Mitigating Nitrogen Leaching in Mineral Soils using Pineapple Leaf Biochar

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ABSTRACT

As nitrogen is an essential nutrient for MD2 pineapple growth as a substantial quantity of nitrogen fertilizer is required for increasing yield production. Highly weathered soils such as Oxisols are low in pH and nutrient contents partly due to leaching. Excessive use of compound chemical fertilizers causes nutrient leaching. Using biochar as a soil amendment to provide nutrients for improving soil properties, nutrient uptake, water retention and nutrient recovery efficiency could also minimize nitrate losses in the soil. A leaching study of six treatments with compound fertilizer (CF) and pineapple leaf biochar (PLB) was conducted. The treatments were as follows: T1= Control (soil only); T2= 100% CF (control); T3= 75% CF + 25% PLB; T4= 50% CF + 50% PLB; T5= 25% CF + 75% PLB; and T6= 100% PLB. Standard Procedures were in this study. The objective of the study was to determine the effects and the PLB rate that improve soil nitrogen retention. The cumulative loss of exchangeable ammonium and available nitrate for the treatment without PLB (T2= 100% CF) at 30 days of leaching was significantly higher than in the treatments with PLB (T3, T4, T5 and T6). Treatment 5 with 25% CF + 75% PLB gave the lowest mean value for both the mineral soils tested. The higher soil organic matter of PLB had a direct effect on the capacity of the soil to retain exchangeable ammonium, available nitrate, and total nitrogen ($p< 0.05$). The PLB combined with compound fertilizer improve nitrogen availability by up to 20% through temporary retention besides enhancing the soil chemical properties via mitigating nitrogen leaching hence, causing lower losses of NH_4^+ and NO_3^- compared with compound fertilizer alone.

Key words: pineapple leaf biochar, soil amendment, nitrogen retention

INTRODUCTION

Excessive use of compound fertilizers in agricultural does not impedes the need for accelerating good agricultural practices to enable achieving the meet global food demands or security but it could also cause significant nutrient loss through leaching. Fertilizers such as nitrate (NO_3^-) are lost though leaching because of the greater mobility of nitrate ions in soils (Klimczyk *et al.* 2021). However, the extent of nutrient leaching in soils primarily depends on climate, soil type and the quantity of nutrients present in soils (Plošek *et al.* 2017; Hossain *et al.* 2020). The loss of nutrients, particularly nitrogen in the form of nitrate through leaching has a significant negative effect on crop yield (Wang *et al.* 2022). Moreover, leaching of nutrients such as nitrate can consequently lead to nitrate eutrophication and soil acidity (Raza *et al.* 2020).

The global annual production of fresh pineapple fruits is approximately 28.3 million metric tons and this makes it one of the most widely consumed tropical fruits (Banerjee *et al.* 2022). Following the harvest and processing stages, an estimated 51 tons to 60 tons of pineapple waste per hectare are generated (Malaysian Pineapple Industry Board 2022). The application of pineapple biochar to mitigate nitrogen leaching emerges as a sustainable and environmental friendly solution not only for managing agricultural wastes but also for enhancing waste management practices.

Biochar, derived from agricultural biomass serves as a green technology which is essential modern agriculture. Its rich nutrients and the nutrient capturing ability plays an essential role in improving the quality of agricultural soils. The positive impact of biochar extends to soil fertility, crop productivity, soil water retention, and carbon sequestration. Furthermore, it mitigates volatilization besides creating a conducive habitat for beneficial microorganisms (Jeffery *et al.* 2011; Limwikran *et al.* 2018; Wang *et al.* 2022).

The use of biochar in soil management contributes to improved soil fertility, fostering an environment where more nutrients become available for plant absorption (Rawat *et al.* 2019). This innovative approach does not only address the challenge of pineapple waste but it also promotes sustainable practices in agriculture and waste utilization.

Related literature on pineapple residue has highlighted the promising potential of converting pineapple leaves into biochar (Bohari *et al.* 2020; Hung *et al.* 2023). The application of organic soil amendments such as pineapple leaf biochar (PLB) could reduce N leaching in the soil by reducing N loss and this based on the ability biochar to retain nutrients through it functional groups and its general pores and large surface areas (Hossain *et al.* 2020). Rawat *et al.* (2019) revealed or uncovered the potential of biochar persistence in soils for several years for a prolonged effect on soil chemical, physical, and biological properties. Pineapple leaf biochar has the potential to establish eco-friendly and sustainable cropping systems to reduce the dependence on synthetic fertilizers in MD2 pineapple cultivation (Jos *et al.* 2023).

