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Ground Sago Bark Ash for Mitigating Major Nutrients Leaching in Tropical Peat Soil

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ABSTRACT

Tropical peat soils in Sarawak, Malaysia, are inherently acidic, nutrient-deficient, and highly susceptible to nutrient leaching under conventional fertilization practices. Ground sago bark ash (GSBA), an alkaline by-product derived from the sago processing industry, has potential to be used as soil amendment for mitigating major nutrient losses. A 30-day leaching experiment was conducted to determine the effects of combined application of GSBA with urea, Egyptian rock phosphate (ERP), and muriate of potash (MOP) on soil pH, major nutrient availability, and nutrient leaching behavior in tropical peat soil. After 30 day of soil leaching, co-application of GSBA with conventional fertilizers enhanced phosphorus retention but not significantly retained nitrogen and potassium. Although GSBA exhibited a slight positive effect on soil available phosphorus retention, GSBA has no effect to substantially improve soil N and K retention, as evidenced by the higher amounts of N and K leached from GSBA-treated soils and the lower residual N and K in the soil after 30 days of leaching study. In leaching study, co-application of GSBA with conventional fertilizer to mitigate N and K losses in peat soils, and its use as a peat soil amendment might not provide comparable N and K retention benefits to conventional fertilizers.

Keywords: bark ash, leaching, nutrient retention, tropical peat soil

INTRODUCTION

Tropical peat soils in Malaysia are characterized by high organic matter content, persistent waterlogging, and inherently low pH (Pakir et al., 2025). These physicochemical conditions contribute to poor nutrient retention and severe leaching losses, particularly for mobile and essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K). Seasonal rainfall patterns further intensify nutrient depletion; during wet seasons, increased percolation enhances the leaching of N, P, and K resulting in elevated groundwater nutrient concentrations (Anggat *et al*., 2024). In addition, the strong acidity of peat soils, coupled with the presence of toxic cations such as aluminium and ferum limits root growth and impairs nutrient uptake efficiency (Paramisparam *et al*., 2021). Malaysia contains approximately 25,000 km² of peat soils, ranking eighth globally in total peatland area (Radwan *et al*., 2021). Despite their ecological fragility, large portions of these peatlands in Southeast Asia are being converted to agricultural use, including the cultivation of maize and oil palm. However, their low cation exchange capacity (CEC), poor nutrient buffering capacity, and high rainfall exposure render conventional fertilization practices inefficient. Fertilizers such as urea, Egyptian rock phosphate (ERP), and muriate of potash (MOP) are prone to rapid leaching, leading not only to nutrient wastage and low fertilizer use efficiency but also to contamination of water bodies. Hence, developing sustainable, low-cost soil management strategies to enhance nutrient retention and improve fertilizer efficiency in tropical peatlands is a pressing need. Ground sago bark ash (GSBA) has a potential to be used as sustainable organo-mineral soil amendment. GSBA is an alkaline, mineral-rich by-product generated from the combustion of sago bark during sago starch processing, an abundant agricultural waste from the sago flour industry in Sarawak. In previous studies, several organic amendments applied to the tropical peat soil for fertility improvement, for example biochar (Khairunnisa *et al*., 2021), organic solid waste from agro-industries (Sari *et al*., 2023), and biosolid (Lugo-Avilés *et al*., 2024). Utilizing GSBA provides a dual advantage such as waste valorization and soil fertility improvement. It was reported that when GSBA co-applied with charcoal, the combination amendments can increase soil pH, enhance soil CEC, and improve soil K availability while reducing exchangeable acidity and mitigating aluminium and ferum toxicity (Hamidi *et al*., 2021; Paramisparam *et al*., 2021). The alkaline nature and high CEC of GSBA enable it to neutralize soil acidity, bind cations, and reduce the mobility of nutrients, thus minimizing leaching losses. Despite these promising findings, the potential of GSBA to mitigate nutrient leaching in fertilized tropical peat soils has not been thoroughly investigated.

Exploring the synergistic effects of GSBA when combined with major fertilizers such as urea, ERP, and MOP could provide valuable insights into its effectiveness as a sustainable amendment for improving nutrient retention, reducing fertilizer losses, and promoting resilient peatland management in Malaysia. The objective of this study is to evaluate the effectiveness of GSBA in mitigating major nutrient losses from fertilized tropical peat soil. Specifically, the study aims to determine the effects of GSBA co-applied with urea, ERP, and MOP on soil pH, N, P, and K availability, and N, P, and K leaching dynamics. It is hypothesized that the co-application of GSBA with conventional fertilizers (urea, ERP, MOP) will increase soil pH and reduce acidity in tropical peat soil, enhance N, P, and K retention and minimize these major nturients leaching losses, and improve overall nutrient availability compared to conventional fertilization alone. This study contributes to the development of sustainable soil management practices for tropical peatlands by introducing an environmentally sound and economically viable solution for major nutrient loss mitigation. The findings are expected to demonstrate the potential of GSBA as a circular-economy soil amendment that converts agro-industrial waste into a valuable input, provide a scientific basis for integrating GSBA into peatland nutrient management strategies, and support national and regional efforts toward reducing agricultural pollution and promoting sustainable fertilizer use efficiency in peat-based agroecosystems.

