11]. The approaches by which K retention can be achieved include using slow-release K fertilizers [12] or using a mineral adsorbent, for example, clinoptilolite zeolite (CZ) or organic amendments, such as composts.

CZ can be used as an adsorbent for cation retention because of its unique features, including crystalline, nanoporous hydrated aluminosilicates of alkali or alkaline earth metals arranged in a three-dimensional rigid crystalline system and framed by the tetrahedral AlO_4 and SiO_4, which meet to form a frame of canals, cavities, and pores [13]. Moreover, the unique ion exchange, dehydration–rehydration, adsorption, and catalytic properties of CZ enable it to control the release of K for plant uptake [14,15]. According to Ashman and Puri [16], CZ improved soil pH and plant productivity because of its high ion exchange capacity and significant adsorptive affinity of this mineral for water and K ions. Perez-Caballero et al. [17] opined that zeolites are a group of highly crystalline hydrated aluminosilicates minerals, which, when dehydrated, develop a porous structure with small pores that selectively absorb molecules based on their size.

Apart from mineral adsorbent, organic amendments, such as compost and biochar, can be applied to retain K from MOP (KCl) in tropical peat soil [18,19]. The results of one study showed that compost applied to tropical peat soil increased soil CEC because it helps to retain cations, including K [20]. The organic matter of composts is negatively charged because of the high contents of carboxylic, alcoholic, and phenolic functionals groups of humic substances, such as fulvic acid, humic acid, and humin. These functional groups combine to form humic and fulvic acids, which bind insoluble metal ions, oxides, and hydroxides and then release them timely for plant uptake [21]. Humic acids, for example, physically alter and improve the soil structure, resulting in soil moisture, soil aeration, water retention, and plant nutrient availability [22]. In the present study, we used forest litter compost (FLC) and chicken litter biochar (CLB) in an attempt to retain K from MOP. The FLC was produced from forest debris and the biochar was produced from chicken litter. According to Maru et al. [23], the inclusion of FLC in urea fertilization enabled exchangeable ammonium retention to minimize the loss of N via volatilization. It is worth noting that the movement of ammonium ions is similar to that of K ions. The CLB used in this study was a mixture of chicken excreta, feathers, feed spillage, straw, and sawdust, which were pyrolyzed up to 600 °C [24]. Chicken litter biochar contains essential plant nutrients, such as magnesium, calcium, sulfur, N, P, iron, manganese, and K [25]. Guo et al. [26] showed that CLB not only improves soil nutrient retention to prevent nutrient leaching from the soil system but it also improves soil pH.

In spite of the fact that the literature is replete with the positive roles of CZ, FLC, and CLB in nutrient management in agriculture and organic soils, such as tropical peat soils, the optimal use of CZ, FLC, and CLB in conjunction with K fertilizer, such as MOP, has scarcely been explored. In this study, it was hypothesized that the right amount of CZ, FLC, and CLB used on tropical peat soils can provide more negative charges in these soils to temporarily hold K ions from MOP in a manner that these ions are released timely for optimum crop use. The pertinent research questions of the present study are as follows: (i) How should CZ, FLC, and CLB be used to retain K from MOP fertilization in tropical peat soil? (ii) What optimum amounts of CZ, FLC, and CLB should be used to retain K from MOP? In line with the aforementioned research hypothesis and questions, the objective of the present study was to determine the optimum amounts of CZ, FLC, and CLB that can be used to improve the retention of K from MOP in tropical peat soils. A study of this kind on K availability using soil amendments such as CZ, FLC, and CLB is essential for determining the ability of tropical peat soils to respond to MOP K fertilization because it is the most used K fertilizer in the world. We used CZ, FLC, and CLB in an attempt to delay K loss from MOP in a tropical peat soil system. With the retention of K ions from MOP fertilization following the use of CZ, FLC, and CLB at optimum amounts, the leaching loss of K was minimized. This study also provided information on K availability from the combined use of different amounts of MOP, CZ, FLC, and CLB, which was reflected by the amount of K in the leachate (soil solution), the total soil K, and the exchangeable soil K retained in tropical peat soils. This approach reduces the effects of the unbalanced or excessive use of fertilizers on the environmental quality. Moreover, the temporary nutrient retention properties of CZ, FLC, and CLB were exploited in the fertilization regimes on peat soils. The information obtained from this study contributes to the understanding of fertilizer management of tropical peat soils, especially K fertilizers. It must be stated that this study is limited to the laboratory as exploratory research.

2. Materials and Methods

2.1. Peat Soil Sampling

Peat soil samples were collected from the Sarawak Oil Palms Plantation at Miri Sarawak, Malaysia, (4°05′51.2″ N, 113°58′54.3″ E). The peat soil samples were taken at a depth of 0 to 25 cm using a peat soil auger. They were then air-dried and ground to pass through a 2 mm sieve for the initial physico-chemical characterization.

2.2. Selected Properties of Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar

The selected physico-chemical properties of the CZ, FLC, and CLB used in this present study are presented in Table 1. The selected physico-chemical of CZ (Table 1) are typical of CZ [27]. The production of FLC and CLB and their analyses presented in Table 1 were carried out by Palanivell et al. [28] and Maru et al. [22]. The selected properties of the CLB used in the present study, as reported by Palani et al. [28], are a high CEC, and high levels of K and calcium (Table 1).

2.3. Initial Characterization of Tropical Peat Soil

The pH and electrical conductivity (EC) of the peat soil were determined at a ratio of 1:10 (peat soil/distilled water) suspension using a digital pH meter [29] (SevenEasy pH, Mettler-Toledo GmbH, Greifensee, Switzerland) and an EC meter (SevenEasy Conductivity, Mettler-Toledo GmbH, Greifensee, Switzerland). The peat soil CEC was determined by leaching the soil with 1 M ammonium acetate buffer adjusted to a pH of 7, followed by leaching with 0.1 M potassium sulfate and the steam distillation technique [30]. Exchangeable K was extracted using the double acid method [31], and the concentration was determined using atomic absorption spectrophotometry (AAS) (Analyst 800, Perkin Elmer, Norwalk, CT, USA). The total K of the peat soil was extracted using the single dry ashing method [32] and the concentration was determined using AAS. The organic matter and total carbon contents of the peat soil were determined using the loss on ignition method [33].