Hence, this study was conducted to determine the effects of PLB on N nutrient retention in alluvial and red yellow podzolic soils. By examining these specific soil types, we could understand how PLB interacts with different soil compositions and their corresponding nutrient retention capabilities. This evaluation could contribute to the understanding of PLB's performance under varying soil conditions and its potential as a sustainable solution for improving nitrogen retention, specifically in MD2 pineapple cultivation.

MATERIALS AND METHODS

Study Site and Soil Sample Preparation

The study was conducted using two types of mineral soils, namely alluvial soil and red yellow podzolic soil, extracted from the existing field trial sites at the Farm Management Unit of UiTM Sarawak. Soil samples were collected from a depth of 0-20 cm using a shovel. The samples then were air-dried and sieved to pass a 2-mm sieve. Table 1 shows the selected physico-chemical properties of the soil at the pre-planting stage in February 2020.

Pineapple Leaf Biochar Preparation

Pineapple leaf biochar was prepared using the procedure of Bohari *et al.* (2020) as published in Jos *et al.* (2023). The nutrient content of PLB in this study is listed in Table 2.

Table 1: Selected physico-chemical properties of alluvial and red yellow podzolic soils

Parameter	Alluvial soil	Red yellow podzolic
pH_w	4.3	4.5
Moisture content, %	2.79	2.93
CEC, $cmol_c\ kg^{-1}$	10.23	3.21
Total Nitrogen, %	0.2	0.13
Total organic carbon, %	0.77	0.01
Total Phosphorus (P), mgL^{-1}	31	37
Available Phosphorus (P), mgL^{-1}	7.5	7.25
Potassium (K), $cmol_c\ kg^{-1}$	0.13	0.08
Magnesium (Mg), $cmol_c\ kg^{-1}$	0.25	0.19
Calcium (Ca), $cmol_c\ kg^{-1}$	0.37	2.16

Source: Jos *et al.* (2023)

Table 2: Chemical composition of the pineapple leaf biochar

Element	Biochar composition (%)
Carbon	19.37 ± 2.03
Nitrogen	8.33 ± 5.34
Oxygen	21.95 ± 5.92
Phosphorus	0.39 ± 0.05
Potassium	48.32 ±9.92
Magnesium	1.27 ± 0.93
Sulfur	0.32 ± 0.14
Calcium	0.05 ± 6.33
pH Value	8.78 ± 0.02
EC ($mS\ cm^{-1}$)	7.38 ± 0.02

Source: Bohari *et al.* (2020)

Leaching Experiment

The rate and amount of PLB and compound fertilizer used are shown in Table 3.

Table 3: Composition of treatment, rates of fertilizer, and application

Treatment	Rate of fertilizer	Quantity (g/plant)
T1	Absolute Control	
T2	100% CF (Control)	20g CF
T3	75% CF + 25% PLB	15g CF + 5g PLB
T4	50% CF + 50% PLB	10g CF + 10g PLB
T5	25% CF + 75% PLB	5g CF + 15g PLB
T6	100% PLB	20g PLB

Note: CF= Compound fertilizer as recommended by MPIB (2020); PLB=Pineapple Leaf Biochar

The treatment evaluated in a nursery trial as published by Jos *et al.* (2023) was used in this laboratory experiment with some modifications (Table 3). A 300 g soil and treatments were mixed and filled into a leaching container (Figure 1). Each treatment was replicated three times and arranged in a Completely Randomized Design. Distilled water was used to leach the mixture. Volume of the distilled water used was based on a five year rainfall data obtained from the Sarawak Meteorological Development, Malaysia (2021). The volume of the distilled water used was based on a count of rainy days over a 30-day period. The leachates were collected in a five day interval and analysed for pH using a digital pH meter (Seven Easy Mettler Toledo). Nitrogen was analysed using the method of Keeney and Nelson (1982) by measuring the amount of exchangeable ammonium and available nitrate (Latifah *et al.* 2017b). Soil total N was determined using the Kjeldahl method (Bremner 1965).