MATERIALS AND METHODS

Characterization of peat soil selected chemical properties and ground sago bark ash

The peat soil used in a leaching study was sampled from Kg Sau, Mukah, Sarawak, Malaysia, at a depth of 0–25 cm, air-dried, and sieved (2 mm) for initial physicochemical characterization. The soil was air dried, and ground passed a 2 mm sieve for initial characterization. Soil CEC was determined using the leaching method (Harada and Inoko, 1980) and total N by steam distillation (Bremner, 1965). Soil pH was determined in a ratio of 1:2 (soil: distilled water suspension) using a pH meter. Total C, N, and organic matter of the soil were determined using loss on ignition method (Tan, 2005). The method of Keeney and Nelson (1982) was used to extract exchangeable ammonium and available nitrate after which their contents were determined using steam distillation. Soil available P was extracted using the double acid method (Tan, 2005) followed by the molybdenum blue method (Murphy and Riley, 1962). Exchangeable cations were extracted using the leaching method (Tan, 2005) after which their contents were determined using Atomic Absorption Spectrophotometry (Analyst 800, Perkin Elmer, Norwalk, USA).

As summarized in Table 1, the peat soil used in this study exhibited characteristics typical of tropical peat soils, with notable variations compared to previously reported values in the previous studies (**Table 1**). The soil was strongly acidic (pH 4.1), which is consistent with the range (pH 3.4–3.5) as reported by Choo *et al*. (2020) for similar tropical peat soils in Sarawak. Such low pH values are commonly attributed to the accumulation of organic acids during peat decomposition and limited base cation exchange. The electrical conductivity (EC) of 178.7 µS cm^{-1} falls within the range (172.7–178.5 µS cm^{-1}) as reported by Choo and Ahmed (2017), indicating a comparable level of soluble salts and confirming the low salinity typical of freshwater peat environments. In contrast, the soil contained a lower total N (0.35%) than the reported range (1.12–1.41%) by Choo *et al*. (2020), suggesting a more advanced stage of peat decomposition or N loss through leaching and volatilization under humid tropical conditions. Total P (68.25 mg kg^{-1}) was recorded for this study, though comparable literature data are unavailable. The relatively low available P (8.74 mg kg^{-1}) compared with Choo et al. (2020) (32.6–39.7 mg kg^{-1}) implies strong P fixation and adsorption by organic colloids or iron–aluminum complexes in acidic conditions.

The exchangeable K^+ (18.65 mg kg^{-1}) was also lower than previously reported values (29.4–35.8 mg kg^{-1}) (**Table 1**), indicating possible depletion due to high leaching potential. However, the total K^+ content (1380 mg kg^{-1}) was considerably higher than that reported by Krishnan *et al*. (2021) (207.23 mg kg^{-1}), suggesting that the soil still contains substantial reserves of non-exchangeable potassium bound to organic matter or clay minerals. Soil CEC of 6.2 cmol(+) kg^{-1} was markedly lower than the range reported by Choo et al. (2020) (141.6–148.4 cmol(+) kg^{-1}). Such a reduction may be attributed to intensive peat decomposition, loss of humic substances, or dominance of non-active organic colloids that limit nutrient retention. Likewise, ammonium (6.54 mg kg^{-1}) and nitrate (8.87 mg kg^{-1}) concentrations were much lower than those reported by Choo *et al*. (2020) (98.3–142.5 mg kg^{-1} and 76.3–87.9 mg kg^{-1}, respectively), suggesting limited mineralization and rapid nitrogen losses through leaching and denitrification. Despite the overall low nutrient status, the soil exhibited organic matter content (99.14%) and total organic carbon (57.41%), consistent with the findings of Krishnan *et al*. (2021) (94.27% OM; 54.68% C). This indicates that the peat remains largely undecomposed and retains a substantial organic carbon pool, which plays a critical role in nutrient adsorption and water retention.

Table 1. Selected physical and chemical properties of tropical peat soil sampled at Mukah

Property	Current study	Range	References
pH (water)	4.1	3.4 (±0.02) - 3.5 (±0.05)	Choo et al. (2020)
EC (µS cm^{-1})	178.7	172.7a ±2.4 - 178.5a ±4.6	Choo & Ahmed (2017)
Total N (%)	0.35492	1.41 (±0.003) -1.12 (±0.007)	Choo et al. (2020)
Total P (mg/kg)	68.250	N.A	N.A
Total K^+ (mg/kg)	1380	207.23 ± 0.005	Krishnan et al. (2021)
Total Ca^{2+} (mg/kg)	1094.5	740 ± 0.05	Krishnan et al. (2021)
Total Mg^{2+} (mg/kg)	568	686.4 ± 0.13	Krishnan et al. (2021)
CEC (cmol(+) kg^{-1})	6.2	148.4 (±3.76) - 141.6 (±2.39)	Choo et al. (2020)
Available P (mg kg^{-1})	8.740	32.6 (±0.75) - 39.7 (±0.58)	Choo et al. (2020)
Exchangeable K^+ (mg kg^{-1})	18.647	29.4 (±0.53) - 35.8 (±0.79)	Choo et al. (2020)
Ammonium (mg kg^{-1})	6.538	142.5 (±3.05) - 98.3 (±2.58)	Choo et al. (2020)
Nitrate (mg kg^{-1})	8.873	76.3 (±1.47) - 87.9 (±2.53)	Choo et al. (2020)
Organic matter (%)	99.14	94.27 ± 3.7	Krishnan et al. (2021)
Total organic carbon (%)	57.4084	54.68 ± 2.1	Krishnan et al. (2021)

Note: EC is electrical conductivity; N is nitrogen; P is phosphorus; K is potassium; Ca is calcium; Mg is magnesium; CEC is cation exchange capacity; The values given are means followed by ± standard error.

