Optimizing the Retention and Leaching of Potassium of Tropical Mineral Acid Soils with Application of Charcoal and Sago Bark Ash

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ABSTRACT

Potassium (K) is a macronutrient required by plants for energy production, enzyme activation, formation of cell wall, production of protein, and photosynthesis. However, its availability is compromised because of leaching. In mineral acid soils such as Ultisols and Oxisols, K in the soil solution is prone to leaching because of high rainfall and abundance of kaolinite clay minerals and sequioxides. As a result, these soils have low cation exchange capacity (CEC) but aluminium (Al) and iron (Fe) predominates. This problem has steered the attention to the application of amendments to increase K retention in such soils. The highly negative-charged sites of charcoal and sago bark ash can increase CEC to enhance K^+ retention. Moreover, the alkalinity of these amendments can improve mineral acid soil pH to suppress Al and Fe toxicity in addition to improving K availability soils. The objective of this study was to optimize the retention to reduce leaching of K in a tropical mineral acid soil (*Typic Paleudults*) through co-application of charcoal and sago bark ash. The proportions of charcoal and sago bark ash used in this present study were varied at 20%, 40%, 60%, 80%, and 100%, but the MOP was fixed at 100% of the recommended rate. Selected soil chemical properties before and after the leaching study were determined using standard procedures. Results revealed that increasing rates of charcoal improved soil CEC, (total carbon) TC, and exchangeable K at 30 days leaching. Leaching of K was relatively high in the soil with chemical fertilizers compared with the soils with charcoal and sago bark ash despite the K source for the former coming solely from MOP. Although the increasing rate of sago bark ash had minimal effect on the soil exchangeable K, the ability of the sago bark ash to activate the functional groups of the charcoal is important to further increase maximum K buffering capacity. Therefore, the findings of this present study suggest that the optimum rates of charcoal and sago bark ash to reduce K leaching in mineral acid soils are 60% charcoal with 60% sago bark ash (6 t ha^{-1} charcoal and 3 t ha^{-1} sago bark ash) and 80% charcoal with 40% sago bark ash (8 t ha^{-1} charcoal and 2 t ha^{-1} sago bark ash), because these rates improved soil exchangeable K^+, TC and CEC significantly, in addition minimizing soil exchangeable acidity at 30 days of leaching.

Key words: **Soil amendments, potassium availability, soil fertility, cation exchange capacity, sustainable agriculture**

INTRODUCTION

In tropical acid soils, loss of nutrients especially K through leaching is common. The loss is not only due to high annual rainfall but also because of inhibition of root growth. Presence of detrimental ions such as aluminium ions (Al^{3+}) and iron ions (Fe^{2+}) in high concentrations in mineral acid soils causes injury to plant roots (Mossor-Pietraszewska, 2001). In Malaysia as an example of a humid tropical environment with mineral acid soils, the abundance of kaolinite clay minerals makes K leaching a serious problem in crop cultivation. Potassium is leached from the soil system before it reacts with the soil colloids or being able to displace other cations on the exchange sites of soils.

Kaolinite clay minerals have smaller surface area compared with other clay minerals such as montmorillonite (Fernandez *et al*., 2011). The hydrogen bonds between the layers of kaolinite clay minerals prevent water and nutrients to enter or adsorb in between these layers (Deng *et al*., 2017). Given that kaolinite clay minerals have low negative charge density, there is little chance for K to be adsorbed. Additionally, in low pH, Al and Fe ions predominates and consequently limiting the ability of K to be adsorbed onto the exchange sites (Paramisparam *et al*., 2021). To this end, many farmers tend to over apply K fertilizers to compensate K loss through leaching although this practice is neither economical nor environmental friendly. Increasing the amount of K applied will reduce farmers' revenues besides wasting limited resources (Rehman *et al*., 2019).

As an alternative, amending potassic fertilizers with organic amendments could provide a solution to mitigate K leaching. Utilization of amendments with high organic matter minimizes nutrient loss from fertilizer application. The highly negative-charged sites of charcoal and sago bark ash can increase CEC to improve cations such as K^+, calcium (Ca^{2+}), and magnesium (Mg^{2+}) retention (Qiu *et al*., 2008). Moreover, the alkalinity of these amendments can improve soil pH to suppress Al and Fe toxicity (Mandre *et al*., 2006; Major *et al*., 2010). Eventually, the likelihood of K being held onto soil colloids can be increased and leaching could be reduced significantly. Therefore, it is hypothesized that co-application of charcoal and sago bark ash will improve K retention in soils to prevent or minimize K from being lost from the soil profile. Hence, the objective of this study was to optimize the retention to reduce leaching of K in a tropical mineral acid soil (*Typic Paleudults*) through co-application of charcoal and sago bark ash.

MATERIALS AND METHODS

Soil sampling and preparation

The soil used in this study was sampled from an uncultivated secondary forest at Universiti Putra Malaysia, Bintulu Sarawak Campus (latitude 3°12'11"N and longitude 113°04'25"E), which is a typical representative of Bekenu Series, *Typic Paleudults*. Despite the high content of Al and Fe in addition to the abundance of kaolinite clay minerals, it is a commonly cultivated soil in the tropics and the subtropics. The area has an elevation of 27.3 m, an annual rainfall of 2993 mm, a mean temperature of 27 °C, and relative humidity of approximately 80%. The soil samples were collected at depth of 0–20 cm using a shovel. Afterwards, the soil samples were air dried, ground, and sieved through a 2 mm sieve, after which they were bulked. A 1 kg of soil was taken for each treatment, with triplicates based on the soil's bulk density.

Initial characterization of soil, charcoal, and sago bark ash

With the exception of soil texture, the selected physical and chemical properties of the soil (Bekenu Series, *Typic Paleudults*) used in this study were within the range reported by Paramananthan (2000). However, the soil texture obtained was comparable to that reported in the Soil Survey Staff (2014). The sago bark ash used in this present study was obtained from Song Ngeng Sago Industries, Dalat, Sarawak, Malaysia whereas the charcoal was obtained from Pertama Ferroalloys Sdn Bhd, Bintulu, Sarawak, Malaysia. The selected physico-chemical properties of the soil, charcoal, and sago bark ash are summarized in Table 1.

TABLE 1
Selected physical and chemical properties of Bekenu Series (*Typic Paleudults*), charcoal, and sago bark ash used in the incubation study

Property	Soil	Charcoal	Sago bark ash
pH (water)	3.95	7.74	9.99
pH (KCl)	4.61	7.31	9.66
EC (µS cm^{-1})	35.10	269.33	5753.00
Bulk density (g m^{-3})	1.25	nd	nd
(%)			
Total carbon	2.16	nd	nd
Total N	0.08	nd	nd
(mg kg^{-1})			
Total P	22.25	nd	nd
Total K	101.27	nd	nd
(cmol kg^{-1})			
Cation exchange capacity	4.67	nd	13.13
Exchangeable acidity	1.15	0.10	nd
Exchangeable Al^{3+}	0.13	0.047	nd
Exchangeable H^{+}	1.02	0.05	nd
Exchangeable K^{+}	0.06	1435.20	9120.00
Exchangeable Ca^{2+}	0.02	2346.67	3361.20
Exchangeable Mg^{2+}	0.22	409.07	433.73
Exchangeable Na^{+}	0.03	99.38	348.00
Exchangeable Fe^{2+}	1.09	41.90	8.43
Sand (%)	71.9	nd	nd
Silt (%)	13.5	nd	nd
Clay (%)	14.6	nd	nd
Texture (USDA)	Sandy loam	nd	nd

Note: Values are on dry-weight basis; values obtained: mean ± standard error; nd: not determined

Leaching Set-us

A laboratory leaching study was carried out in the Soil Science Laboratory of Universiti Putra Malaysia Bintulu Sarawak Campus, Malaysia. The air dried, ground, and sieved soil samples were bulked, and 1 kg of the soil was weighed using a digital balance into a polypropylene container. The bottom of the polypropylene container was perforated and covered with filter paper. Before commencing the leaching experiment, charcoal and sago bark ash were added and mixed thoroughly with the soil, based on the treatments evaluated. The samples were moistened to 60% field capacity and left overnight to equilibrate. Thereafter, muriate of potash (MOP) was surface applied except for T1 (soil only). Afterwards, a 250 mL of distilled water was sprayed in the containers with the soil and treatment (first leaching). The first leachates were collected in a base container on day five. For the second leaching, another 250 mL of distilled water was sprayed in the containers with the treatments after which the leachates were collected on day 10. This step was repeated at five days interval until the last leachates were collected on day 30. Volume of the distilled water applied was deduced based on rainy days of a 30 days' time frame. Average amount of rainfall per month was calculated from a 10-year rainfall data obtained from the Drainage and Irrigation Department, Bintulu Division, Sarawak, Malaysia. Three replicates of each treatment were arranged to suit completely randomized design (Figure 1).