Table 1. Selected physico-chemical properties of clinoptilolite zeolite, forest litter compost, and chicken litter biochar.

Property	Clinoptilolite Zeolite	Forest Litter Compost	Chicken Litter Biochar
pH	8.20	8.52	9.54
EC (mS cm^{-1})	0.13	nd	3.50
CEC (cmol(+) kg^{-1})	71	79.33	59.27
(%)			
Total N	0.22	0.27	2.39
Total P	0.01	0.75	4.52
Total K	0.37	2.67	6.05
Total Ca	0.67	nd	4.80
Total Mg	0.10	1.24	1.77
Total Na	0.76	nd	1.75
Total Fe	0.11	nd	0.49
Organic Matter	nd	89.00	71.67
(mg kg^{-1})			
Total Zn	15	nd	772
Total Mn	17	nd	1479
Total Cu	125	nd	264

nd = not determined.

2.4. Leaching Study

The 300 g of the peat soil used for each treatment in this leaching study was measured based on the bulk density of the peat soil. The rates of MOP, CZ, FLC, and CLB are summarized in Table 2. The rate of MOP used was based on the pineapple (*Ananas comosus*) cultivation requirement per hectare (556.56 kg MOP ha^{-1}). The pineapple planting density (44,444 plant ha^{-1}) and its fertilizer requirements were used to scale down the MOP rate to usage per pot. Peat soil only (S0) was used as a control to determine the losses of K from the peat soil throughout the 30 days of leaching, whereas SK (Soil + MOP) was used to obtain the amount of K leached from the MOP for 30 days without the addition of CZ. The inclusion of CZ in SZ1, SZ2, SZ3, and SZ4, FLC in SC1, SC2, SC3, and SC4, and CLB in SB1, SB2, SB3, and SB4 were compared to obtain the optimum amounts of the amendments used to retain K from the MOP used (Table 2). The amounts of CZ, FLC, and CLB in SZ2, SZ3, SZ4, SC2, SC3, SC4, SB2, SB3, and SB4 were reduced by 25%, 50%, and 75%, respectively, from the standard recommendation of the amendments used for pineapple cultivation in tropical peat soils.

The peat soil and amendments were mixed thoroughly, and the mixture was kept in transparent polypropylene containers before the leaching experiment commenced. Distilled water (230 mL) was sprayed into each pot with the peat soil every five days. The volume of water applied was based on rainy days over 30 days. Five years (2015–2019) of rainfall data was obtained from the Malaysian Meteorological Department, and the average amount of rainfall per month was used. The pH and total K in the peat soil leachates were analyzed using a digital pH meter and AAS, respectively. The leaching study was set up as shown in Figure 1.

2.5. Experimental Design and Statistical Analysis

The leaching study was arranged in a completely randomized design (CRD) with three replications. The data obtained were analyzed statistically using analysis of variance (ANOVA) to detect treatment effects, and the treatment means were compared using Tukey's Test ($p < 0.05$). The statistical software used was Statistical Analysis System (SAS) version 9.3.

Table 2. Treatments evaluated in the leaching experiment.

Treatment Codes	Peat Soil (g)	Clinoptilolite Zeolite (g)	Forest Litter Compost (g)	Chicken Litter Biochar (g)	MOP (g)
S0	300	-	-	-	-
SK	300	-	-	-	1.78
SZ1	300	7.7	-	-	1.78
SZ2	300	5.8	-	-	1.78
SZ3	300	3.9	-	-	1.78
SZ4	300	1.9	-	-	1.78
SC1	300	-	4.82	-	1.78
SC2	300	-	3.62	-	1.78
SC3	300	-	2.41	-	1.78
SC4	300	-	1.21	-	1.78
SB1	300	-	-	4.82	1.78
SB2	300	-	-	3.62	1.78
SB3	300	-	-	2.41	1.78
SB4	300	-	-	1.21	1.78

Note: S0: soil only; SK: soil with MOP only; SZ1: 100% clinoptilolite zeolite; SZ2: 75% clinoptilolite zeolite; SZ3: 50% clinoptilolite zeolite; SZ4: 25% clinoptilolite zeolite; SC1: 100% forest litter compost; SC2: 75% forest litter compost; SC3: 50% forest litter compost; SC4: 25% forest litter compost; SB1: 100% chicken litter biochar; SB2: 75% chicken litter biochar; SB3: 50% chicken litter biochar; SB4: 25% chicken litter biochar.

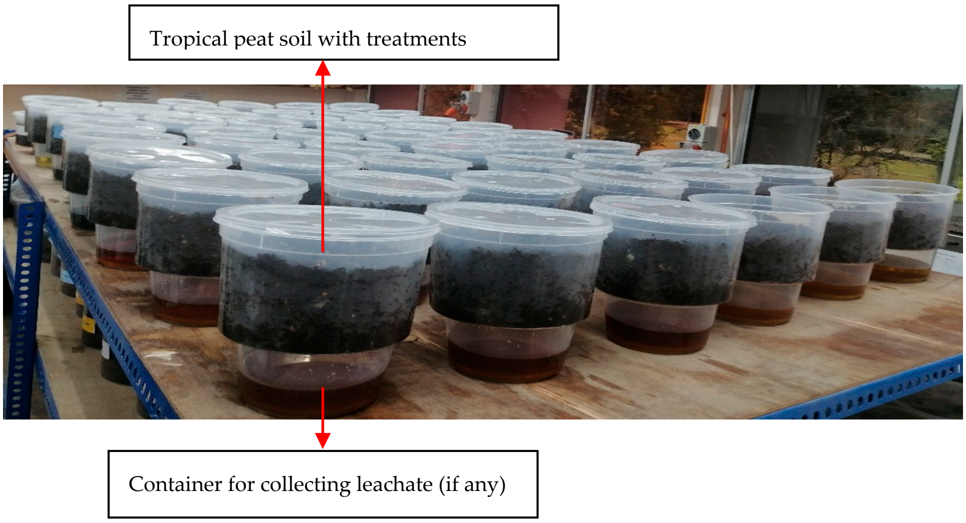


Figure 1. Setup of the leaching study.