Figure 1. Leaching experiment

Statistical Analysis

Data were analysed using Statistical Analysis System version 9.4 (SAS, 2013). Analysis of Variance (ANOVA) was used to test the effect of different treatments. A mean comparison of all treatments was performed using Tukey's Honestly Significant Difference (Tukey's HSD) at $P \leq 0.05$.

RESULTS AND DISCUSSION

Effects of Pineapple Leaf Biochar on Ammonium and Nitrate Leaching at a Five Day Interval

The amount of exchangeable ammonium (NH_4^+) leached from the alluvial soil and red yellow podzolic soil amended with the different rates of the pineapple leaf biochar (T3, T4, T5 and T6) compared to the compound fertilizer alone (T2) is shown in Table 4. At day 10, the compound fertilizer alone (T2) exhibited significantly higher NH_4^+ loss (845.27 mg/kg) compared to the red yellow podzolic soil with the different rates of the PLB. The amounts of NH_4^+ leached from T2 and T4 slowly increased after 15 days of leaching followed by a decrease at 30 days of leaching. Treatment 5 with a higher rate of PLB showed a gradual decrease in NH_4^+ loss with increasing days of leaching.

The role of PLB in improving soil microbial activities might have contributed to the NH_4^+ loss reduction. The gradual decrease of NH_4^+ in the soil with T5 is related to the amount of PLB used and the need for it to reactive because PLB functions as a slow-release fertilizer (Wang *et al.* 2022). Notably, the lowest NH_4^+ losses were observed in T1 (absolute control) and T6 (100% PLB) for the two soil types partly because of the inherently low N of these soils (Jos *et al.* 2023).

Contrary to NH_4^+, the NO_3^- loss over the 30-day of leaching showed a continuous decrease for T2, T3, T4 and T5. The amount of available nitrate (NO_3^-) leached from the alluvial soil and red yellow podzolic soil amended with the different rates of PLB (T3, T4, T5 and T6) compared to compound fertilizer alone (T2) is shown in Table 5 where in the two soils, the amount of NO_3^- generally decreased with the increasing rate of the PLB (T3, T4, T5 and T6). Furthermore, the loss of NO_3^- from the treatments gradually decreased throughout the leaching study. The possible explanations for the decrease in NO_3^- loss could be several. Firstly, increased soil sorption as affected by T3, T4, and T5 might have caused a higher capacity to sorb nitrate ions from being leached out of the soil. This also relates to the presence of clay minerals or organic

matter with a high surface area in the soil. Secondly, microorganisms in the soil might have converted nitrate into other forms of nitrogen, such as organic nitrogen, which are less mobile and less likely to be leached rapidly. Lastly, the PLB in T3, T4, and T5 might have sorb more nitrate from the soil, hence reducing the amount available for leaching; suggesting that T3, T4, and T5 were effective in reducing nitrate leaching from the soil compared with the control group (T1 and T2).

TABLE 4
Effects of different treatments on NH_4^+ leached at five day intervals over a thirty day leaching