The GSBA used in this study was collected at Sagolink Sdn Bhd., Mukah, Sarawak and was analysed for selected physico-chemical properties as summarized in Table 2. The GSBA exhibited distinct alkaline and nutrient-rich characteristics (**Table 2**), reflecting its potential as a soil amendment material. The pH (7.79) indicates that the GSBA is moderately alkaline**,** which has potential to be used in peat soil to neutralize soil acidity. This alkalinity is attributed to the presence of basic oxides and carbonates of calcium, potassium, and magnesium produced during the combustion process.

The EC value of 179 µS cm^{-1} suggests a moderate concentration of soluble salts**,** indicating that the ash contains readily available ions without posing a salinity risk when applied in moderate quantities. However, the CEC of 2.77 cmol(+) kg^{-1} is relatively low, implying that the ash has limited ability to retain cations due to its predominantly mineral composition and low proportion of reactive organic colloids. The GSBA contained low total nitrogen (0.056%)**,** consistent with the thermal decomposition of organic matter during combustion, which typically volatilizes N. The organic matter (11.62%) and total organic carbon (6.74%) indicate the partial presence of incompletely burned carbonaceous material, which may still contribute to some degree of nutrient adsorption and slow nutrient release.

Table 2. Selected chemical properties of ground sago bark ash used in the study

Property	Ground Sago Bark Ash
pH (water)	7.79
EC (µS cm^{-1})	179
CEC (cmol kg^{-1})	2.767
Total N (%)	0.056
Organic matter (%)	11.624
Total organic carbon (%)	6.74192
------------------------------(mg kg^{-1})--------------------------	
Available P	17.288
Exchangeable K^+	27752
Exchangeable Ca^{2+}	6467.5
Exchangeable Mg^{2+}	1370.4
Total P	6831.75
Total K	53953.333
Total Mg^{2+}	17300
Total Ca^{2+}	35275
Ammonium	4.203
Nitrate	5.8375

Note: EC is electrical conductivity; CEC is cation exchange capacity; N is nitrogen; P is phosphorus; K is potassium; Ca is calcium; Mg is magnesium;; The values given are means followed by ± standard error.

Soil leaching experiment set up

A soil leaching experiment was carried out for 30 days in the Soil Science Laboratory of Universiti Putra Malaysia Sarawak, Malaysia. The treatments evaluated in this experiment are summarized in **Table 3**. GSBA was applied at rates of 100% in T3 (without chemical fertilizers), and co-applied at 100%, 80% and 60% in other treatments with conventional fertilizers based on standard recommendation for maize cultivation (based on a planting density of 66,666 plants ha^{-1}) in a 30-day leaching experiment.

The study employed a completely randomized design with three replications, using 1 kg of soil per polypropylene container, which was perforated and lined with filter paper to collect leachates. Treatments were moistened to 60% field capacity, surface-applied with fertilizer (except control), and leached at 5-day intervals using distilled water volumes equivalent to average monthly rainfall derived from 10-year data.

Leachates were analyzed for pH, EC, soil exchangeable ammonium and available nitrate, available P (molybdate blue) and exchangeable K (flame photometry). After 30 days of leaching study, post-leaching soils were tested for pH and EC by using potentiometric method, organic matter and total carbon by using loss on ignition method, total N by using Kjeldahl method, soil exchangeable ammonium-nitrate and available nitrate-nitrogen by using steam distillation, total P, and cations by using single dry ashing method and available P and exchangeable cations by using double acid method. All statistical analyses were conducted using SAS software, version 9.4 (SAS Institute, Cary, NC, USA), with means separated by Tukey's HSD at $p \leq 0.05$.

Table 3. Treatment composition tested in a soil leaching study

Treatment	**Ground Sago Bark Ash (g)**	**Urea (g)**	**ERP (g)**	**MOP (g)**
TI	-	-	-	-
T2	-	7	7	4
T3	50	-	-	-
T4	50	5.6	5.6	3.2
T5	50	4.2	4.2	2.4
T6	40	5.6	5.6	3.2
T7	40	4.2	4.2	2.4
T8	30	5.6	5.6	3.2
T9	30	4.2	4.2	2.4

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

RESULTS AND DISCUSSION

The pH of leachate and nutrients leached over thirty days of leaching study

The incorporation of GSBA demonstrated significant effects on the soil pH with the higher pH observed in all soil treated with co-application of GSBA with conventional fertilizers compared (T3 – T9) compared with conventional fertilizer alone (T2) (**Figure 1**). The higher pH in all leachates with GSBA is attributed to the inherent alkalinity of GSBA (**Table 2**), which counteract soil acidity (**Figure 1**). These effects are particularly relevant for peat soils, which naturally contain high organic matter (**Table 1**). Nutrient leaching analysis revealed complex interactions between GSBA and conventional fertilizers.

