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# Ameliorating Sapric Soil Potassium Availability and Enhancing *Ananas comosus* L. Merr cv. MD2 Productivity via Clinoptilolite Zeolite

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## ABSTRACT

*Insufficient supplies of potassium ($K^+$) in acidic sapric soils impedes pineapple growth and development, fruit quality attributes, and yield. Clinoptilolite zeolite was incorporated in the MD2 pineapple fertilization programme to evaluate this mineral's effectiveness to improve peat soils' $K^+$ availability and pineapple productivity. Field studies with two MD2 pineapple seasons and laboratory leaching column experiments were utilized to determine $K^+$ availability in drained sapric soils with the following treatments: (i) four rates of clinoptilolite at 25, 60, 75, and 100% incorporated with compound NPK 30:1:32 fertilizer, (ii) standard pineapple fertilization (NPK 30:1:32), and (iii) untreated soils. Clinoptilolite amended sapric soils improved $K^+$ availability due to the absorption of $K^+$ ions onto clinoptilolite's lattices and surface frameworks via ion exchange and mass transport. Co-application of clinoptilolite (100%) and NPK 30:1:32 was more effective in improving peat $K^+$ availability, whereas clinoptilolite fertilization at rates of 25 to 100% improved soil pH (pH: 4.27 – 5.62), increased pineapple K uptake and use efficiency, and yield (2.42–2.66 kg/fruit or 92.0–101.1 t/ha) due to the ability of clinoptilolite to regulate soil exchangeable $K^+$ ions for optimum MD2 plant uptake compared with standard pineapple fertilization (1.50–1.76 kg/fruit or 57.0–66.9 t/ha). The recommended clinoptilolite fertilization (25% zeolite + NPK 30:1:32) at the vegetative (3- and 6-months plant age) and flower induction (9 months plant age) phase provides alternative agronomic management for pineapple growers to improve peat soil productivity without compromising MD2 yield production.*

**Keywords**: histosols, natural zeolite, pineapple, potassium, soil conditioners

## INTRODUCTION

There are 2.6 million hectares of peat soils in Malaysia (Vijayanathan *et al.,* 2021) and these organic soils or 'histosols' are designated as problematic soils (Class 4) with extreme restrictions for agricultural development (Kang *et al.,* 2013). Peat soils are very acidic (pH 3 – 4), deficient in macro and micronutrients, and their water source depends on precipitation and deposition from the atmosphere (Ratai *et al.,* 2024). Tropical peat soils are K deficient. Although the cation exchange capacity (CEC) of peat soils is high because of the presence of exchangeable hydrogen ($H^+$) from organic acids, peat soils do not easily adsorb exchangeable $K^+$ (Ahmed *et al.,* 2005). This is because the peat humic compounds with functional groups of carboxyl (–COOH) and hydroxyl (–OH) do not establish coordination bonds with monovalent cations like $K^+$ (Maftu'ah *et al.,* 2014) as the $H^+$ ions of the organic acids are firmly attached to their functional groups. Also, $K^+$ is easily leached from peat soils because of their paltry clay content and absence of mineral matter (Ahmed *et al.,* 2013). Although substantial amount of exchangeable $K^+$ exists in the peat soil solution, exchangeable $K^+$ is vulnerable to leaching because $K^+$ ions is highly mobile under high rainfall conditions.

*Ananas comosus* L. Merr, locally known as pineapple plants require higher and constant supply of K compared with nitrogen throughout their growth and development until harvest because K significantly affects fruit quality (Hepton, 2003; Malézieux and Barthalomew, 2003; Ahmed *et al.,* 2006). Furthermore, $K^+$ regulates opening and closing of plant stomata, particularly photosynthesis for the absorption of carbon dioxide (Malézieux and Barthalomew, 2003). Higher amount of $K^+$ increases total soluble solids (TTS) and ascorbic acid content, decrease internal fruit darkening, increase fruit peduncle diameter, and improve fruit aroma, flavour, and pulp firmness (Hepton, 2003; Malézieux and Barthalomew, 2003; Souza and Reinhardt, 2007). Pineapple cultivation in Malaysia is unique because 90% of this cash crop is planted on peat soils with a total acreage of approximately 16,779 ha in 2025 (DOA, 2025). However, the country's pineapple production has deteriorated annually since the 1970s. The declined in pineapple production is not only caused by parasitic nematode infestation (*Paratylenchus* sp.) (Nik Masdek, 2007) and conversion of agricultural peatlands to other high-value crops (e.g. rubber and oil palm), but largely due to the degradation of peat soil quality after extended use for monocrop pineapple cultivation (Suhaimi and Fatah, 2019). Therefore, an effective rehabilitation measure via soil amelioration is required to restore the conditions of degraded peat soils to ensure a sustainable pineapple production.