Soil	Treatment	Leaching of exchangeable ammonium (NH_4^+) mg/kg by day					
		5	10	15	20	25	30
Red yellow Podzolic	T1	$8.87^{c}\pm0.47$	$11.66^{c}\pm1.24$	$10.74^{d}\pm0.93$	$11.68^{d}\pm1.24$	$7.94^{d}\pm0.47$	$11.21^{d}\pm0.81$
	T2	$197.07^{b}\pm7.94$	$246.58^{b}\pm20.25$	$285.80^{ab}\pm23.54$	$312.42^{a}\pm13.75$	$250.31^{a}\pm4.88$	$137.77^{a}\pm13.83$
	T3	$198.94^{b}\pm9.15$	$452.06^{a}\pm26.04$	$245.18^{b}\pm22.65$	$212.49^{b}\pm13.08$	$216.22^{b}\pm14.20$	$63.05^{c}\pm3.43$
	T4	$236.30^{b}\pm13.83$	$430.57^{a}\pm25.48$	$324.57^{a}\pm19.57$	$220.89^{b}\pm14.92$	$193.81^{b}\pm12.17$	$108.81^{b}\pm13.59$
	T5	$301.22^{a}\pm27.75$	$373.13^{a}\pm18.81$	$152.71^{c}\pm14.98$	$98.54^{c}\pm2.84$	$51.84^{c}\pm3.71$	$26.62^{d}\pm3.43$
	T6	$28.95^{c}\pm5.74$	$15.88^{c}\pm1.24$	$11.68^{d}\pm0.47$	$9.34^{d}\pm0.47$	$10.74^{d}\pm0.93$	$9.34^{d}\pm0.47$
Alluvial	T1	$16.35^{c}\pm0.93$	$12.61^{d}\pm0.81$	$7.47^{d}\pm0.47$	$7.94^{c}\pm0.47$	$7.94^{d}\pm0.47$	$9.34^{d}\pm0.47$
	T2	$259.19^{b}\pm26.81$	$845.27^{a}\pm21.05$	$203.61^{c}\pm23.57$	$426.37^{a}\pm19.69$	$491.75^{a}\pm28.62$	$330.17^{a}\pm22.62$
	T3	$301.21^{b}\pm12.58$	$568.34^{b}\pm22.85$	$399.29^{a}\pm25.84$	$208.05^{b}\pm24.90$	$474.94^{a}\pm26.45$	$297.01^{a}\pm18.85$
	T4	$464.67^{a}\pm18.93$	$457.19^{bc}\pm17.42$	$294.21^{bc}\pm23.76$	$443.65^{a}\pm26.15$	$396.02^{b}\pm21.80$	$246.11^{b}\pm25.69$
	T5	$500.16^{a}\pm24.63$	$383.87^{c}\pm17.23$	$317.09^{ab}\pm24.46$	$155.98^{b}\pm8.14$	$165.79^{c}\pm3.37$	$103.67^{c}\pm7.80$
	T6	$32.69^{c}\pm2.60$	$17.28^{d}\pm2.60$	$24.28^{d}\pm2.04$	$14.01^{c}\pm1.62$	$14.94^{d}\pm1.24$	$19.61^{d}\pm2.80$

Note: Mean ± standard error of the mean was analysed by ANOVA.
Different letters within each row indicate significant differences at $p < 0.05$ based on Tukey's HSD. T1 = absolute control; T2 = 100% CF (control); T3 = 75% CF + 25% PLB; T4 = 50% CF + 50% PLB; T5 = 25% CF + 75% PLB; T6 = 100% PLB

TABLE 5
Effects of different treatments on NO_3^- leached at a five day interval over a thirty day leaching

Soil	Treatment	Leaching of available nitrate (NO_3^-) mg/kg by day					
		5	10	15	20	25	30
Red yellow Podzolic	T1	15.88^{c}±2.60	13.08^{d}±1.87	15.88^{cd}±2.60	8.87^{c}±0.93	11.68^{c}±0.93	9.81^{c}±0.81
	T2	443.42^{b}±19.76	568.81^{b}±24.31	421.70^{a}±27.20	309.62^{a}±19.19	143.37^{a}±12.17	80.32^{a}±10.24
	T3	416.56^{b}±15.82	832.19^{a}±21.31	358.66^{b}±12.45	186.33^{b}±17.74	104.61^{b}±9.75	47.63^{b}±1.14
	T4	406.29^{b}±28.35	877.03^{a}±20.58	342.31^{b}±24.10	142.44^{b}±12.38	80.79^{b}±12.17	55.34^{b}±9.72
	T5	1090.45^{a}±24.59	354.45^{c}±5.30	91.53^{c}±10.56	39.70^{c}±2.34	18.21^{c}±1.40	11.21^{c}±1.14
	T6	13.54^{c}±1.68	10.74^{d}±1.24	10.27^{d}±1.236	9.81^{c}±0.81	9.81^{c}±0.81	10.27^{c}±0.47
Alluvial	T1	21.48^{c}±0.93	8.87^{d}±0.93	8.87^{c}±0.47	9.34^{c}±0.47	9.34^{c}±0.47	9.34^{c}±0.47
	T2	1346.36^{b}±28.09	1630.30^{a}±21.09	1017.83^{a}±18.99	1149.75^{a}±19.57	544.06^{a}±25.81	342.31^{a}±23.84
	T3	1139.01^{c}±16.03	1443.96^{a}±26.06	738.33^{b}±20.35	613.17^{b}±19.59	334.84^{b}±19.12	253.11^{ab}±23.52
	T4	1622.83^{a}±20.97	941.01^{b}±7.52	817.72^{b}±23.49	444.12^{b}±18.11	333.91^{b}±26.93	189.60^{b}±14.70
	T5	615.04^{d}±21.18	432.91^{c}±20.05	76.59^{c}±6.97	123.76^{c}±5.74	68.18^{c}±4.45	49.97^{c}±6.59
	T6	23.82^{e}±2.14	15.88^{d}±1.24	15.41^{c}±1.62	16.81^{c}±1.62	23.35^{c}±2.47	10.74^{c}±0.47