Ammonium leached was more pronounced in T2 (conventional fertilizer without GSBA) among all treatments suggesting that the higher NH_4^+ loss through leaching without addition of GSBA (**Figure 2**). The results indicate that the soil receiving a higher N input in T2 exhibited substantially greater NH_4^+ loss compared to the soil treated with a lower N rate as observed in T3 to T9. The higher loss in T2 is attributed to the greater availability of NH_4^+ generated during the hydrolysis of urea without GSBA. The greater GSBA addition in T4 has no significant effects on enhancing NH_4^+ retention compared with T6 and T8 (similar urea amount but differ in GSBA addition). For T6 and T8, where lower GSBA application rates resulted in lower NH_4^+ leaching. This indicates that the performance of T4 is a function of the disproportionate GSBA quantity rather than the urea application rate, highlighting the importance of considering material dosage when evaluating treatment effectiveness.

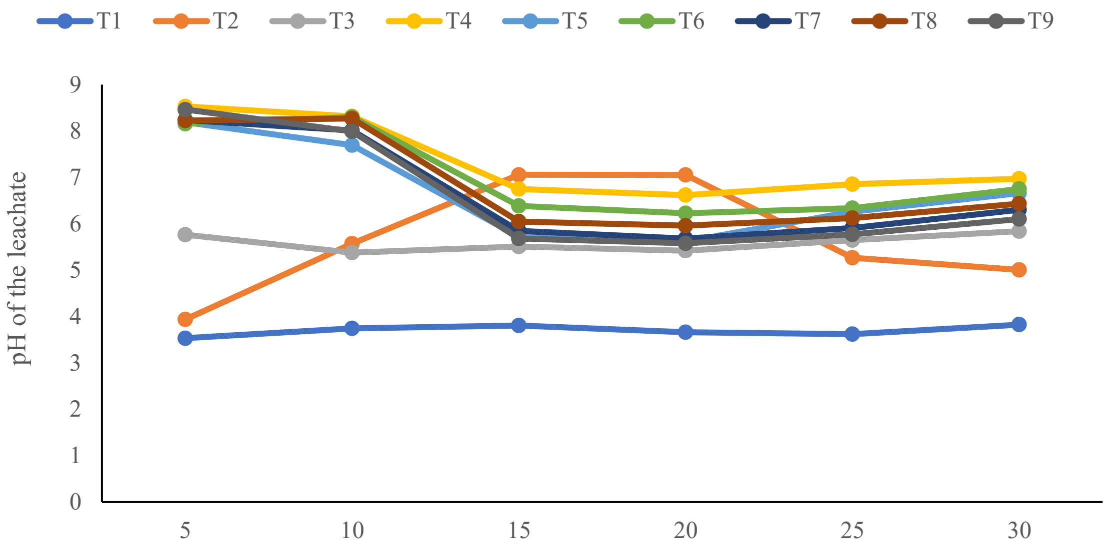

Figure 1. pH value in the leachate over thirty days of leaching

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

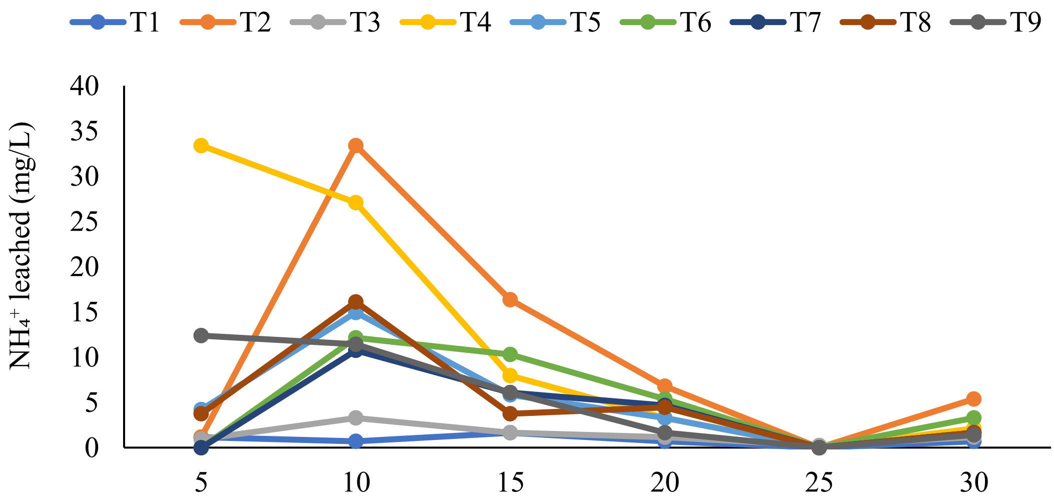

Figure 2. Ammonium content in the leachate over thirty days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

The lower NO_3^- leached observed in T2 compared to all conventional fertilizers added with GSBA (T4 - T9) could be attributed to the fact that most of the applied N in T2 was leached in the form of NH_4^+ as previously mentioned in **Figure 2**. As substantial NH_4^+ leaching occurred prior to nitrification, less NH_4^+ remained available in the soil for conversion to NO_3^-.

Consequently, the reduced substrate for nitrification resulted in lower NO_3^- concentrations and, therefore, lower NO_3^- leaching in T2 compared with other treatments (**Figure 3**). This suggests that the pathway of N loss in T2 occurred at the NH_4^+ phase rather than after nitrification (**Figure 3**). The treatment combining 80% GSBA application with 80% conventional fertilizer (T7) showed the lowest losses of both NH_4^+ and NO_3^- among all treatments. The 80% reduced rate of GSBA and conventional fertilizer (T7) decreased the instantaneous pool of mineral N in the soil solution, lowering concentration-driven fluxes that promote N leaching. With less surplus mineral N present after application, there was a smaller reservoir available for rapid loss pathways.