3. Results and Discussion

3.1. Selected Physico-Chemical Properties of Tropical Peat Soil

The selected physico-chemical properties of the tropical peat soil used in this present study are presented in Table 3. The peat soil used throughout this laboratory experiment was Saprists. Tropical peat soils are categorized based on the stage of decomposition; saprists represent a high stage of decomposition, followed by hemists and fibrists [34]. The selected chemical properties of the tropical peat soil used in this study were consistent with those reported by Hikmatullah and Sukarman [35]. The organic matter (91.78%) of the tropical peat soil approximated that reported by Afip and Jusiff [36]. The peat soil was acidic, with a pH of 3.82, due to its organic matter content [37] because organic matter is high in carboxyl and phenolic hydroxyl groups. These function groups affect the acidity of tropical peat soils. Organic matter humification releases insoluble and soluble products that contain substituted radicals such as -COOH, phenol-OH, alcohol-OH, -NH_2, and quinones. The release of hydrogen ions from carboxyl and hydroxyl groups increases the acidity of tropical peat soils. The soil exchangeable K in this study was consistent with the value reported by Hikmatullah and Sukarman [35]. The total organic carbon and organic matter contents recorded were comparable to those reported by Afip and Jusiff [36] and Melling et al. [37].

Table 3. Selected physico-chemical properties of a tropical peat soil.

Variable	Data Obtained (0–25 cm)	Standard Data Range *
pH in water	3.82 ± 0.09	3.6
Electrical conductivity (µS/cm)	160.47 ± 0.3	159.8–358
Cation exchange capacity (cmol (+)/kg)	55.33 ± 3.6	68
	(cmol kg^{-1})	
Total soil K	0.53 ± 0.005	nd
Exchangeable K	0.12 ± 0.007	0.12
Total soil Ca	3.7 ± 0.05	nd
Exchangeable Ca	1.11 ± 0.02	2.55
Total soil Mg	5.72 ± 0.13	nd
Exchangeable Mg	1.06 ± 0.03	1.24
	(%)	
Organic matter	94.27 ± 3.7	nd
Total organic carbon	54.68 ± 2.1	nd

Note: nd = not determined; * standard data range reported by Hikmatullah and Sukarman [35], Afip and Jusiff [36], and Melling et al. [37].

The initial characterization of the peat soil demonstrated that the pH, exchangeable K, and Mg were in a similar range as those of the standard data range. However, the cation exchange capacity and exchangeable Ca of the obtained results were lower than those of the standard data range. This was due to the continued leaching of Ca caused by high rainfall. This process also reduces peat soil CEC. The electrical conductivity and total soil K, Ca, and Mg appear to be higher because there were no values reported for the standard data range. CEC is the measure of the ability of peat soil to adsorb exchangeable cations that are mainly available to plants. In addition, CEC determines how peat soils will resist the leaching of nutrients during peat decomposition. The CEC of peat soil is pH-dependent; however, that of natural peat may have CEC values as low as 50 cmol kg^{-1}. Cation exchange capacity values of peat are high but they vary between species and degrees of decomposition. Sedge peat has a lower CEC than Sphagnum peat. Highly decomposed black peat with a high proportion of humic acids has the highest value. The high CEC pf peat soil suggests that it has a good capacity to store cationic nutrients for plants. However, by contrast, the anion exchange capacity of peat soil is very low, suggesting that unlike in most soils, phosphate can easily be leached from peat growing media. In general, the pH of raw peat (untreated, as harvested from a bog) ranges from 3.5 to 4.1, confirming the levels reported for this initial characterization.

3.2. Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar on pH of Leachate and Peat Soil after Thirty Days of Leaching

The initial peat soil pH was less than 4. However, after amending the soils with the treatments, the pH of the leachates on Day 5 suggested that the SZ1 leachate pH was higher, followed by SZ2, SZ3, SZ4, S0, and SK (Figure 2). A similar pattern of pH was observed on Days 10, 15, 20, 25, and 30, although the leachate pH increased with progressing days of leaching (Figure 2). Higher pH levels of the leachates for SZ1, SZ2, SZ3, and SZ4 were due to higher base cations of their CZ (Figure 2) because the pH of the leachates increased with the increasing rate of CZ. The addition of CZ partly increased the soil pH because of its Ca, Mg, K, and Na [38]. Polat et al. [39] stated that CZ is not acidic but marginally alkaline, and its use with fertilizers enhances the soil buffering capacity, thus reducing the need for liming. Ming and Boetingger [40] also observed an increase in the soil pH with the application of CZ. The leaching of cations, such as Na, Mg, and Ca, explains the peat soil's lower pH without CZ (SK) (Figures 2 and 3).