Note: Mean ± standard error of the mean was analysed by ANOVA. Different letters within each row indicate significant differences at p <0.05 based on Tukey's HSD. T1 = absolute control; T2 = 100% CF (control); T3 = 75% CF + 25% PLB; T4 = 50% CF + 50% PLB; T5 = 25% CF + 75% PLB; T6 = 100% PLB

The quantity of NH_4^+ and NO_3^- released through the leaching process dictates the extent to which they are retained in the soil. The cumulative loss of NH_4^+ and NO_3^- on alluvial and red yellow podzolic soils over 30 days of leaching is presented in Figure 2. Notably, the total amount of NH_4^+ leached was consistently lower than NO_3^- in both soils, reflecting the significantly higher mobility of NO_3^- in the soil solution. This is related to electrostatic repulsion between the negative charge of NO_3^- and negatively charged clay particles in the soil. From the results, the treatments exhibited significantly different total amount of NH_4^+ leached from the alluvial and red yellow podzolic soils with T5 having the lowest cumulative amount of NH_4^+ leached for both soils compared to the other treatments amended with PLB (T3 and T4). This suggests that the increased PLB rate effectively reduced NH_4^+ leaching because of the enhanced adsorption onto the biochar surface. In contrast, the cumulative NO_3^- leached was consistently higher in the alluvial soil compared with the red yellow podzolic soil because of the improved soil exchangeable NH_4^+ retention via the organic matter content of the PLB. The build-up or loading of the exchangeable NH_4^+ decreased negative charge sites available for NO_3^- adsorption to maintain the equilibrium between the NH_4^+ and NO_3^- (Weldon *et al.*, 2022).