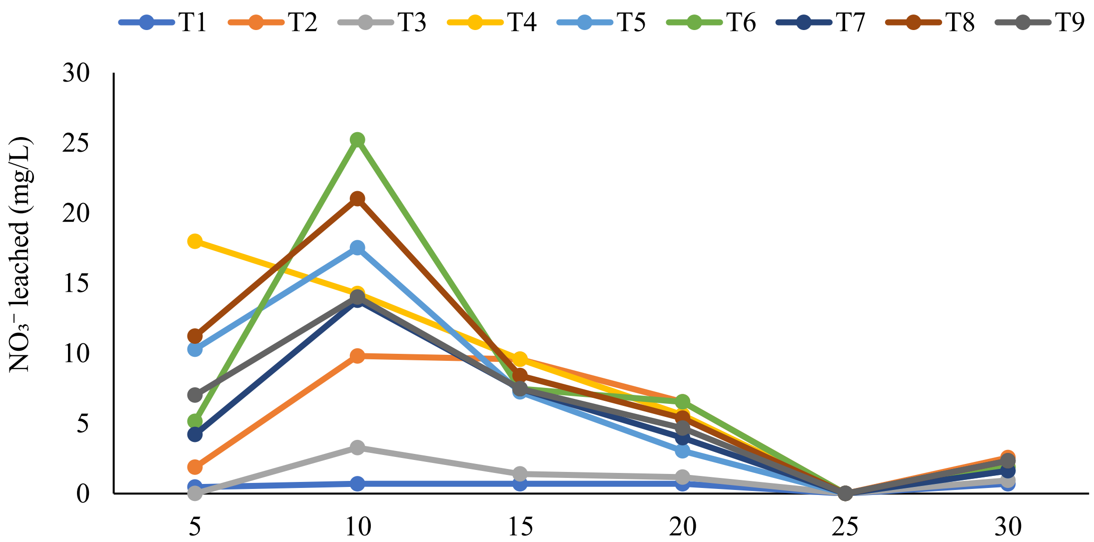

Figure 3. Nitrate content in the leachate over thirty days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

Similar to N losses, the higher P leaching in soils fertilized with larger amounts of P from ERP in T2 indicates that the high external P input exceeded the soil's retention capacity, resulting in greater P mobility and subsequent loss (**Figure 4**). In contrast, soils amended with GSBA showed moderate P leaching despite receiving similar or lower P inputs. This suggests that GSBA improved P retention within the peat matrix. Soils amended with GSBA showed a more moderate amount of P leached despite receiving similar P inputs. This suggests that GSBA improved P retention by providing additional adsorption sites or enhancing the soil matrix stability, thereby reducing the mobility of phosphate ions. The characteristics of GSBA such as higher surface area, functional groups, and calcium or magnesium rich compounds partly contributed to the increased immobilization or slow release of P, effectively mitigating P loss.

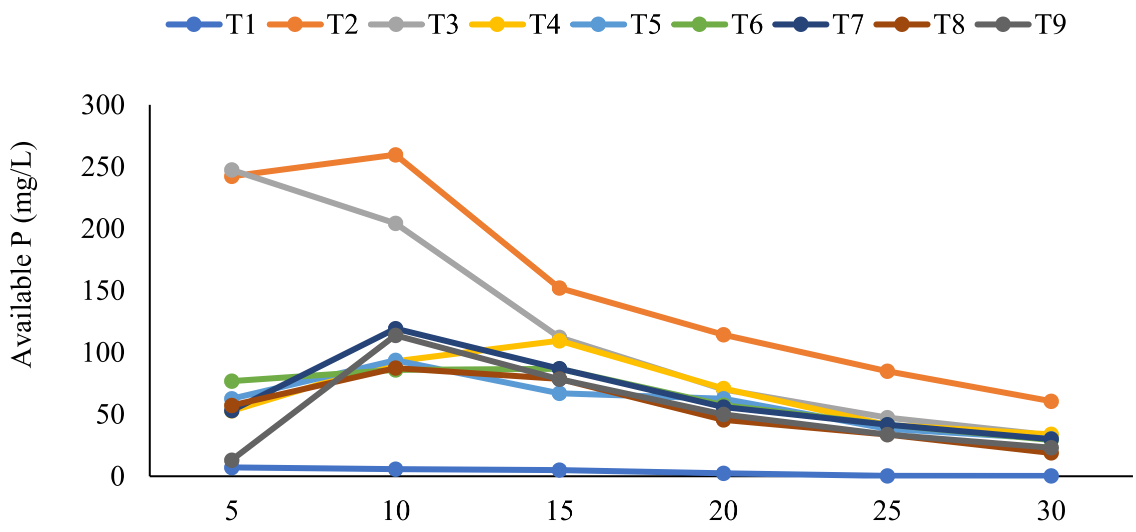

Figure 4. Phosphorus content in the leachate over thirty days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

The higher K leaching in all soils amended with GSBA is seemingly due to the intrinsically high K content present in the GSBA. Owing to GSBA contributes a substantial amount of readily exchangeable K to the soil, the concentration of soluble K in the soil solution increases as compared to conventional fertilizers, which have comparatively lower K inputs. When the soil's exchange complex becomes saturated with K, the excess ions are prone to displacement and downward movement, leading to elevated K leaching rates. Therefore, while GSBA enhances overall nutrient availability, its high inherent K content results in greater K mobility and leaching relative to conventional fertilizer treatments (**Figure 5**).