Figure 1. Set up of laboratory leaching study.

The rates of K fertilizer used in this study were scaled down from the standard K fertilizer recommendation for *Zea mays* L. cultivation by MARDI (1993) which was 40 kg K_2O ha^{-1} (67 kg MOP ha^{-1}). Thereof, the recommended rate for the K fertilizer was then adjusted to per plant basis (planting density of 27777 maize plants ha^{-1}). The percentages of charcoal and sago bark ash were derived from the respective literature [charcoal (Free *et al*., 2010; Ndor *et al*., 2015) and sago bark ash (Mandre *et al*., 2006; Ozolinicius *et al*., 2007; Perucci *et al*., 2008)]. The 100% recommended rate of charcoal was 10 t ha^{-1}, whereas that for sago bark ash was 5 t ha^{-1}. These recommendations were scaled down to the equivalent proportions for one kg soil. Charcoal and sago bark ash rates were varied by 20%, 40%, 60%, 80%, and 100%, whereas the MOP rate was kept constant at 100% of the recommended rate. The treatments evaluated in this study are summarized in Table 2.

Table 2.
Amounts of muriate of potash, charcoal, and sago bark used in the leaching study

Treatment	Soil (kg)	MOP (g)	Charcoal (g)	Sago Bark Ash (g)
T1	1	-	-	-
T2	1	2.41	-	-
T3	1	2.41	51.4	25.7
T4	1	2.41	-	25.7
T5	1	2.41	51.4	-
T6	1	2.41	41.1	20.6
T7	1	2.41	30.8	20.6
T8	1	2.41	20.6	20.6
T9	1	2.41	10.3	20.6
T10	1	2.41	41.1	15.4
T11	1	2.41	30.8	15.4
T12	1	2.41	20.6	15.4
T13	1	2.41	10.3	15.4
T14	1	2.41	41.1	10.3
T15	1	2.41	30.8	10.3
T16	1	2.41	20.6	10.3
T17	1	2.41	10.3	10.3
T18	1	2.41	41.1	5.1
T19	1	2.41	30.8	5.1
T20	1	2.41	20.6	5.1
T21	1	2.41	10.3	5.1

Note: 2.41 g MOP refers to 100% of the recommended rate of the MOP fertilizer; 51.4 g charcoal: charcoal recommended rate at 100%; 41.1 g charcoal: charcoal recommended rate at 80%; 30.8 g charcoal: charcoal recommended rate at 60%; 20.6 g charcoal: charcoal recommended rate at 40%, 10.3 g charcoal: charcoal recommended rate at 20%; 25.7 g sago bark ash: sago bark ash recommended rate at 100%; 20.6 g sago bark ash: sago bark ash recommended rate at 80%; 15.4 g sago bark ash: sago bark ash recommended rate at 60%; 10.3 g sago bark ash: sago bark ash recommended rate at 40%; 5.1 g sago bark ash: sago bark ash recommended rate at 20%.

Leachate and soil analysis

Leachates were collected at five days interval over the 30 days of leaching for determination of pH, electrical conductivity (EC), and leached K. At the end of the 30 days leaching, the soil samples were air-dried, crushed, and analyzed for pH, total carbon (TC), CEC, exchangeable acidity, Al^{3+}, H^{+}, total K, and exchangeable K using standard procedures. The soil samples were characterized for physical and chemical properties before and after the leaching study. Soil pH in water and potassium chloride (KCl) and EC were measured in a 1:2.5 (soil: distilled water/KCl) using a digital pH meter and an EC meter, respectively (Peech, 1965). Determination of pH and EC of the leachates followed the preceding procedures. Soil texture was determined using the hydrometer method (Bouyoucos, 1962). Soil TC was calculated as 58% of the organic matter that was determined using loss of weight on ignition method (Chefetz *et al*., 1996). Soil samples were analyzed for soil bulk density using coring method (Dixon and Wisniewski, 1995). The soil CEC was determined using leaching method (Cottenie, 1980) followed by steam distillation (Bremner, 1965). Exchangeable cations [K, Ca, Mg, Sodium (Na), and Fe] were extracted with 1 M ammonium acetate (NH4OAc), pH 7 using the leaching method (Cottenie, 1980). Total K was extracted using Aqua Regia method (Bernas, 1968). Afterwards, the cations in soil and leachate were quantified using Atomic Absorption Spectrophotometry (AAnalyst 800, Perkin Elmer Instruments, Norwalk, CT, USA). Soil-exchangeable acidity, H^{+}, and Al^{3+} were determined using acid-base titration method (Rowell, 1994).

Statistical analysis

A normality test was performed to ensure the data obtained fit the assumption before analyzing using analysis of variance (ANOVA) to detect treatment effects. The means of the treatments were compared using Tukey's HSD test at $p \leq 0.05$. The Statistical Analysis System (SAS) Version 9.4 was used for the statistical analysis.

RESULTS AND DISCUSSION

Effect of treatments on pH and electrical conductivity of leachate

Effects of the treatments on the pH and electrical conductivity of the leachates over 30 days of leaching are presented in Figure 2 and Figure 3. Leachate of the soil alone (T1) had the lowest pH and electrical conductivity throughout the leaching study. This is related to the inherently low pH and cation content of Bekenu series (Table 1). These results corroborate the findings of Johan *et al*. (2021) who also reported low pH and electrical conductivity for leachates of a mineral acid soil alone. Electrical conductivity of all the treatments reduced with increasing days of leaching. Electrical conductivity of the leachates at day 5 increased with the increasing rate of the sago bark ash in the treatments with this amendment. This is attributable to the substantial amount of base cations in the sago bark ash (Table 1). Throughout the 30-day leaching study, leachates of the soil with 100% for the recommended rate of charcoal and sago bark ash (T3) demonstrated the highest pH compared with other treatments because of highest rates of the amendments in this treatment. Charcoal and sago bark ash are inherently high in pH (Table 1) and because of this they are able to improve pH buffering capacity of soils.