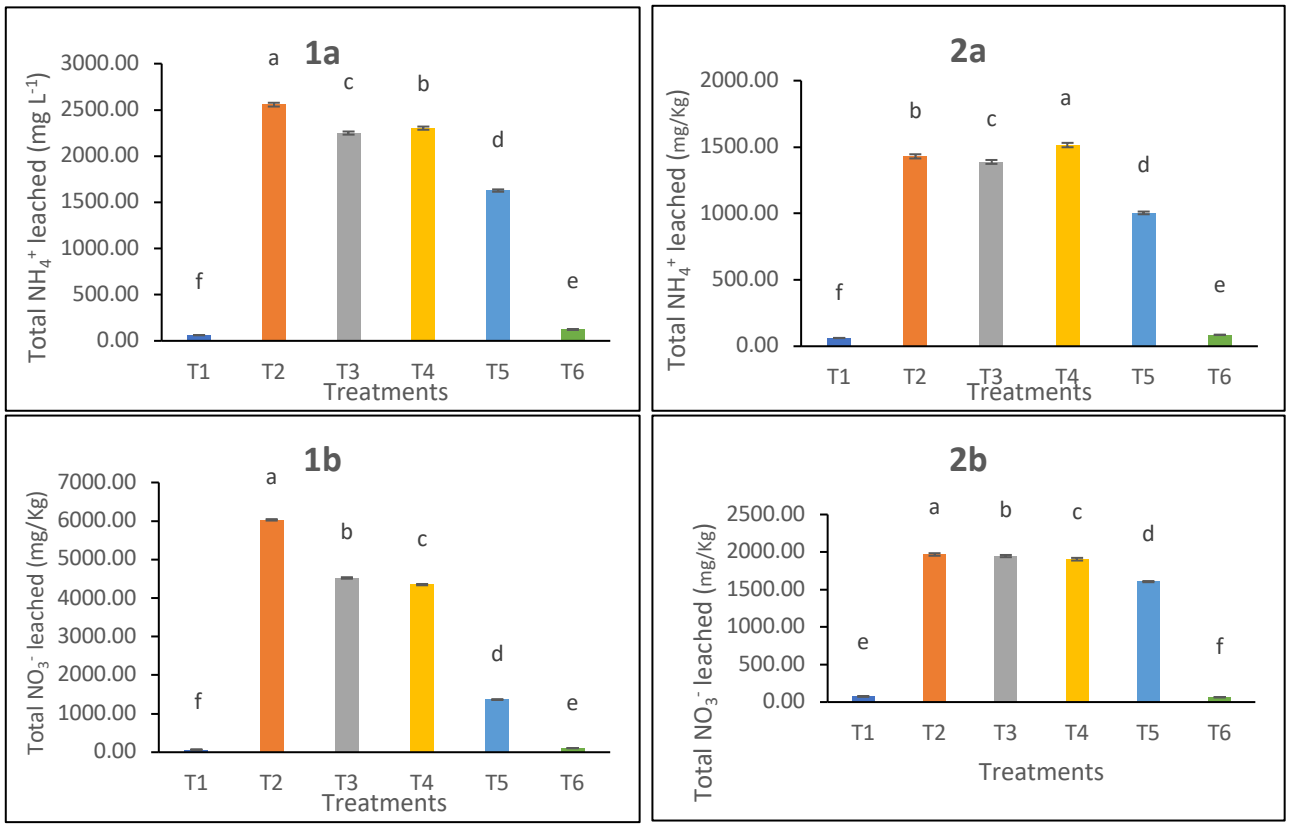

Figure 2. Effects of different treatments on cumulative amount NH_4^+ and NO_3^- leached over 30 days on alluvial soil (1a & 1b) and red yellow podzolic soil (2a & 2b). Different letters within each row indicate significant differences at p <0.05 based on Tukey's HSD. T1 = absolute control; T2 = 100% CF (control); T3 = 75% CF + 25% PLB; T4 = 50% CF + 50% PLB; T5 = 25% CF + 75% PLB; T6 = 100% PLB

Effects of Pineapple Leaf Biochar on pH of Leachate over 30 Days of Leaching

The leaching losses of both NH_4^+ and NO_3^- negatively correlated with the pH of the leachates in soils amended with PLB (Table 6). This suggests that the higher pH values observed in PLB-amended soils played a crucial role in retaining these nutrients. For the alluvial soils, the increase in soil pH also relates to the initial pH of the PLB. Treatments 5 and 6 which had higher initial PLB pH, exhibited significantly lower losses of NH_4^+ and NO_3^- compared with the rest of the treatments on alluvial soils. This finding is consistent with the observations of Latifah *et al.* (2017a) who reported that the release of H^+ ions associated with NH_4^+ dissolution lowers leachates pH. Furthermore, a temporal trend was observed where pH of the leachates gradually increased whereas the leaching losses of NH_4^+ and NO_3^- decreased over the days of the leaching study (Table 4 and Table 5). This suggests a dynamic interaction between PLB amendment, nutrient retention, and soil acidity. A detailed study by Vu *et al.* (2018) corroborates this finding, attributing the increased pH to the sorption of NH_4^+ onto biochar, which effectively retains the nutrient within the soil matrix. The combined use of the PLB and compound fertilizer effectively reduced the leaching losses of NH_4^+ and NO_3^- from the two mineral soils. This beneficial effect is attributed to the increase in soil pH induced by PLB amendment, highlighting the potential of biochar as a sustainable soil amendment for nutrient management.

TABLE 6
Effects of different treatments on pH of leachates leached over thirty days of leaching red-yellow podzolic and alluvial soils