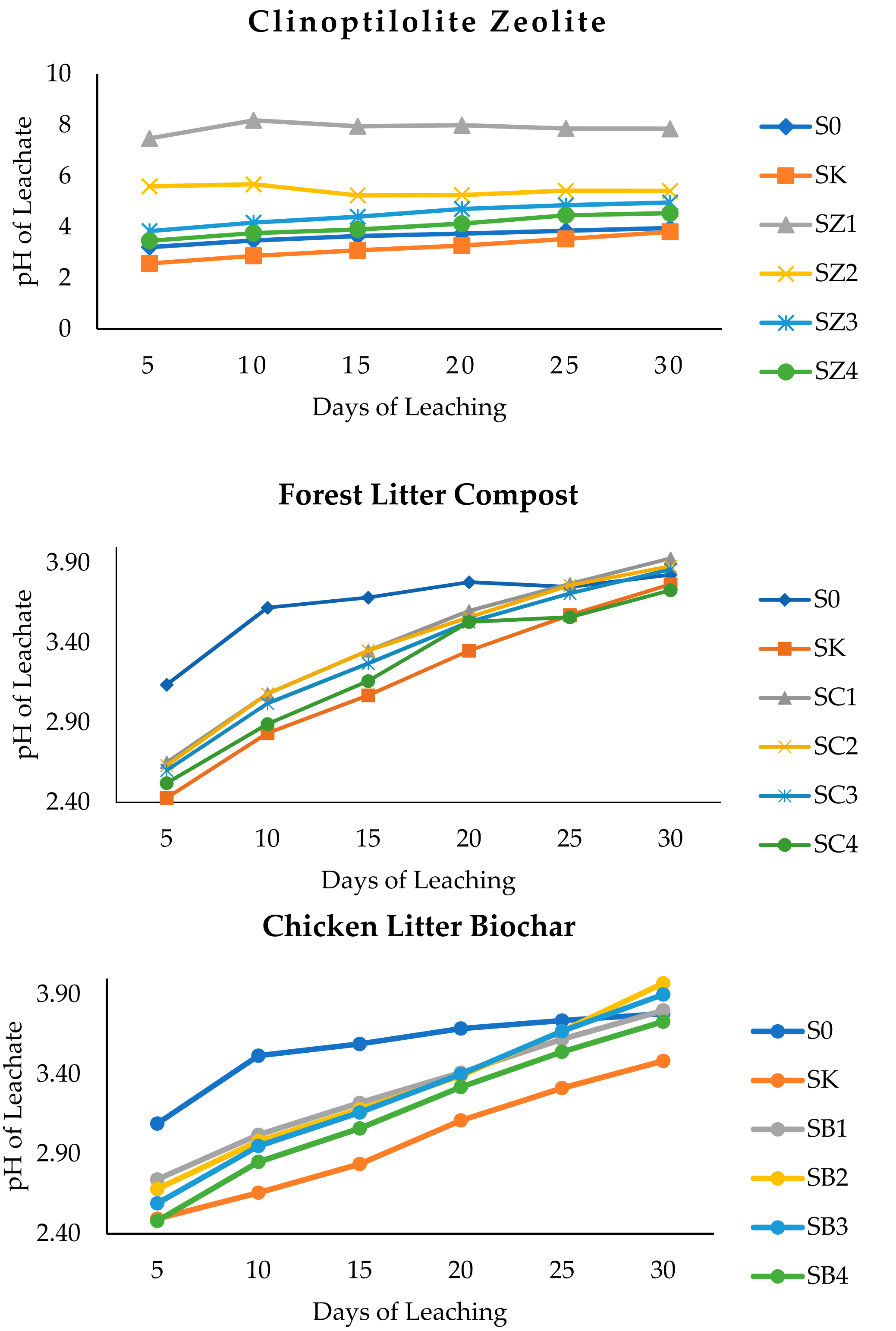


Figure 2. The pH levels of leachate from peat soils with clinoptilolite zeolite, forest litter compost, and chicken litter biochar.

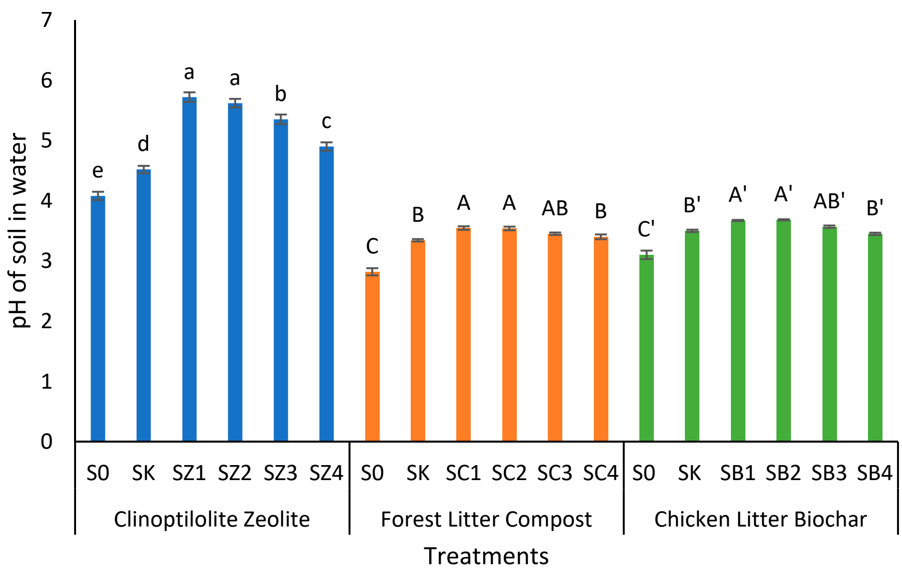


Figure 3. The pH levels of a tropical peat soil with clinoptilolite zeolite, forest litter compost, and chicken litter biochar after thirty days of leaching. Means between columns with different letter(s) indicate significant differences between treatments by Tukey's test at $p < 0.05$. Bars represent the mean values ± SE. Small letters, capital letters, and capital letters with indicate mean comparisons of clinoptilolite zeolite, forest litter compost, and chicken litter biochar, respectively.

A different pattern of pH was observed when the peat soil was amended with a well-composted forest litter. The pH levels of the leachates for SK, SC1, SC2, SC3, and SC4 were lower than those of S0 on Days 5, 10, 15, and 20 (Figure 2). The pH levels of SK, SC1, SC2, SC3, and SC4 increased with progressing days of leaching and were similar to those of S0 on Day 25 and 30 (Figure 2). Generally, the FLC did not increase the pH of the leachate compared to soil only (Figure 2). This was due to the low base cations of the FLC. It is also possible that some of the base cations were adsorbed by the FLC to prevent them from being leached because of its high content of humic substances, unlike CZ, which is a mineral and not organic. However, with progressing days of the leaching study, the release of the base cations increased because of the mineralization of FLC to increase the leachate pH of SC1, SC2, SC3, and SC4 (Figure 2).