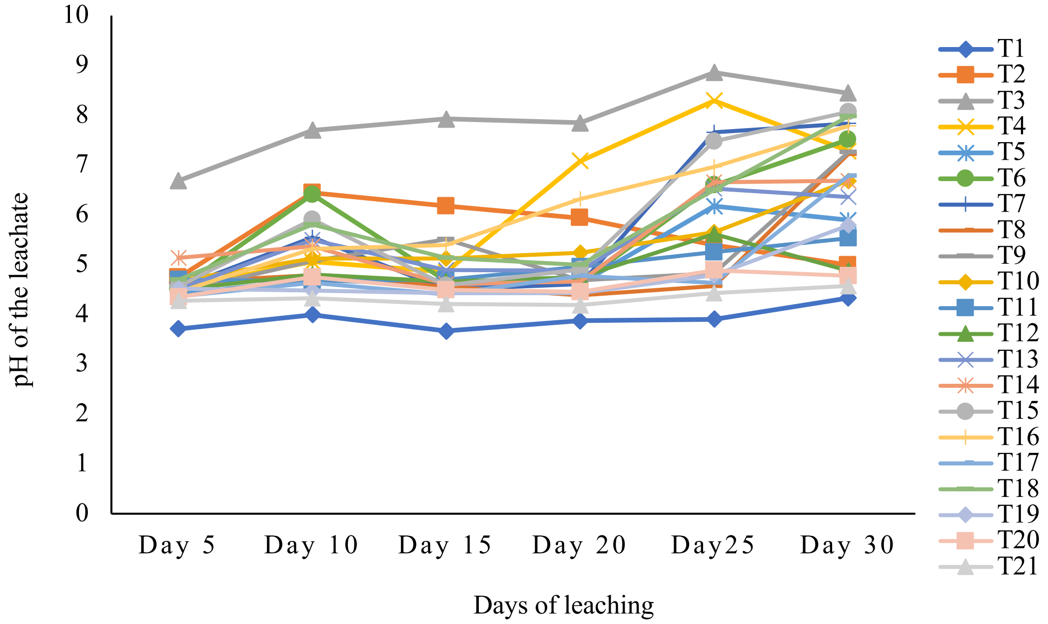

Figure 2. Effect of treatments on pH of leachate over thirty days of leaching.

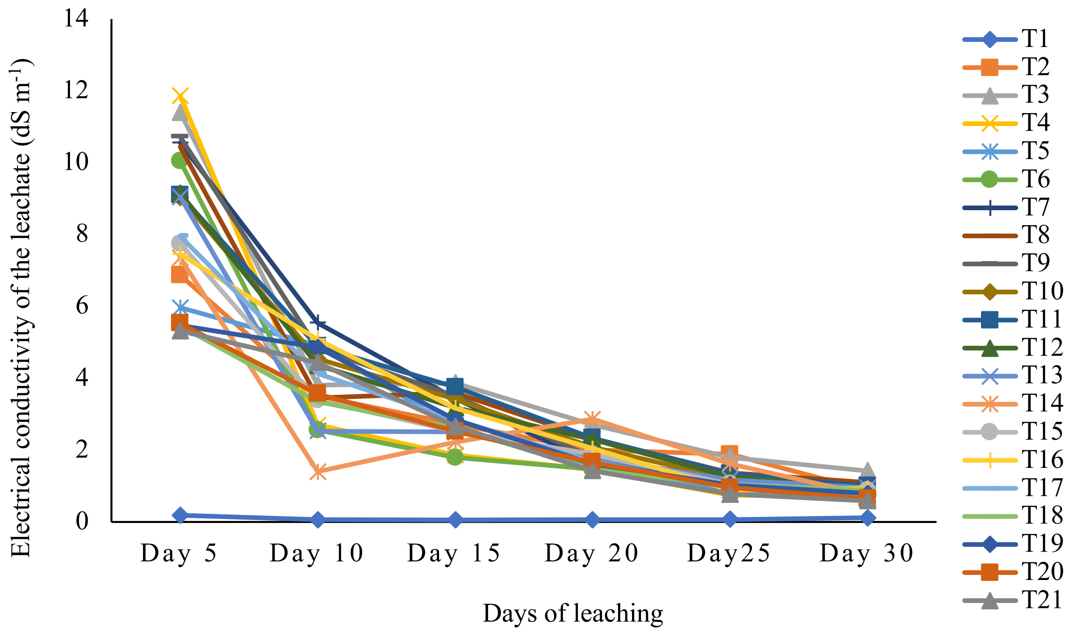

Figure 3. Effect of treatments on the electrical conductivity of leachate over thirty days of leaching.

Effect of treatments on potassium availability in leachate

Potassium concentrations in the leachates and cumulative concentrations of the K leached for 30 days are presented in Figure 4 and Figure 5. Soil alone (T1) demonstrated the lowest amount of K leached because of the inherently low K content of Bekenu series (Table 1). This finding is consistent with that of Kevin *et al*. (2007) who also reported low amount of K in Bekenu series. The low K content of Bekenu series is due to the composition of kaolinite and sesquioxides in the Bekenu series to render K susceptible to leaching (Palanivell, 2016).

On the other hand, application of charcoal and sago bark ash to the soil increased the total amount of K leached compared with soil alone (T1) or the existing K fertilization (T2) because charcoal and sago bark ash are high in K (Table 1). Chien *et al*. (2011) asserts that addition of rice husk charcoal to soils increases K, Ca, and Mg concentrations. Priyadharshini and Seran (2009) also concluded that paddy husk ash could be used as a source of K in cowpea cultivation. This indicates that addition of charcoal and sago bark ash to soils are able to increase plant available K pools (WSK and exchangeable K). However, this leaching study was carried out in a closed system without plants, thus the effects of the treatments on plant uptake of K did not feature in this present study. Therefore, WSK was prone to leaching.

Despite the fact that the additional K of the existing K fertilization (T2) comes from MOP alone, the amount of K leached at day 5 was relatively high. The high concentrations of Al and Fe ions in mineral acid soils reduce the affinity of exchanges sites for bases such as K (Gazey, 2018). In addition, in 1:1 layer lattice clay such as kaolinite predominates in acid soils. These clays have limited adsorption sites for cation retention (Li and Xu, 2013; Schneider *et al*., 2013). Hydrogen bondings which stack kaolinite minerals prevent nutrients from being adsorbed between layers, hence the adsorption occurs only on the edges of the crystalline structure (Miranda-Trevino and Coles, 2003; Palanivell, 2016). Therefore, addition of amendments with high CEC such as charcoal is important for increasing K sorption capacity of acid soils.

In spite of having lower amounts of charcoal compared with T3 and T5, the soil with 60% of the recommended rate of charcoal and sago bark ash (T11) and the soil with 60% of the recommended rate of charcoal and 20% of the recommended rate sago bark ash (T19) leached lower amounts of K at day 5. This implies that sago bark ash in considerable amounts could compensate for the reduction of charcoal which would contribute higher CEC to soils. Reduction in the amounts of K leached at day 5 demonstrated for T11 and T19 is related to the ability of carbonates and oxides of ash to deprotonate the functional groups of charcoal.

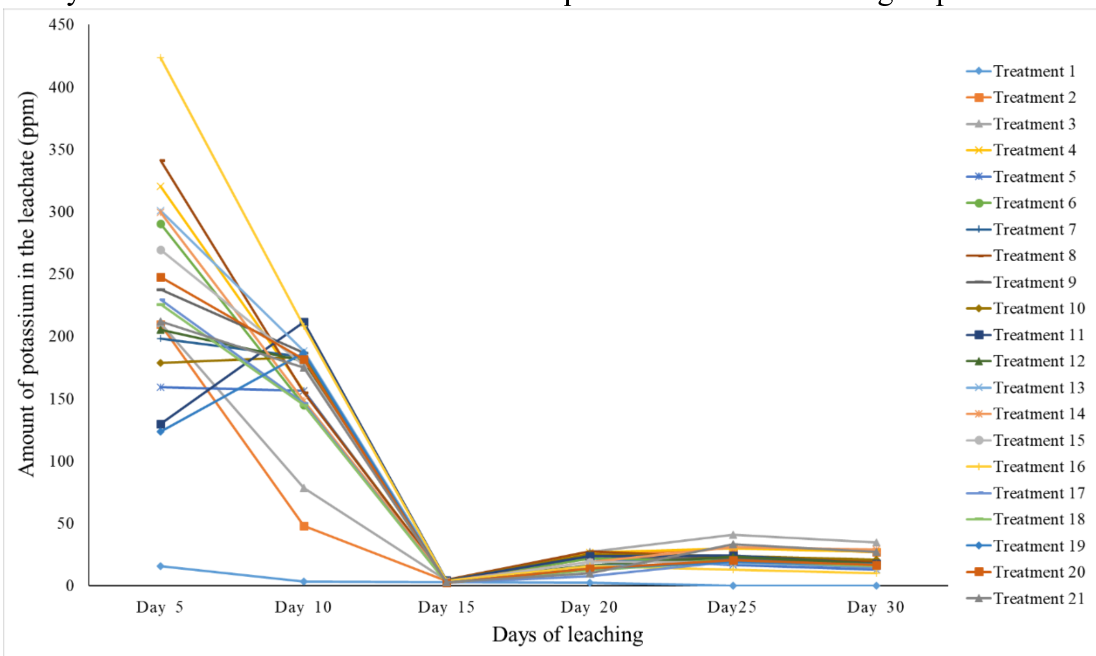

Figure 4. Effect of treatments on potassium availability in leachate over thirty days of leaching.