Soil	Treatment	Leachate pH by day					
		5	10	15	20	25	30
Red Yellow Podzolic	T1	7.98^{b}±0.10	7.61^{b}±0.23	7.30^{bc}±0.35	7.00^{b}±0.21	7.58^{b}±0.41	7.92^{ab}±0.29
	T2	4.72^{f}±0.03	5.10^{f}±0.01	7.01^{bc}±0.35	7.09^{b}±0.20	7.42^{b}±0.08	7.73^{ab}±0.26
	T3	5.03^{e}±0.03	5.59^{e}±0.05	6.16^{d}±0.30	7.41^{b}±0.28	7.60^{b}±0.12	6.34^{b}±0.71
	T4	5.44^{d}±0.03	5.98^{d}±0.02	6.56^{cd}±0.09	7.91^{ab}±0.16	7.32^{b}±0.56	6.37^{b}±0.91
	T5	5.98^{c}±0.06	6.64^{c}±0.00	7.71^{b}±0.16	7.93^{ab}±0.59	7.16^{b}±0.78	7.75^{ab}±1.07
	T6	8.27^{a}±0.03	8.81^{a}±0.05	8.80^{a}±0.10	8.74^{a}±0.16	9.35^{a}±0.30	9.27^{a}±0.29
Alluvial	T1	4.59^{b}±0.08	6.07^{a}±0.25	4.88^{c}±0.03	6.09^{c}±0.15	7.25^{b}±0.15	7.12^{b}±0.23
	T2	2.82^{e}±0.02	3.57^{c}±0.03	3.57^{d}±0.04	5.25^{d}±0.17	5.75^{d}±0.23	5.83^{c}±0.25
	T3	2.92^{de}±0.04	3.73^{c}±0.06	4.49^{c}±0.11	5.98^{c}±0.16	6.66^{c}±0.05	7.02^{b}±0.21
	T4	3.18^{d}±0.12	3.90^{bc}±0.07	5.43^{b}±0.30	6.80^{b}±0.15	7.14^{b}±0.07	7.29^{b}±0.10
	T5	3.52^{c}±0.11	4.21^{b}±0.13	6.72^{a}±0.23	7.66^{a}±0.11	7.75^{a}±0.19	7.57^{b}±0.11
	T6	5.31^{a}±0.09	6.20^{a}±0.22	5.76^{b}±0.18	7.17^{ab}±0.24	8.05^{a}±0.17	8.62^{a}±0.30

Note: Mean ± standard error of mean was analysed by ANOVA. Different letters within each row indicate significant differences at p <0.05 based on Tukey's HSD. T1 = absolute control; T2 = 100% CF (control); T3 = 75% CF + 25% PLB; T4 = 50% CF + 50% PLB; T5 = 25% CF + 75% PLB; T6 = 100% PLB

Effects of Pineapple Leaf Biochar on Nitrogen Availability at 30 Days of Leaching

The retention of soil exchangeable NH_4^+, available NO_3^-, and total N in both soils with amended PLB is shown in Figure 3. The higher retention of NH_4^+ and NO_3^- in alluvial soil relates to the slow mineralization of NH_4^+ and NO_3^- from PLB. The amount of NH_4^+ and NO_3^- in treatment with only compound fertilizer (T2) was higher than in the other treatments with PLB (T3, T4 and T5) and this reflects the amount of fertilizer applied. However, the amount of total N was higher and comparable in treatments with PLB compared to treatments with only compound fertilizer. This demonstrates that PLB can retain N in the soil in slow release.