The results of using CLB as a peat soil amendment were not different from those of using FLC. The pH levels of the leachates for SK, SB1, SB2, SB3, and SB4 were lower than those of S0 on Days 5, 10, 15, 20, and 25 (Figure 2). The pH levels of SK, SB1, SB2, SB3, and SB4 increased with progressing days of leaching and were similar to that of S0 on day 30 (Figure 2). Generally, the effects of CLB on the peat soil leachate pH levels were similar to those of the FLC, although it did not increase the pH of the leachate as compared to soil only (Figure 2). This was due to the low base cations of CLB compared to CZ, and some of the base cations were adsorbed by CLB to prevent them from being leached because of its high content of humic substances similar to those of FLC. However, with increasing days of the leaching study, the release of the base cations increased because of the mineralization of CLB to increase the leachate pH levels of SB1, SB2, SB3, and SB4 (Figure 2).

Generally, the peat soils amended with CZ had higher pH values of leachate than those with composted forest litter and CLB (Figure 3). This was partially due to the higher cation contents of the CZ than that of the composted forest litter and CLB (Figure 3). This could also indicate that the composted forest litter and CLB retained the leaching of more cations compared to that of CZ, or that the CZ was leaching its excess cations into the solution, thereby increasing the leachate pH levels (Figure 3). After 30 days of leaching, the results indicate that the CZ, FLC, and CLB increased the peat soil pH. However, the pH levels of the soils amended with CZ were significantly higher than those of the composted forest litter and CLB soils (Figure 3).

3.3. Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar on Cation Exchange Capacity of Peat Soil after Thirty Days of Leaching

The analysis of the soils with CZ revealed that the CEC of SZ1 was similar to those of SZ2, SZ3, and SZ4 but significantly higher than those of S0 and SK (Figure 4). The higher amount of CZ in SZ1 increased the exchange site of the soil to increase its CEC. This finding is consistent with that of Perez-Cabellora et al. [17]. The higher soil CEC with CZ is attributed to the higher number of channels in the CZ, which are responsible for selective cation exchange [41]. Different observations were made when composted forest litter was used as the soil amendment. The cation exchange capacities of SC1, SC2, SC3, and SC4 were similar but significantly higher than those of S0 and SK (Figure 4). Although treatments with CZ did not significantly increase the soil CEC than those with FLC (Figure 4), the CEC of their respective control varied in value, causing a distinct difference in treatment. The higher CEC of the peat soils with FLC was partly due to the accumulation of organic matter, which enabled the peat soils to retain the base cations [42]. Similar observations were made when CLB was used as the soil amendment. After 30 days of leaching, the soil CECs of the CLB (SB1, SB2, SB3, and SB4) were significantly higher compared to that of SK (Figure 4). The increased CEC of the tropical peat soil with CLB was due to an increase in the net charges of the biochar surface, which are able to attract more cations [43]. The slow oxidation of biochar increased the number of carboxylic, phenolic, alcoholic, and functional groups, resulting in an increase in the CEC of the soil with CLB [44]. Generally, amending tropical peat soil with CZ, FLC, and CLB increased the CEC of the peat soil (Figure 4). The high pH levels and CECs of these amendments increased the pH levels and CECs of the peat soils. The ability of these amendments to increase the soil pH and CEC is related to their alkaline substances, surface properties, and the ability to reduce exchangeable acidic cations, such as Al^{3+}, Fe^{2+}, and H^{+}. Soil CEC can also be defined as the total negative charges of a soil to adsorb cations. In the present study, the FLC and CLB were rich in humic substances, such as humic and fulvic acids, which are known to have a large molecular structure dominated by carboxylic, phenolic, and alcoholic functional groups. Their functional groups become negatively charged under alkaline conditions to increase the soil CEC. On the other hand, CZ is naturally highly negatively charged at its exchange complexes and this property contributes to the soil CEC.

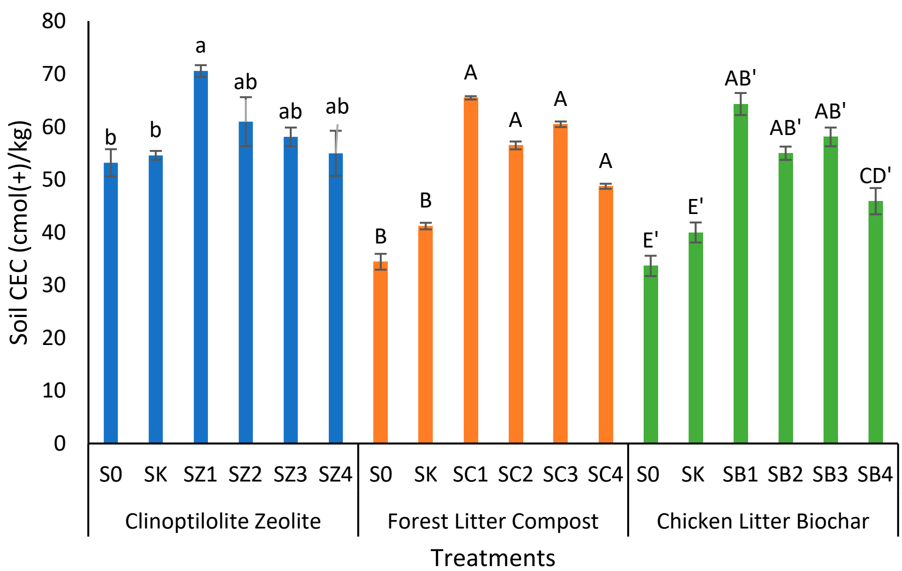
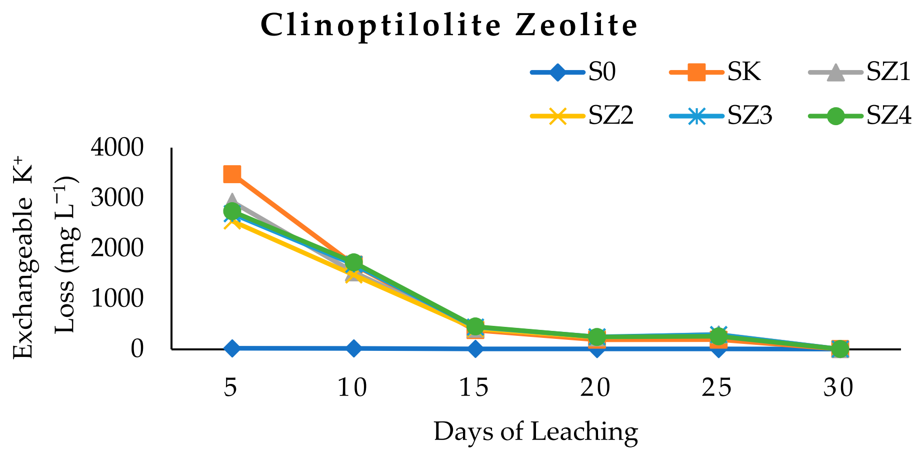