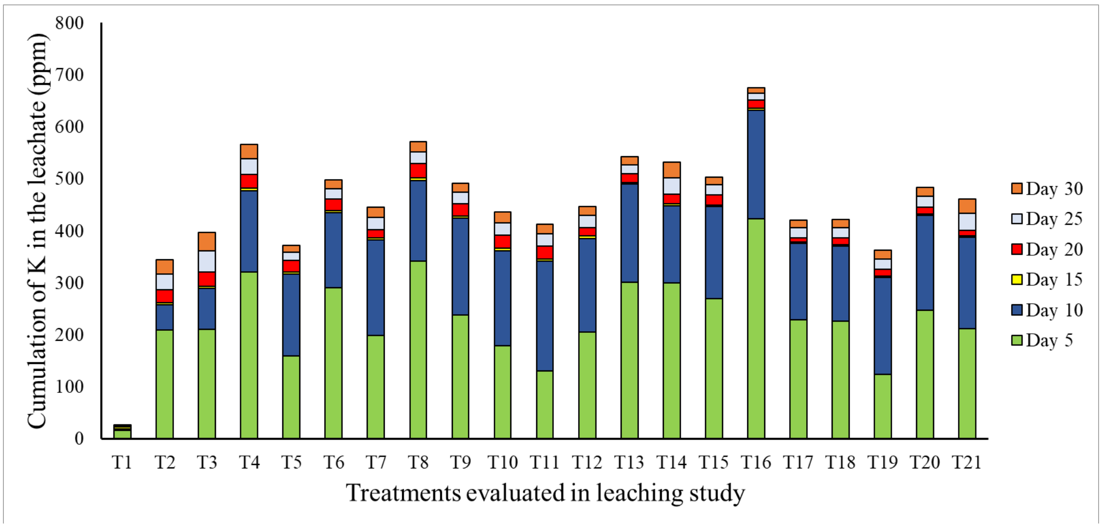

Figure 5. Effect of treatments on the cumulative concentration of potassium in leachate over thirty days of leaching.

Selected soil chemical properties at 30 days of Leaching

The soil pH, exchangeable acidity, exchangeable Al^{3+}, and exchangeable H^+ at 30 days of leaching are presented in Figure 6, Figure 7, Figure 8, and Figure 9. Soil alone (T1) and normal fertilization (T2) demonstrated lower pH, but higher exchangeable acidity, exchangeable Al^{3+}, and exchangeable H^+ compared with the treatments with charcoal and sago bark ash. Nevertheless, the soil pH at 30 days of leaching for the soil with 20% of the recommended rate of charcoal and sago bark ash (T21) were similar to the soil alone (T1). This observation suggests that the rate of the amendments used were not able to resist acidification during the leaching process. The low pH, high exchangeable acidity, exchangeable Al^{3+}, and exchangeable H^+ of T1 and T2 relate to the low pH buffering capacity of Bekenu series (Johan *et al*., 2021). Moreover, Bekenu series is inherently low in base cations such as K^+, Ca^{2+}, Mg^{2+}, and Na^+, thus unable to resist acidification (Ch'ng, 2015).

With the exception of the soil with 20% of the recommended rate of charcoal and sago bark ash (T21), the combined use of MOP with charcoal and sago bark ash (T3, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20) resulted in higher pH compared with soil alone (T1) and the existing K fertilization (T2). On the other hand, the treatments with charcoal (T5), sago bark ash (T4) or both (T3, T6, T7, T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21) demonstrated lower soil exchangeable acidity and exchangeable H^+ compared with T1 and T2. The amended treatments also demonstrated negligible amounts of soil exchangeable Al^{3+}. Despite the ineffectiveness in improving pH at 30 days of leaching in comparison to soil alone (T1), the soil with 20% of the recommended rate of charcoal and sago bark ash (T21) reduced soil exchangeable acidity, suggesting that T21 is capable of mitigating H^+ and Al^{3+} retained on soil colloids but not those in the soil solution. This explains why T21 demonstrated lower amounts of soil exchangeable H^+ and negligible amounts of soil exchangeable Al^{3+}.

The significant reduction in soil exchangeable acidity, exchangeable Al^{3+}, and exchangeable H^+ by the treatments with the soil amendments is associated with the ability of the sago bark ash to deprotonate the functional groups of charcoal to create negatively charged sites which are able to chelate the exchangeable Al^{3+} (Kolb *et al*., 2013; Qiu *et al*., 2008; Zinati *et al*., 2001). On the other hand, improvement in the soil pH with the amendments is attributable to the release of base cations such as K^+, Ca^{2+}, Mg^{2+}, and Na^+ from the amendments because these base cations are capable of immobilizing H^+ in the soil solution. Furthermore, the $CaCO_3$, CaO, and MgO of the sago bark ash neutralized the active acidity by consuming H^+ in the soil solution (Jacobson and Gustafsson, 2001; Lerner and Utzinger, 1986; Campbell, 1990).

Figure 10 and Figure 11 reveals the trend of the effects of the treatment on soil TC and soil CEC. It appears that the soil TC and CEC are directly proportional to the rate of charcoal applied because the soil TC and CEC increased with increasing the amount of the charcoal. This finding is in accordance with that of Borchard *et al*. (2014) who also asserted that addition of charcoal to soil increases soil carbon stocks in a manner that translates into improved soil fertility indicators such as CEC and water retention. Furthermore, the oxidation of charcoal surfaces results in the formation of oxygen containing functional groups to increase negatively charged sites (Calvelo Pereira *et al*., 2014; Cheng *et al*., 2008), thus increasing soil CEC.

Soil alone (T1) and the existing K fertilization (T2) demonstrated low soil TC and CEC at 30 days of leaching because of absence of organic matter. Bekenu series is inherently low in soil TC and CEC (Table 1). At 30 days of leaching, there were no significant differences in the soil TC and CEC for the soil with sago bark ash only (T4) compared to T1 and T2. This is ascribed to the fact that ash does not contribute a significant amount of C. Demeyer *et al*. (2001) stated that ashing volatilizes C and other organic materials from a sample.

The fact that the charcoal at 20% of the recommended rate, T13, T17, and T21 demonstrated no difference on effects on the soil TC and CEC compared to T1 and T2 suggests that the low rate of charcoal is not effective to improve soil TC and CEC. On the other hand, the soil with 60% of the recommended rate of charcoal and sago bark ash (T11) and the soil with 80% of the recommended rate of charcoal and 40% of the recommended rate sago bark ash (T14) demonstrated similar effects on the soil CEC compared with the soil with 100% of the recommended rate of charcoal and sago bark ash (T3). In spite of the lower amount of the charcoal in T11 and T14 compared with the latter treatments, addition of sago bark ash at substantial amounts could compensate for the reduction of charcoal which would contribute higher CEC to soils. This is based on the ability of carbonates and oxides of ash to deprotonate the functional groups of charcoal to create large number of cation exchange sites.