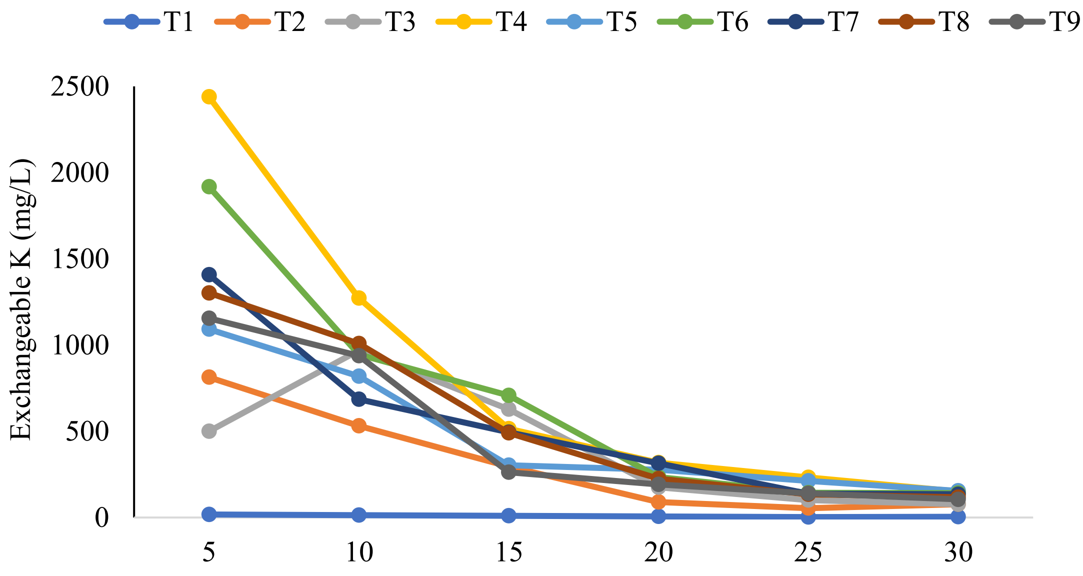

Figure 5. Exchangeable potassium content in the leachate over thirty days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

Soil pH and soil major nutrients after thirthy days of leaching study

There is no significant difference in soil pH was observed between soils treated with conventional fertilizers and those amended with GSBA after 30 days of leaching (Figure 6). This outcome could be attributed to the substantial leaching of base cations such as K^+ from the GSBA during the leaching period, reducing the GSBA liming effect as observed in Figure 5. Although GSBA initially contains alkaline constituents capable of increasing soil pH, the continuous removal of these cations through leaching seemingly minimized pH elevation after 30 days of leaching study. Additionally, partial retention of some cations within the soil matrix may have contributed to maintaining a slightly acidic condition. Peat soils, characterized by high organic matter and intrinsic acidity, also exhibit limited buffering capacity, further explaining the minimal pH variation over 30 days of leaching study. Previous studies have similarly reported that ash-induced pH increases are not sustained when high leaching potential exists, especially in organic soils (Vassilev *et al*., 2013).

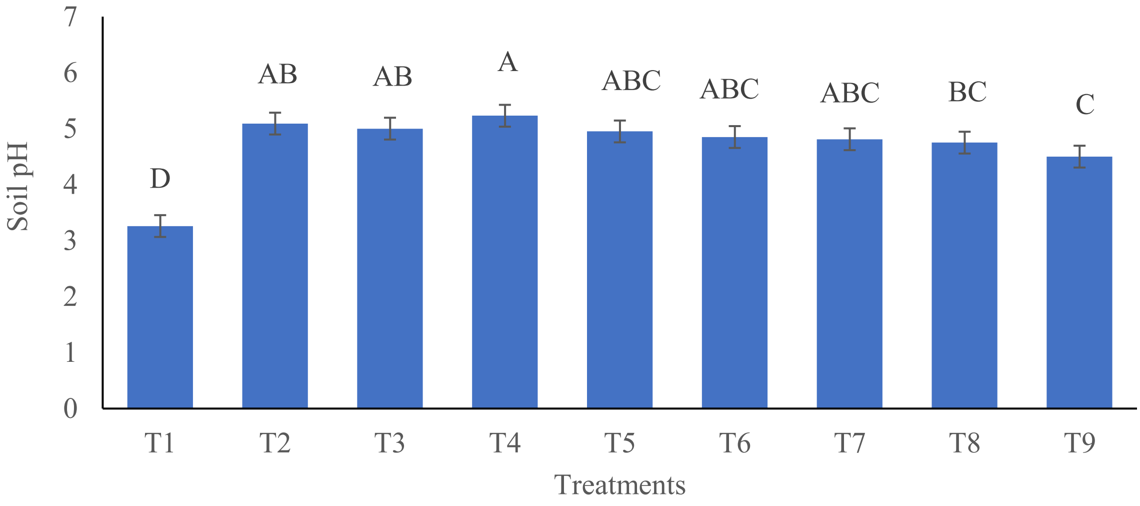

Figure 6. Soil pH after 30 days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

Ammonium and NO_3^- retention in soil was found to be higher under conventional fertilizer application than in GSBA-treated soils (**Figures 7 and 8**). This difference can be explained by the limited capacity of GSBA to retain N, as most of the N supplied was rapidly transformed into NO_3^- and subsequently lost through leaching as corroborated in Figures 2 and 3. The porous and weakly charged nature of peat soils provides minimal adsorption surfaces for NH_4^+, and the presence of GSBA did not appear to enhance NH_4^+ fixation. Furthermore, the accelerated nitrification of NH_4^+ into NO_3^-, an anion that is highly mobile in peat environments seemingly contributed to the reduced NH_4^+ accumulation in GSBA-amended soils. These findings indicate that GSBA has negligible effects in retaining soil N, particularly when N loss occurs predominantly in the form of NO_3^-, corroborating earlier findings that peat soils exhibit high NO_3^- leaching due to low anion-exchange capacity.