Figure 4. Cation exchange capacity of a tropical peat soil with clinoptilolite zeolite, forest litter compost, and chicken litter biochar after thirty days of leaching. Means between columns with different letter(s) indicate significant differences between treatments by Tukey's test at $p < 0.05$. Bars represent the mean values ± SE. Small letters, capital letters, and capital letters with indicate mean comparisons of clinoptilolite zeolite, forest litter compost, and chicken litter biochar, respectively.

3.4. Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar on Exchangeable K of Leachate after Thirty Days of Leaching

Potassium leached in the first 5 days in S0 was high, and then it declined from Day 10 to Day 20 (Figure 5). The lower exchangeable K concentration of S0 confirms its low levels of available K of peat soil. The exchangeable K leached from the SK peat soil on Day 5 was higher than from SZ1, SZ2, SZ3, and SZ4 but similar on Days 10, 15, 20, 25, and 30 (Figure 5). The potassium loss from the SK (treatment without CZ) from Day 5 to Day 30 was higher than the K loss from SZ1, SZ2, SZ3, and SZ4 (treatments with CZ) because there was no CZ to hold the K in the SK (Figure 5). The cumulative concentrations of K leached over 30 days were the highest SK (Figure 6). The absence of MOP in S0 was associated with a lower amount of K leached (Figure 6). In a related study, Ahmed and Liza [45] reported similar observations of K retention of a tropical peat soil, which was amended with CZ in pineapple cultivation. Ahmed and Liza [45] attributed the low recovery rate of K in pineapple cultivation on tropical peat soil (28.22%) to the leaching of K because of low clay levels and high rainfall. Potassium, which exists as solution K, is mobile and prone to leaching, thus contributing to K deficiency in organic soils [46]. Syed Omar et al. [47] also observed lower K concentrations in the leachate of a soil with CZ; this is possibly due to the high affinity of CZ for K^+.



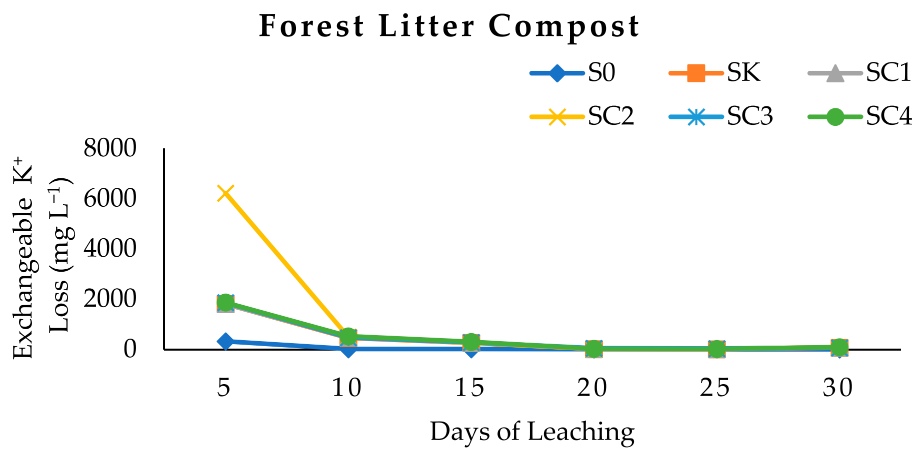


Figure 5. *Cont.*

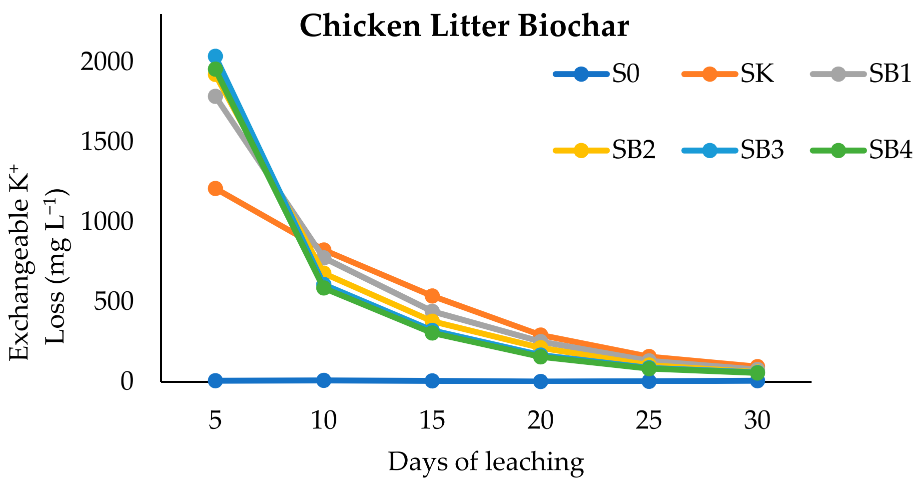


Figure 5. Potassium concentration in leachate with clinoptilolite zeolite, forest litter compost, and chicken litter biochar.