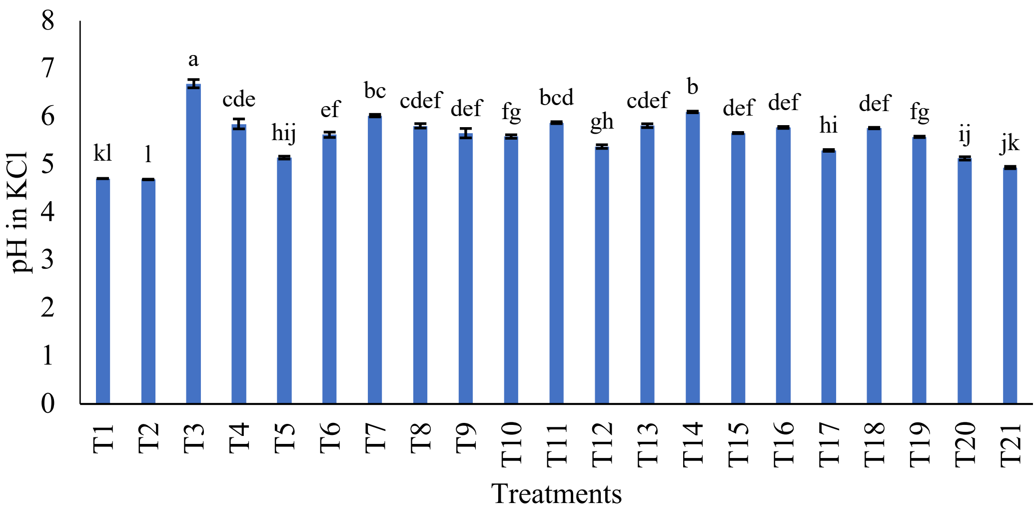

Figure 6. Effect of treatments on soil pH in KCl at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

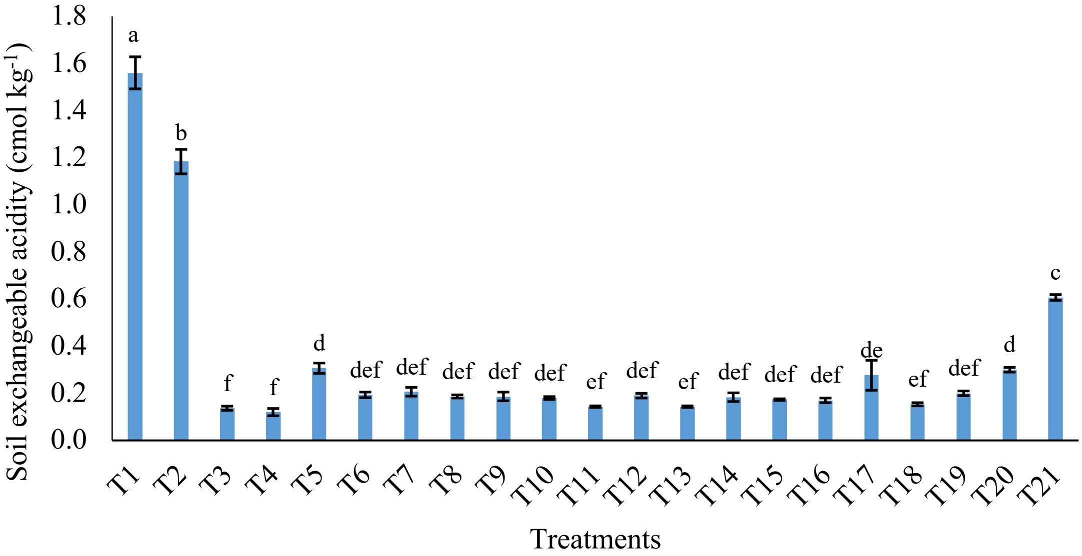

Figure 7. Effect of treatments on soil exchangeable acidity at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

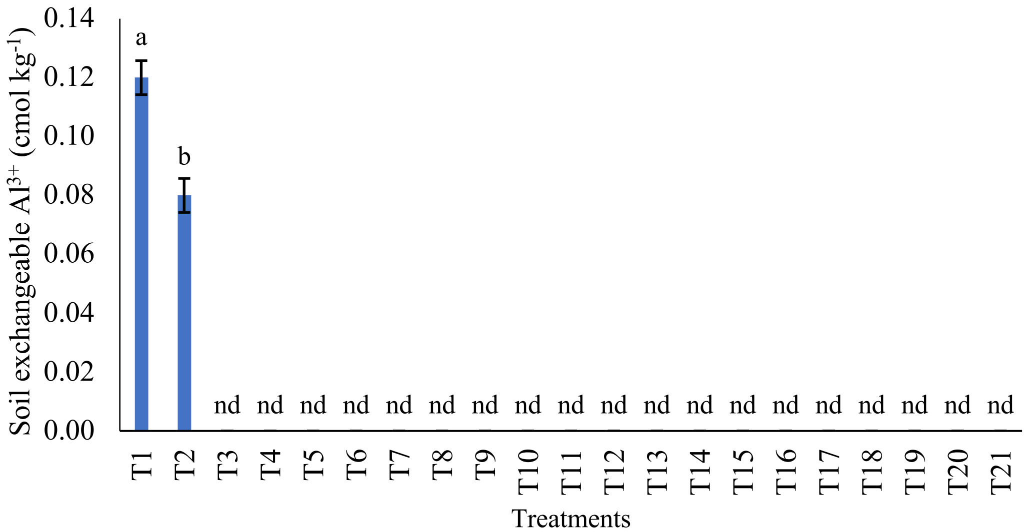

Figure 8. Effect of treatments on soil exchangeable aluminium at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

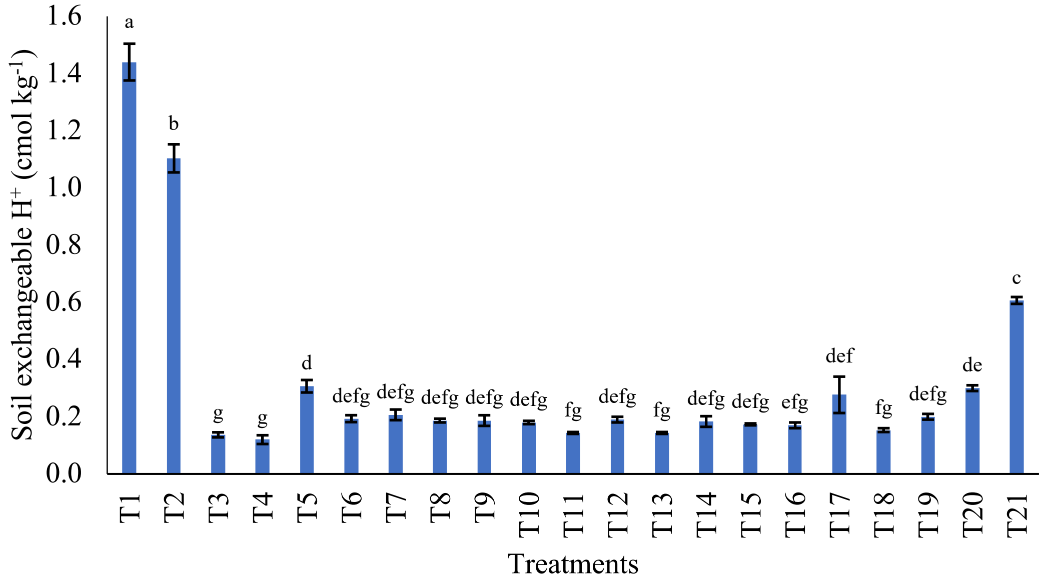

Figure 9. Effect of treatments on soil exchangeable hydrogen at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