Treatment with GSBA resulted in significantly higher P retention in the peat soil compared with conventional fertilizer (**Figure 9**). This outcome likely reflects GSBA's alkalinity and its high P and Ca content which favor precipitation and stabilization of P into less mobile Ca-bound forms and increase the soil's pH buffering capacity. Additionally, ash particles and associated porous matrices created by co-amendments (GSBA) provide adsorption or occlusion sites for phosphate, limiting downward P transport during leaching events. These mechanisms collectively explain the lower P losses from GSBA-amended peat relative to conventional fertilizers.

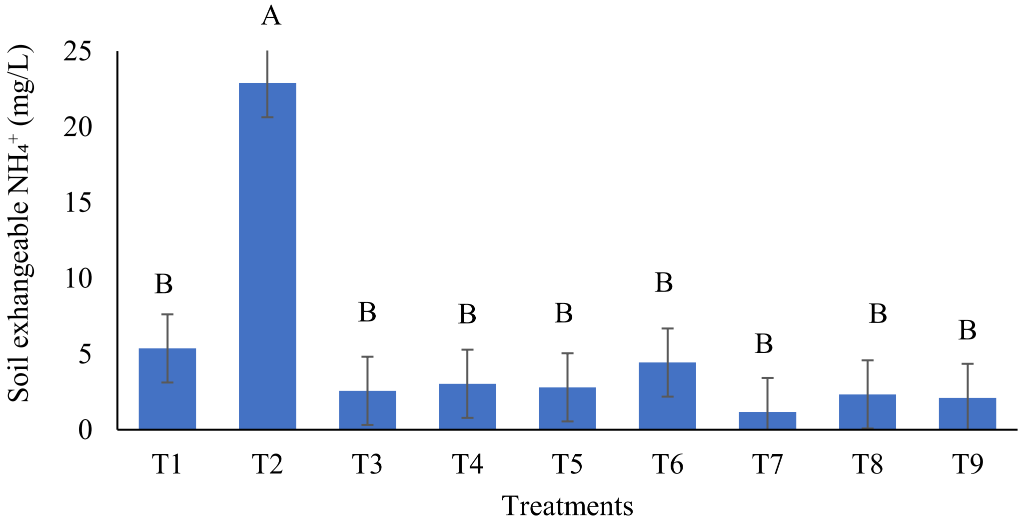

Figure 7. Soil exchangeable ammonium after 30 days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

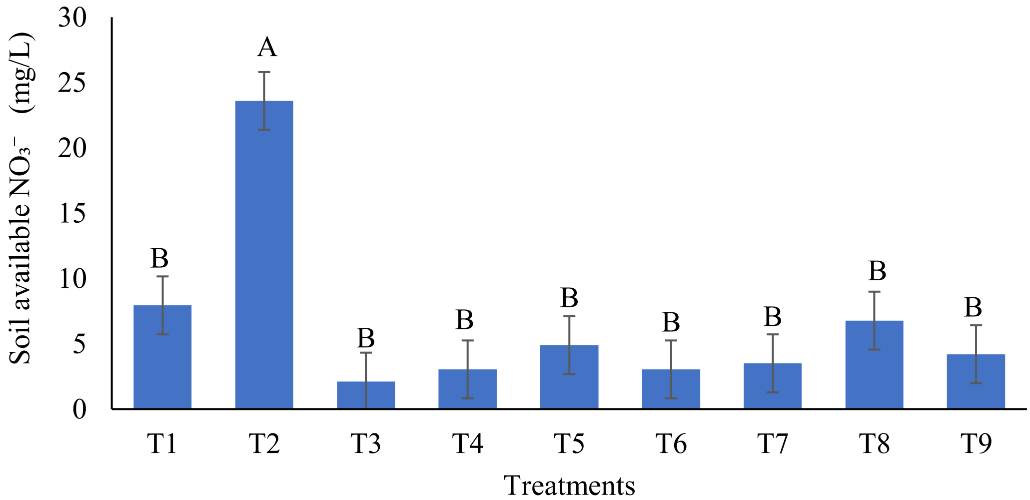

Figure 8. Soil available nitrate after 30 days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