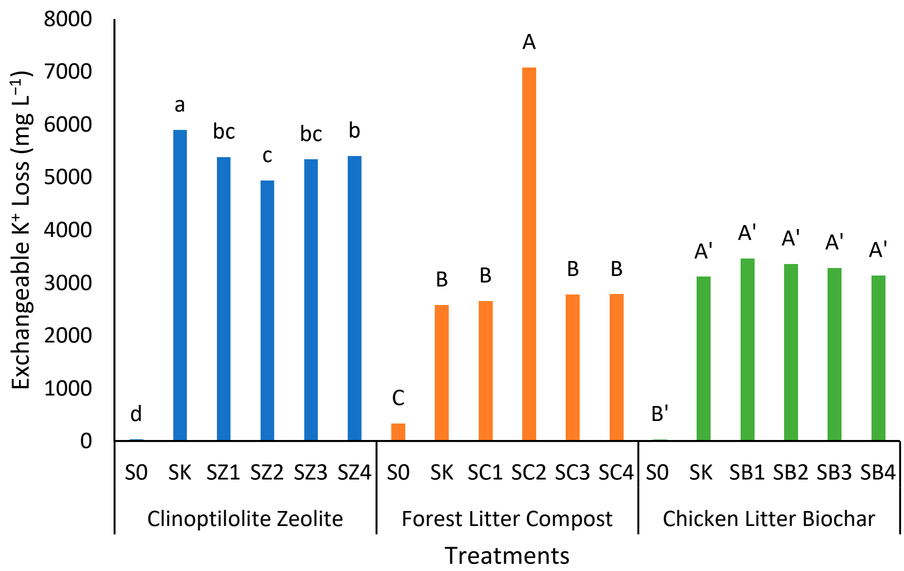


Figure 6. Cumulative concentrations of potassium in leachate for clinoptilolite zeolite, forest litter compost, and chicken litter biochar. Means between columns with different letter(s) indicate significant differences between treatments by Tukey's test at $p < 0.05$. Small letters, capital letters, and capital letters with indicate mean comparisons of clinoptilolite zeolite, forest litter compost, and chicken litter biochar, respectively.

Potassium loss from the soils with all treatments except for SC2 was highest on Day 5, after which a declining trend was observed on Days 10, 15, and 20 (Figure 5). The cumulative concentrations of K leached over 30 days were highest for SC2 (Figure 6). This suggests that FLC applied at 75% of the standard recommended usage amount was not effective for retaining K from MOP. The decrease of K in the leachates was due to the fact that some of these ions were leached from the soil. Unlike the findings on the use of CZ and FLC, the CLB in SB1, SB2, SB3, and SB4 did not significantly improve K ion retention. This is observable in Figure 6. Exchangeable potassium loss from SB1, SB2, SB3, and SB4 was higher compared to that of SK (treatment with MOP) on Day 5 of leaching (Figure 5). A decreasing trend of potassium loss was observed for all treatments except S0 on Days 10, 15, 20, 25, and 30. There were no significant differences in the cumulative concentrations of K leached over 30 days for SK, SB1, SB2, SB3, and SB4 (Figure 6). According to Hoskins [48], there is usually an inverse and adverse relationship between a high concentration of one cation in the soil and the availability and uptake of other cations by plants. That is, if Ca and/or Mg dominate the exchange complex over K, it may reduce K availability. This implies that K availability does not solely depend on the K content of soils but also depends on the relative amounts of other cations (Ca, Mg, and K).

3.5. Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar on Exchangeable and Total Potassium of Peat Soil after Thirty Days of Leaching

After thirty days of leaching, exchangeable K in the peat soil with SZ1 and SZ2 were similar but significantly higher than those with SZ3, SZ4, SK, and S0 (Figure 7). Exchangeable K for the SZ4 and SK soils were similar and lower than that of SZ3 (Figure 7). The exchangeable K levels of the S0 peat soil after thirty days of leaching was the lowest, confirming the findings for the leachate. Additionally, the total K in the peat soil after thirty days of leaching further suggests that SZ1 had the highest amount of total K, followed by SZ2 and SZ3 (Figure 8), and confirms that peat soils are generally low in K (Figure 7). The total K contents of SK and SZ4 were similar (Figure 8), confirming the contents of exchangeable K (Figure 7).

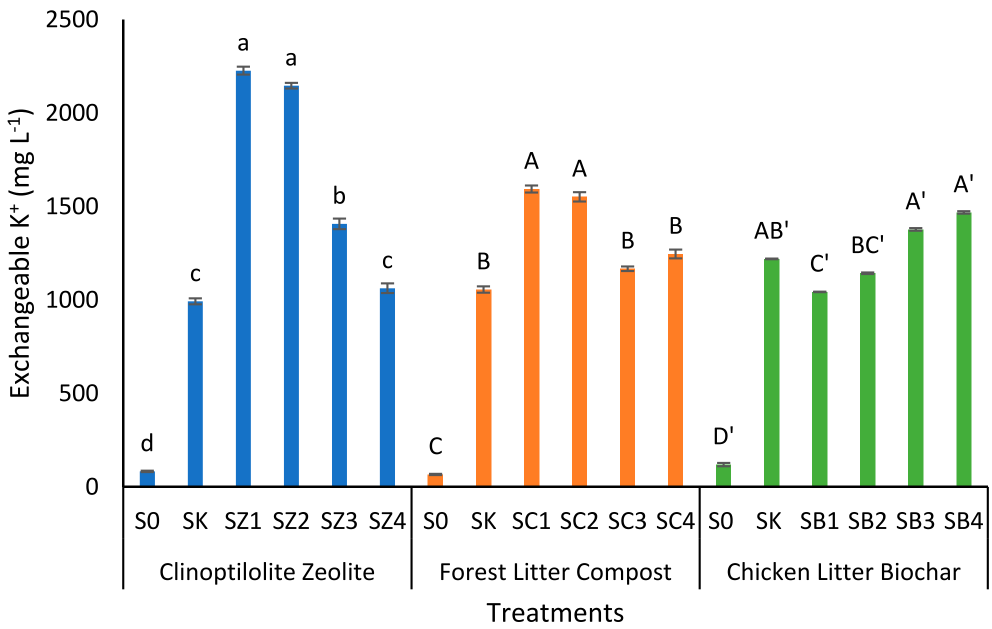


Figure 7. Exchangeable potassium of a tropical peat soil with clinoptilolite zeolite, forest litter compost, and chicken litter biochar after thirty days of leaching. Means between columns with different letter(s) indicate significant differences between treatments by Tukey's test at $p < 0.05$. Bars represent the mean values ± SE. Small letters, capital letters, and capital letters with indicate mean comparisons of clinoptilolite zeolite, forest litter compost, and chicken litter biochar, respectively.