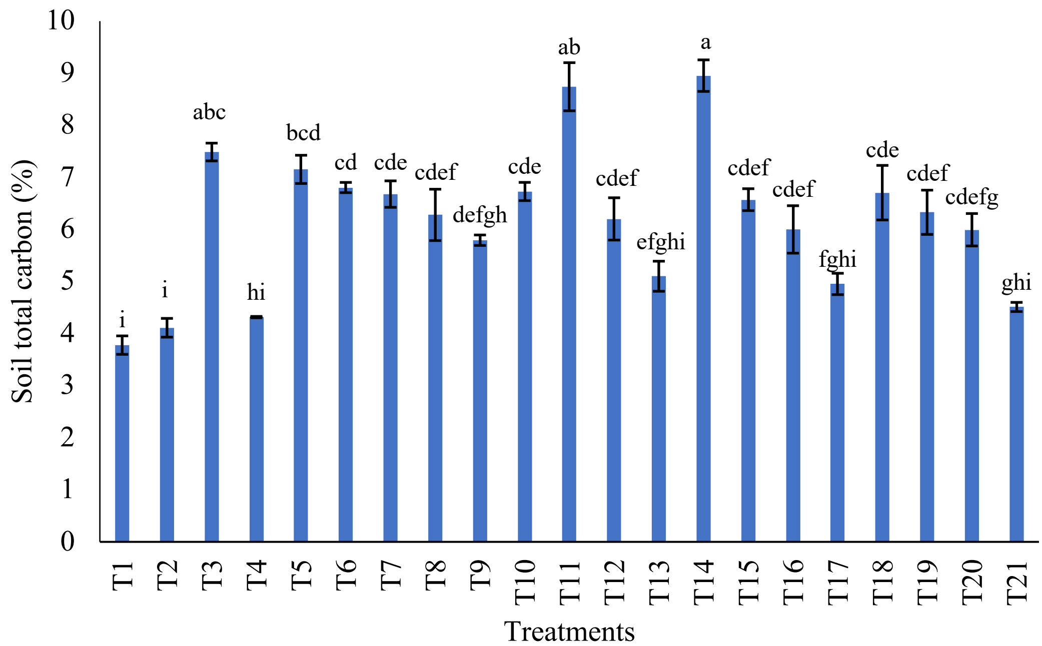

Figure 10. Effect of treatments on soil total carbon at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

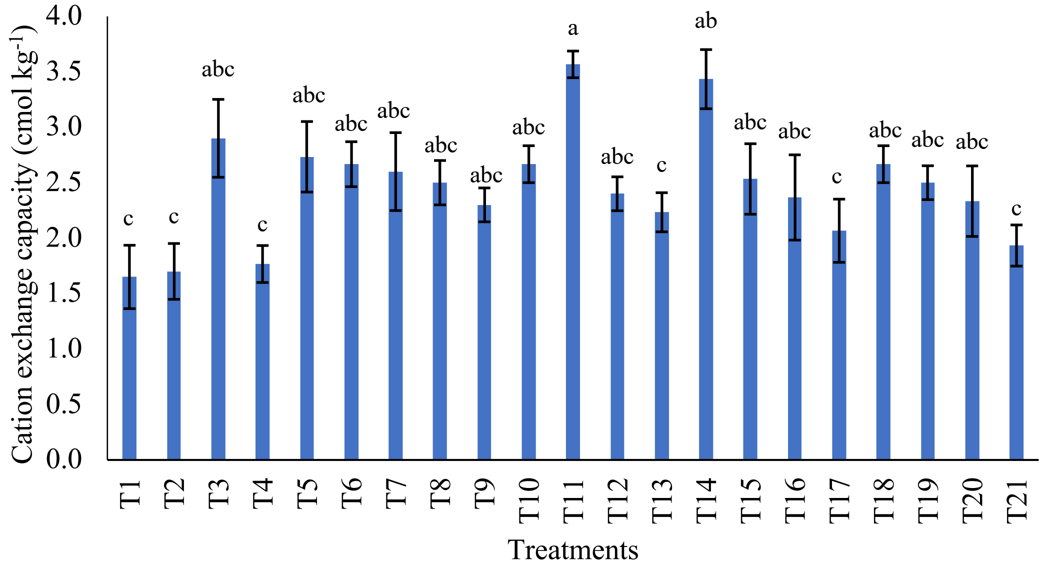

Figure 11. Effect of treatments on soil cation exchange capacity at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

Total potassium and exchangeable potassium after 30 days days of leaching

Soil alone (T1) had significantly lower total K compared with the treatments with MOP, charcoal, and sago bark ash (Figure 12) because of the inherently low K content of Bekenu series (Table 1). Effects of the treatments with charcoal and sago bark ash on soil total K were similar to that of the existing K fertilization (T2), except the soil with 100% of the recommended rate of charcoal and sago bark ash (T3). The similarity is due to the fact that soil total K is made up of water-soluble K, exchangeable K, nonexchangeable K, and mineral K or fixed K (Sparks, 2000; Jaiswal *et al*., 2016), and it does not adequately reflect the K retention or availability in soils.

Rather, exchangeable K reflects the soils ability to hold K onto adsorption sites. Effect of the existing K fertilization (T2) on soil exchangeable K at 30 days of leaching was not significantly different compared to that of the soil alone (T1) (Figure 13). This suggests that the existing practice is unable to prevent K deficiency because of leaching. Additionally, effects of the soil with sago bark ash only (T4), the soil with 20% recommended rate of charcoal and sago bark ash (T21), the soil with 40% recommended rate of charcoal and 42% recommended rate of sago bark ash (T20), the soil with 20% recommended rate of charcoal and 40% recommended rate of sago bark ash (T17), the soil with 40% recommended rate of charcoal and sago bark ash (T16), and the soil with 20% recommended rate of charcoal and 60% recommended rate of sago bark ash (T13) on soil exchangeable K were similar to the existing K fertilization (T2). This indicates that these treatments are ineffective in preventing leaching of K. The lower amount of exchangeable K in the soils with these treatments relates to the low or absence of charcoal which does not provide cation exchange sites. This explains the large amount of K in the leachates (Figure 5).

The soil with 60% of the recommended rate of charcoal and sago bark ash (T11) and that with 80% of the recommended rate of charcoal and 40% of the recommended rate sago bark ash (T14) improved the soil exchangeable K. However, the effects were similar to the soil with 100% of the recommended rate of charcoal and sago bark ash (T3). The fact that these treatments have lower rates of the amendments suggest that the use of sago bark ash compensates for the reduced amount of charcoal in the treatments. This is possible because of the oxidation of carbon surfaces by the carbonates and oxides released by sago bark ash facilitate sorption of cations (Borchard *et al*., 2012; Pignatello *et al*., 2006). The results also suggests that the treatments effect on the soil exchangeable K was directly proportional to the CEC and the rate of charcoal applied (Figure 11). This observation is related to the large internal surface areas of the charcoal (Antal and Grønli, 2003) which causes entrapment of cations within their inner pores in addition to surface adsorption. However, increasing the rate of the sago bark ash application had minimal effect on the soil exchangeable K. Instead, the sago bark ash serves as a catalyst to facilitate K sorption of the charcoal. The improved soil pH upon the ash application increased K reactivity at the same time, it limited Al and Fe reactivity. This reaction enhanced the affinity of the sorption sites for K. Furthermore, the pH neutralizing compounds in ash were capable of deprotonating the functional groups of charcoal. Therefore, in a system with plants, sago bark ash could potentially facilitate a slow-release mechanism of K from exchange sites to soil solution. To this end, the thresholds of sago bark ash application rates should be carefully studied.