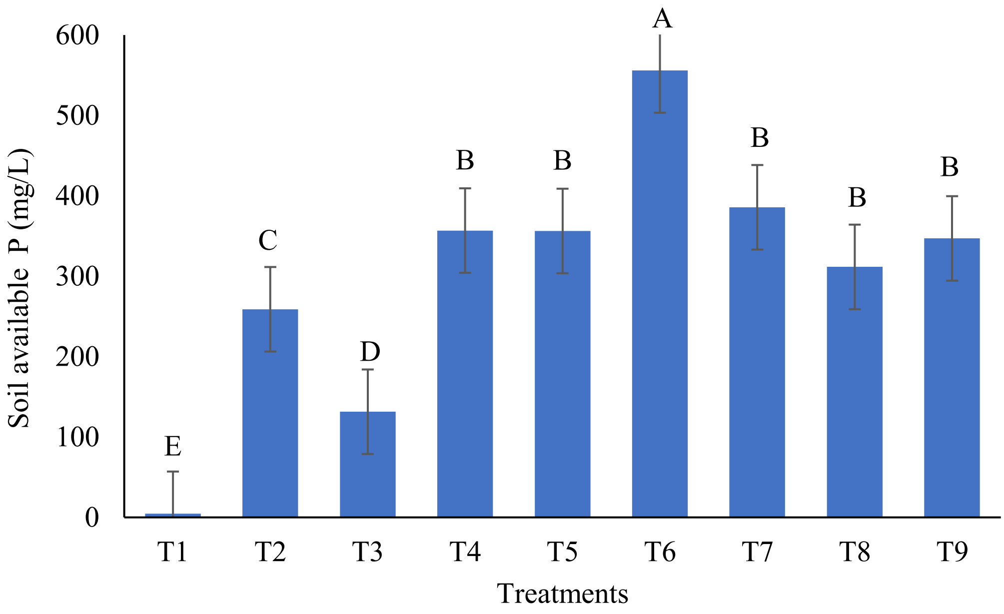

Figure 9. Soil available phosphorus after 30 days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

Soil exchangeable K concentrations in soil after the leaching period were significantly higher in the treatment receiving conventional K fertilizer compared to the soil amended with GSBA suggests that GSBA did not contribute significantly to K retention in soil after 30 days of leaching study (**Figure 10**). Despite of GSBA inherently contains K, the form in which K is present in the GSBA may be less available for strong sorption to soil exchange sites, or probably subject to leaching, compared to the more soluble and exchangeable forms provided by conventional fertilizers (MOP). This is supported by related work showing that water-soluble K derived from sago bark ash does not necessarily accumulate in the soil in the similar way as exchangeable K derived from mineral K fertilizers. For instance, Paramisparam *et al*. (2021) reported that co-application of sago bark ash and MOP increased exchangeable K, yet they observed no significant improvement in soil exchangeable K in soils over a 90-day incubation.

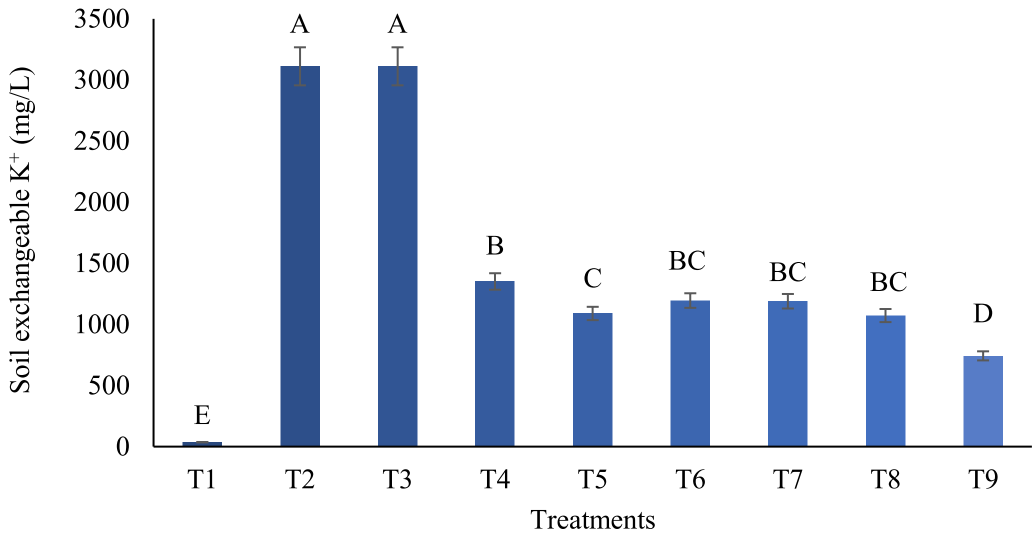

Figure 10. Soil exchangeable potassium at 30 days of leaching.

Notes: T1 is Treatment 1 (Soil Only); T2 is Treatment 2 (100% standard fertilizer recommendation); T3 is Treatment 3 (100% ground sago bark ash); T4 is Treatment 4 (100% ground sago bark ash + 80% standard fertilizer); T5 is Treatment 5 (100% ground sago bark ash + 60% standard fertilizer); T6 is Treatment 6 (80% ground sago bark ash + 80% standard fertilizer); T7 is Treatment 7 (80% ground sago bark ash + 60% standard fertilizer); Treatment 8 (60% ground sago bark ash + 80% standard fertilizer); Treatment 9 (60% ground sago bark ash + 60% standard fertilizer).

CONCLUSION

Co-application of conventional fertilizer with GSBA did not significantly enhance N and K retention in peat soil compared with conventional fertilizer application. Although GSBA exhibited a slight positive effect on soil available P retention, GSBA has no effect to substantially improve N and K retention, as evidenced by the higher amounts of N and K leached from GSBA-treated soils and the lower residual N and K in the soil after 30 days. These results suggest that, under the conditions of this study, co-application of GSBA with urea, ERP, and MOP to mitigate major nutrients such as N and K losses in peat soils, and its use as a peat soil amendment might not provide comparable N and K retention benefits to conventional fertilizers.

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