In a related study in which a soil was amended with CZ, Rabai et al. [49] reported an increase in the concentrations of exchangeable K and total K in the soil. In the present study, the higher amount of CZ (100%) in SZ1 produced the highest concentration of exchangeable K and total K compared to the soil with CZ of 75% (SZ2), 50% (SZ3), and 25% (SZ4) of the recommended usage amount of MOP (SK) (Figures 7 and 8). This was due to the fact that CZ has a high affinity for K ions. According to Jakkula and Wani [50], CZ gets recharged to prevent free nutrients from leaching when K sources become available either naturally or applied as an external input in farming systems. In a related study, it was reported that CZ is capable of adsorbing nutrients from K fertilizers to minimize K ions from leaching [51]. Clinoptilolite zeolite has large internal and external surfaces and a high CEC because of its negative charges resulting from isomorphic substitution in the crystal structure and surface chemistry of CZ, which resembles that of smectite clays [51]. This unique property of CZ improved the K retention in the soil to minimize K ions from being leached.

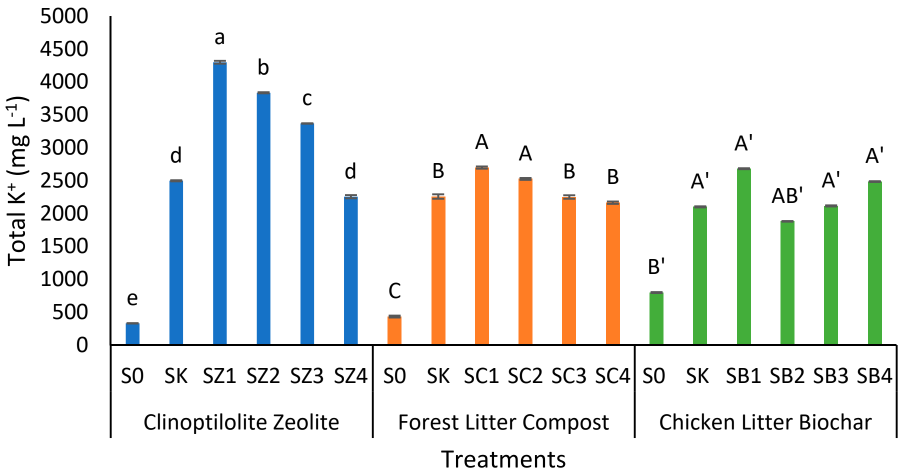


Figure 8. Total potassium of a tropical peat soil with clinoptilolite zeolite, forest litter compost, and chicken litter biochar after thirty days of leaching. Means between columns with different letter(s) indicate significant differences between treatments by Tukey's test at $p < 0.05$. Bars represent the mean values ± SE. Small letters, capital letters, and capital letters with indicate mean comparisons of clinoptilolite zeolite, forest litter compost, and chicken litter biochar, respectively.

The exchangeable K and total K of the tropical peat soil were higher with FLC applied at 100% (SC1) and 75% (SC2) than without FLC (SK) (Figures 7 and 8). However, the application of FLC at 50% (SC3) and 25% (SC4) of the recommended FLC levels did not significantly improve K retention from MOP (Figures 7 and 8). Treatments SC1 and SC2 had sufficient amounts of humic and fulvic acids [21] to retain K ions in the soil. Humic substances were reported to increase the CEC and pH of soils [52]. Increases in the pH increased the ability of humic substances to bind cations, including K. This explains the high concentration of K for treatments with FLC (SC1 and SC2) than without FLC (SK).

Unlike the findings on the use of CZ and FLC, the CLB in SB1, SB2, SB3, and SB4 did not significantly improve K ion retention. (Figures 7 and 8). The CLB had no effect on K retention because of the competition between K, Ca, Mg, and Na ions. These cations are high in the CLB. The rapid release of nutrients from CLB caused the leaching of K from the soil [53]. A high content of K and other cations were released following the mineralization of CLB; the released K, in particular, appeared to be leach rapidly from the soil. This explains the high concentration of K in leachates of the SB1, SB2, SB3, and SB4 soils (Figures 5 and 6). Most cations are available within a pH range of 6.5 and 7.5. The low pH levels of SB1, SB2, SB3, and SB4 (Figure 3) affected the availability of exchangeable K in SB1, SB2, SB3, and SB4 (Figure 7).

4. Conclusions

In addition to their organic acids, peat soils are acidic because of the high leaching of base cations, especially K. Over the years, liming has been a temporal solution in increasing plant yield. However, this practice is not sustainable because the use of $CaCO_3$, for example, does not cause the retention of cations and it also replaces some of the cations. The replaced cations are often leached during heavy rainfall. In the search for an alternative and sustainable solution, the results of this study suggest that using CZ and FLC at 100% and 75% of the recommended rate for pineapple cultivation improved the K availability, pH, and CEC of the tropical peat soil. Co-application of MOP and CZ of MOP and FLC at 100% and 75% improved K availability because the high CEC and humic substances of these amendments have a high affinity for K ions. The results of this study provide an alternative method of retaining some peat cations, such as K, which will reduce peat acidity. This is an alternative to liming, which only replaces a few of the leached cations, such as calcium. This method of retaining peat soils cations, especially K, is a practical and sustainable way to improve peat soil productivity. However, further studies are essential to consolidate the findings of the present study.

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Abbreviations

MOP	Muriate of potash	Ca	Calcium
K	Potassium	Mg	Magnesium
CZ	Clinoptilolite zeolite	Na	Sodium
FLC	Forest litter compost	N	Nitrogen
CLB	Chicken litter biochar	P	Phosphorus
CEC	Cation exchange capacity	AAS	Atomic absorption spectrophotometry

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