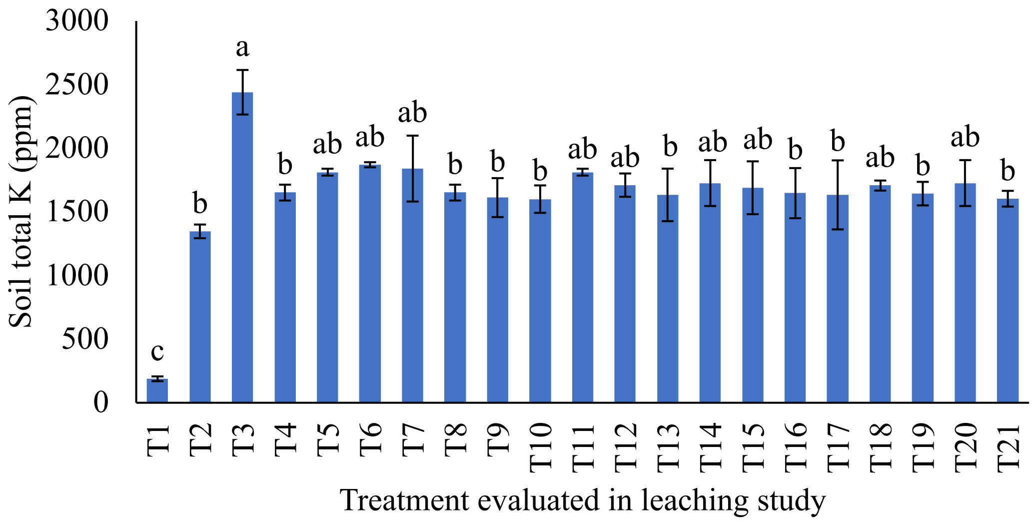

Figure 12. Effect of treatments on soil total potassium at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

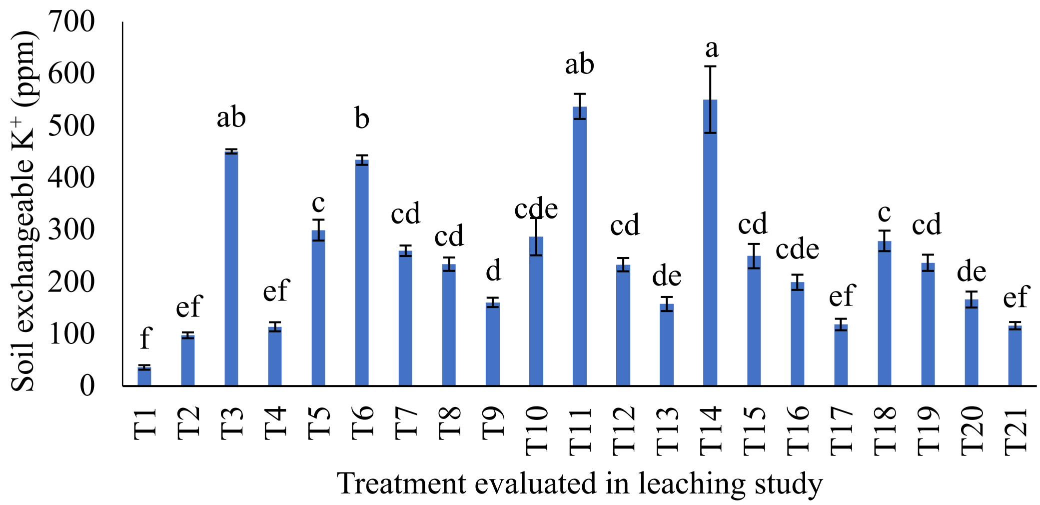

Figure 13. Effect of treatments on soil exchangeable potassium at 30 days of leaching. Different letters indicate significant differences between means using Tukey's HSD test at $p \leq 0.05$. The error bars are the ± standard error of triplicates.

CONCLUSION

Application of charcoal improves soil CEC to regulate K leaching. Increasing rates of charcoal improved soil CEC, TC, and exchangeable K. The fact that leaching of K is relatively high with chemical fertilization compared with soils which are co-applied with charcoal and sago bark ash suggests that using chemical fertilizers alone will not solve K deficiency in soils that are prone to K leaching. Therefore, inclusion of charcoal which has high CEC in farming systems on mineral acid soils is essential because of their pore-filling property and sorption capability to retain K. Although increasing rate of sago bark ash had minimal effect on the soil exchangeable K, the ability of the sago bark ash to activate the functional groups of charcoal is important for increasing K buffering capacity. Therefore, the findings of this present study suggest that the optimum rates of charcoal and sago bark ash to reduce K leaching in mineral acid soils are 60% charcoal with 60% sago bark ash (6 t ha^{-1} charcoal and 3 t ha^{-1} sago bark ash) and 80% charcoal with 40% sago bark ash (8 t ha^{-1} charcoal and 2 t ha^{-1} sago bark ash), because these rates are capable of improving soil exchangeable K^+, TC, and CEC besides reducing soil exchangeable acidity. The improved CEC and TC reflect the soil's ability to prevent K leaching, whereas reduction in the soil exchangeable acidity prevents competition of K with Al and Fe for exchange sites. Because K in the leachate were detected for the treatments with charcoal and sago bark ash this laboratory leaching study only demonstrates ability of the charcoal and sago bark ash to minimize K leaching and not their effects on plant uptake and recovery efficiency of K. Hence, further studies are essential to consolidate the findings of this present study.

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REFERENCES

Antal, M.J. Grønli, M. 2003. The art, science, and technology of charcoal production. *Ind. Eng. Chem. Res 42*, 1619–1640.

Bernas, B. 1968. New method for decomposition and comprehensive analysis of silicates by atomic absorption spectrometry. *Anal. Chem*, *40*, 1682–1686.

Borchard, N., Ladd, B., Eschemann, S., Hegenberg, D., Möseler, B. M., Amelung, W. 2014. Black carbon and soil properties at historical charcoal production sites in Germany. *Geoderma 232*, 236-242.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agron. J*, *54*, 464–465.

Bremner, J.M. 1965. Total Nitrogen. In *Methods of Soil Analysis: Part 2*; Black, C.A., Evans, D.D., Ensminger, L.E., White, J.L., Clark, F.F., Dinauer, R.C., Eds.; American Society of Agronomy: Madison, WI, USA, pp. 1149–1178.

Calvelo Pereira, R., Camps Arbestain, M., Kaal, J., Vazquez Sueiro, M., Sevilla, M., Hindmarsh, J. 2014. Detailed carbon chemistry in charcoals from pre-European Māori gardens of New Zealand as a tool for understanding biochar stability in soils. *European Journal of Soil Science 65*(1), 83-95.

Campbell, A.G. 1990. Recycling and disposing of wood ash. *TAPPI J 73*, 141–146.

Ch'ng, H.Y. 2015 Phosphorus Management for Tropical Acid Soils Using Amendments from Agro-Industrial Wastes. Doctoral Thesis, Universiti Putra Malaysia, Serdang, Selangor, Malaysia.

Chefetz, B. Hatcher, P.H. Hadar, Y. Chen, Y. 1996. Chemical and biological characterization of organic matter during composting of municipal solid waste. *J. Environ. Qual*, *25*, 776–785.

Cheng, C. H., Lehmann, J., Engelhard, M. H. 2008. Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta 72*(6), 1598-1610.

Chien, C.C., Huang, Y.P., Sah, J.G., Cheng, W.J., Chang, R.Y. Lu, Y.S. 2011. Application of rice husk charcoal on remediation of acid soil. In *Materials Science Forum* (Vol. 685, pp. 169-180). Trans Tech Publications Ltd.