Natural zeolite of the clinoptilolite species is largely used as an inorganic soil ameliorant to improve clayey, sandy, and acidic soils properties, particularly soil macronutrients retention, acidity, and water holding capacity (Latifah *et al.,* 2017; Jakkula and Wani, 2018; Nur Aainaa *et al.,* 2018). Clinoptilolites are aluminosilicates ($SiO_4$–$AlO_4$) crystalline compounds arrayed in a three-dimensional lattice (Kurniawan *et al.,* 2019; Belviso, 2020). These $SiO_4$–$AlO_4$ lattices consist of open cavities and are affixed with auxiliary exchangeable cations comprising Na, K, Ca, Ba, Sr, Fe, and Mg (Wahono *et al.,* 2020). The open cavities of clinoptilolites are interlinked, erecting long and wide channels that enables the exchange, adsorption, and mobilization of ions and molecules within the zeolite's structured lattices. Because of clinoptilolite's high CEC and cation frameworks, zeolite fertilization may facilitate sorption and desorption of $K^+$ ions to improve soil $K^+$ availability via ion exchange. Moreover, the alkaline nature of clinoptilolite may increase $K^+$ availability by reducing soil acidity. To date, there are limited agronomic guidelines on the utilization of clinoptilolite as a soil amendment to rehabilitate degraded drained peat soils for pineapple production. Thus, the goal of this present study was to evaluate the effectiveness of incorporating clinoptilolite in the MD2 pineapple fertilization regime to improve peat soil $K^+$ availability, enhance plant growth performance, and increase uptake and use efficiency of K, MD2 yields and fruit attributes. For this, field studies with two MD2 pineapple seasons was conducted to assess whether clinoptilolite fertilization could retained peat soil exchangeable K and improve MD2 pineapple production, whereas laboratory column leaching experiments were utilized to validate the performance of clinoptilolite in controlling the losses of $K^+$ in peat soils throughout the dry and wet seasons. Findings derived from the study could be used to develop viable agronomic guidelines for improving pineapple productivity on drained peat soils using natural zeolites.

## MATERIALS AND METHODS

### Peat soil characteristics and experimental site description

For this study, the evaluation on the effectiveness of clinoptilolite as a potential soil amendment for pineapple production was conducted on drained histosols situated at Saratok district in the region of Sarawak, Malaysia at the following geographical coordinates: latitude 1° 55" N and longitude 111° 14'09" E. The histosols at the site is categorized as extremely degraded organic soil which is sapric in nature and falls in the H7 to H9 classes of the von Post. The mineral soil substratum underlying these organic deposits is sulphidic marine. The sapric peat soils at Saratok are shallow (0.5 m) to deep (3.0 m) organic soils. These organic soils are composed of amorphous materials with barely discernible plant structure. The selected chemical properties of the sapric soil at the study site is presented in **Table 1**. The peat soil is acidic, demonstrating that liming is requisite during land preparation before crop cultivation. The sapric soil have high CEC but low in base saturation. The soil total organic carbon and total nitrogen contents are high, whereas exchangeable $K^+$ is low, which is the norm for cultivated drained peat soils. The peat area at Saratok receives high annual rainfall (3923 mm), whereas reported annual mean temperature was 27.7 °C.

**Table 1.** Selected chemical properties of the sapric soil at Saratok at different depths

| **Soil properties** | **Mean values** | |
|---|---|---|
| | **0 cm to 20 cm** | **20 cm to 40 cm** |
| pH | 3.84 (± 0.06) | 3.91 (± 0.04) |
| Cation exchange capacity ($cmol_{(+)}$/kg) | 141.4 (± 2.1) | 144.9 (± 1.6) |
| Total organic nitrogen (%) | 1.29 (± 0.05) | 1.13 (± 0.02) |
| Total organic carbon (%) | 42.7 (± 0.6) | 43.3 (± 0.4) |
| Exchangeable potassium (mg/kg) | 106.4 (± 0.7) | 89.7 (± 0.9) |

Notes: Values in parentheses represent standard error of the mean

**Selected morphological and chemical features of clinoptilolite zeolite**

Clinoptilolite zeolite in powder form (greyish white) was selected for used in the field and laboratory studies because of the mineral's distinctive ion exchange and nutrient sorption traits. The zeolite mineral was commercially obtained from Indonesia. Chemical pretreatment was not performed on the zeolite mineral to ensure its effectiveness as a soil amendment under field conditions. The clinoptilolite is a crystalline compound with uneven structured particles as demonstrated by the scanning electron microscope (SEM) micrographs in **Figure 1**. The surface area of the clinoptilolite is low (23.19 $m^2$/g), which is typical for the natural zeolite from Indonesia (surface area ranging from 21.5–25.95 $m^2$/g) (Hernawan *et al.,* 2015; Wahono *et al.,* 2019). This clinoptilolite mineral is composed primarily of Si (78.08%), Al (7.03%) and Fe (10.70%) oxides but contained low amount of K (1.29%), Ca (1.27%), Mg (1.10%), and Na (0.53%) oxides. The zeolite is alkaline (pH 8.77) and has a high CEC (103.8 $cmol_{(+)}$/kg), reflecting this mineral's high ion sorption and retention capacity, albeit subjected to the total number of cations within clinoptilolite's lattices and ion selectivity favoured by zeolite.