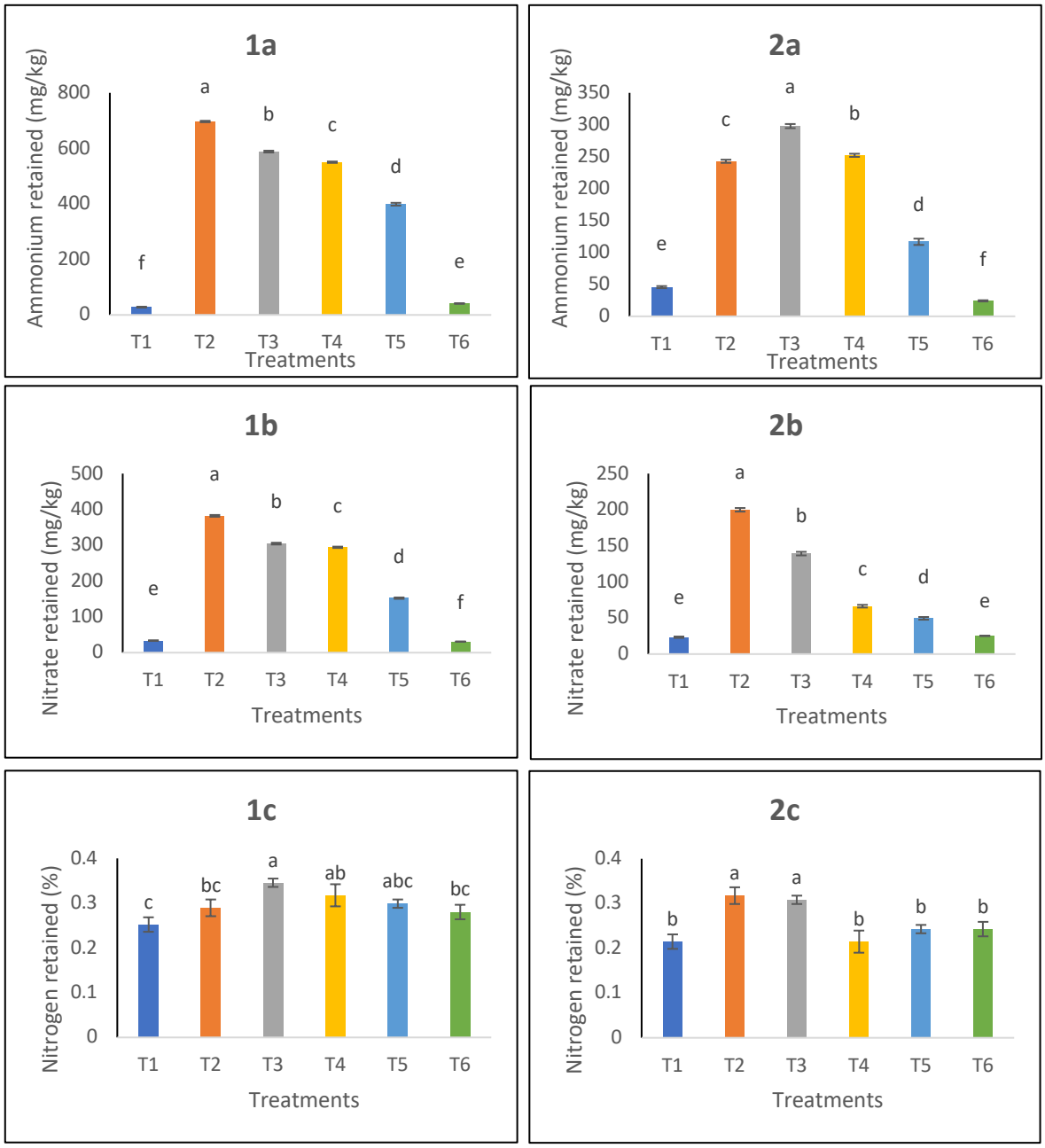

Figure 3. Effects of different treatments on retention of soil exchangeable NH_4^+, available NO_3^- and total N after at thirty days of leaching on alluvial (1a, 1b & 1c) and red yellow podzolic soils (2a, 2b & 2c). Different letters within each row indicate significant differences at p <0.05 based on Tukey's HSD. T1 = absolute control; T2 = 100% CF (control); T3 = 75% CF + 25% PLB; T4 = 50% CF + 50% PLB; T5 = 25% CF + 75% PLB; T6 = 100% PLB

However, as the mineralization of N continued from the compound fertilizer, NH_4^+ and NO_3^- were released with increasing time and the organic contents of PLB improved soil exchangeable NH_4^+ retention because of the increasing negative charges from PLB as the biochar has a net negative charge at agriculturally relevant pH (>6). Therefore, it is suitable for the retention of NH_4^+ (Weldon *et al.* 2022). The improvement in NH_4^+ and NO_3^- retention in both soils counters the downward movement of water through the soil profile. For N retention on biochar, it is suggested that biochar is a better sorbent for NH_4^+ and NO_3^- (Zhang *et al.*2020; Jellali *et al.* 2022). Al-Wabel *et al.* (2018) mention that biochar is also regarded a soil organic amendment which is capable of reducing N loss in soils. The higher soil organic matter of PLB (Table 2) has direct and positive impact on the capacity of the soil to retain N.

CONCLUSION

Pineapple leaf biochar enhances plant-available NH_4^+ and NO_3^- in alluvial and red yellow podzolic soils by fostering microbial activity and providing additional adsorption sites. This indirectly improves the retention availability of N while controlling their leaching in both mineral soils. The PLB combined with compound fertilizer can significantly improve nitrogen availability by up to 20% through temporary retention and enhance the soil chemical properties by mitigating nitrogen leaching and causing lower losses of NH_4^- and NO_3^- compared to compound fertilizer alone. Thus, PLB acts as a slow-release fertilizer, temporarily immobilizing NH_4^+ through adsorption and gradually releasing it over time. Therefore, PLB emerges as a promising amendment for optimizing and mitigating nitrogen (N) management in tropical soils. An in-depth understanding of the long-term effects of PLB on soil microbial communities and nutrient dynamics, exploring its synergistic potential with other organic amendments or fertilizer practices, and modelling nutrient leaching under diverse environmental conditions are crucial for future research directions in sustainable N management.

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