Cottenie, A. 1980. Soil testing and plant testing as a basis of fertilizer recommendation. *FAO Soils Bull*, *38*, 70–73.

Demeyer, A. Nkana, J.V. Verloo, M.G. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: An overview. *Bioresour. Technol 77*, 287–295.

Deng, L., Yuan, P., Liu, D., Annabi-Bergaya, F., Zhou, J., Chen, F., Liu, Z. 2017. Effects of microstructure of clay minerals, montmorillonite, kaolinite and halloysite, on their benzene adsorption behaviors. *Applied Clay Science 143*, 184-191.

Dixon, R.K. Wisniewski, J. 1995. Global Forest systems: An uncertain response to atmospheric pollutants and global climate change? *Water Air Soil Pollut*, *85*, 101–110.

Fernandez, R., Martirena, F., Scrivener, K. L. 2011. The origin of the pozzolanic activity of calcined clay minerals: A comparison between kaolinite, illite and montmorillonite. *Cement and concrete research 41*(1), 113-122**.**

Free, H.F. Mcgill, C.R. Rowarth, J.S. Hedley, M.J. 2010. The effect of biochars on maize (*Zea mays*) germination. *N. Z. J. Agric. Res*, *53*, 1–4.

Gazey, C. Effects of Soil Acidity; Agriculture and Food Department of Primary Industries and Regional Development Government of Western Australia. 2018. Available online: https://www.agric.wa.gov.au/soil-acidity/effects-soil-acidity?page=0%2C1 (accessed on 22 April 2021).

Jacobson, S. Gustafsson, L. 2001. Effects on ground vegetation of the application of wood ash to a Swedish Scots pine stand. *Basic Appl. Ecol 2*, 233–241.

Jaiswal, D.K. Verma, J.P. Prakash, S. Meena, V.S. Meena, R.S. 2016. Potassium as an important plant nutrient in sustainable agriculture: A state of the art. *Potassium Solubilizing Microorg. Sustain. Agric* 21–29,2776-2_2.

Johan, P.D., Ahmed, O.H., Omar, L., Hasbullah, N.A. 2021. Charcoal and Sago Bark Ash on pH Buffering Capacity and Phosphorus Leaching. *Agronomy*, *11*(11), p.2223.

Kevin, M. T. S., Ahmed, O. H., Asrina, W. Y. W., Rajan, A., Ahzam, M. 2007. Towards growing Bario rice on lowland soils: A preliminary nitrogen and potassium fertilization trial. *American Journal of Agricultural and Biological Sciences*, *2*(2), 99-105**.**

Kolb, S.E. Fermanich, K.J. Dornbush, M.E. 2013. Effect of charcoal quantity on microbial biomass and activity in temperate soils. *Soil Sci. Soc. Am. J 73*, 1173–1181.

Lerner, B.R. Utzinger, J.D. 1986. Wood ash as soil liming material. *HortScience 21*, 76–78.

Li, J.Y. Xu, R.K. 2013. Inhibition of acidification of kaolinite and an Alfisol by aluminum oxides through electrical double-layer interaction and coating. *Eur. J. Soil Sci*, *64*, 110–120.

Major, J. Lehmann, J. Rondon, M. Goodale, C. 2010. Fate of soil-applied black carbon: Downward migration, leaching and soil respiration. *Glob. Chang. Biol, 16*.

Malaysian Agricultural Research and Development Institute (MARDI). 1993. *Jagung Manis Baru, Masmadu [New Sweet Corn, Masmadu]*; Malaysian Agricultural Research and Development: Serdang, Malaysia, pp. 3–5.

Mandre, M. Pärn, H. Ots, K. 2006 Short-term effects of wood ash on the soil and the lignin concentration and growth of *Pinus sylvestris* L. *For. Ecol. Manag 223*, 349–357.

Miranda-Trevino, J.C. Coles, C.A. 2003. Kaolinite properties, structure and influence of metal retention on pH. *Appl. Clay Sci. 23*, 133–139**.**

Mossor-Pietraszewska, T. **2001.** Effect of aluminium on plant growth and metabolism. *Acta Biochimica Polonica 48*(3), 673-686**.**

Ndor, E. Dauda, S.N. Azagaku, E.D. 2015. Response of maize varieties (*Zea mays*) to biochar amended soil in Lafia, Nigeria. *J. Exp. Agric. Int*, *5*, 525–531.

Ozolincius, R.; Buozyte, R.; Varnagiryte, K.I. 2007. Wood ash and nitrogen influence on ground vegetation cover and chemical composition. *Biomass Bioenergy 31*, 710–716.

Palanivell, P. 2016. Organic and Mineral Amendments on Rice (*Oryza sativa* L.) Yield and Nutrients Recovery Efficiency. Ph.D. Thesis, Universiti Putra Malaysia, Seri Kembangan, Malaysia.
Paramananthan, S. 2000 *Soil of Malaysia: Their Characteristics and Identification*; Academy of Sciences Malaysia: Kuala Lumpur, Malaysia, Volume 1, pp. 11–125.
Paramisparam, P., Ahmed, O. H., Omar, L., Ch'ng, H. Y., Johan, P. D., Hamidi, N. H. 2021. Co-Application of Charcoal and Wood Ash to Improve Potassium Availability in Tropical Mineral Acid Soils. *Agronomy 11*(10), 2081.
Peech, H.M. 1965. Hydrogen-ion Activity. In *Methods of Soil Analysis Chemical and Microbiological Properties*; Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark, F.E., Eds.; American Society of Agronomy: Madison, WI, USA, pp. 914–926.
Perucci, P. Monaci, E. Onofri, A. Vischetti, C. Casucci, C. 2008. Changes in physico-chemical and biochemical parameters of soil following addition of wood ash: A field experiment. *Eur. J. Agron*, *28*, 155–161.
Pignatello, J.J., Lu, Y., Leboeuf, E.J., Huang, W., Song, J. Xing, B. 2006. Nonlinear and competitive sorption of apolar compounds in black carbon-free natural organic materials. *Journal of Environmental Quality 35*(4), pp.1049-1059.
Priyadharshini, J., Seran, T. H. 2009. Paddy husk ash as a source of potassium for growth and yield of cowpea (*Vigna unguiculata* L.). The Journal of Agricultural Sciences 6(2), 67-76.
Qiu, Y. Cheng, H. Xu, C. Sheng, G.D. 2008 Surface characteristics of crop-residue-derived black carbon and lead (II) adsorption. *Water Res 42*, 567–574.
Qiu, Y. Cheng, H. Xu, C. Sheng, G.D. 2008. Surface characteristics of crop-residue-derived black carbon and lead (II) adsorption. *Water Res*, *42*, 567–574.
Rehman, A., Chandio, A. A., Hussain, I., Jingdong, L. 2019. Fertilizer consumption, water availability and credit distribution: Major factors affecting agricultural productivity in Pakistan. *Journal of the Saudi Society of Agricultural Sciences 18*(3), 269-274**.**
Rowell, D.L. 1994. *Soil Science: Methods and Application*; Longman Publishers Ltd: London, UK, p. 169.
Schneider, A. Tesileanu, R. Charles, R. Sinaj, S. 2013. Kinetics of soil potassium sorption–desorption and fixation. *Commun. Soil Sci. Plant Anal*, *44*, 837–849.
Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12th ed.; USDA-Natural Resources Conservation Service: Washington, DC, USA.
Sparks, D.L. 2000. Bioavailability of soil potassium, D-38-D-52. In *Handbook of Soil Science*; Sumner, M.E., Ed.; CRC Press: Boca Raton, FL, USA.
Zinati, G.M. Li, Y.C. Bryan, H.H. 2001. Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil. *Compos. Sci. Util 9*, 156–162.