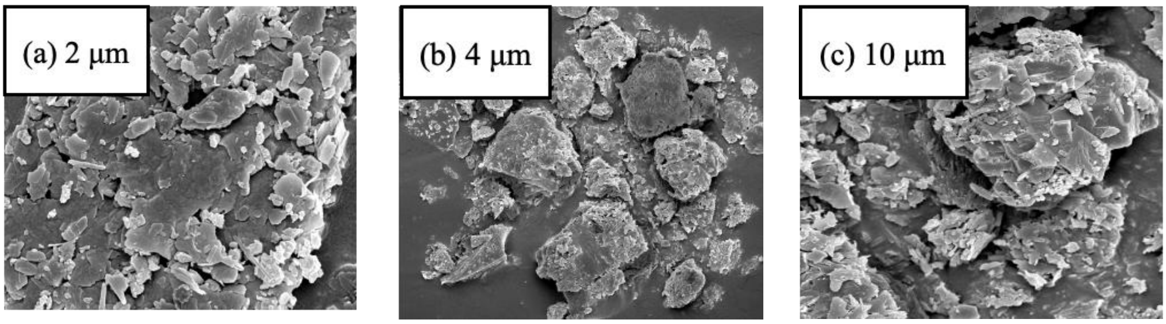



**Figure 1**. Surface morphology of clinoptilolite zeolite at selected optical magnifications

**MD2 pineapple cultivation, field experimental design, and fertilization treatments**

The effects of clinoptilolite fertilization on peat soil exchangeable $K^+$ availability in MD2 pineapple cultivation was monitored for two planting cycles (first season: January 2023 to January 2024 and second season: December 2023 to December 2024). For this field experiment, pineapple cv. MD2 was selected as the test crop because this cultivar is one of the economic drivers under Malaysia's National Key Economic Area due to MD2's high demand in the global premium fruit market, exceptional sweetness (12 to 19°Brix), and long shelf life (~30 days). Prior to pineapple cultivation, approximately 0.054 ha of the peatlands at the study site in Saratok was cleared using the 'clean-clear' technique via hydraulic excavator for the removal of trees, woody biomass, old crop stands, and vegetation. The experimental design utilized in this field study was a randomized complete block design with four blocks and six treatments. The dimensions of each treatment block were 15.7 m (length) x 8.6 m (width). For each pineapple planting cycle, a total of 4200 MD2 suckers (average height of 0.3 m) were planted in two rows on drained sapric soils at a planting distance of 0.3 m x 0.6 m x 0.9 m. There were 400 MD2 pineapple plants for each treatment block. Trenches measuring 0.3 m (width) x 0.5 m (depth) were constructed between treatment blocks to prevent inter-plot fertilizer residual contamination and to drain excessive rainwater during heavy rainfall. The MD2 pineapple care and maintenance were carried out utilizing the standard agronomic guidelines for pineapples planted on tropical peat soils (Mohammed Selamat, 1996). Details of the selected fertilizer treatments assessed in the field experiment is outlined in **Table 2**. The recommended rates of clinoptilolite fertilization were calculated according to the K requirement for MD2 pineapples cultivated on drained peat soils at the vegetative and flower induction phase. Surface application method was used to fertilize the pineapple plants. Treatments (**Table 2**) were placed onto the peat soil approximately 5 cm from the collar of the pineapple stems in a circular manner. For each planting season, fertilizer treatments were applied three times at three, six, and nine months of pineapple plant growth. Throughout the MD2 pineapple growth period, water table depth of the peat soil varies between 41 cm and 56 cm.

**Table 2.** Selected clinoptilolite and NPK fertilization treatments for MD2 pineapple grown on drained sapric peat soils

| Treatments | Application rate (per plant) |
|---|---|
| T1 | 5 g of clinoptilolite (25%) + 20 g of compound NPK 30:1:32 |
| T2 | 12 g of clinoptilolite (60%) + 20 g of compound NPK 30:1:32 |
| T3 | 15 g of clinoptilolite (75%) + 20 g of compound NPK 30:1:32 |
| T4 | 20 g of clinoptilolite (100%) + 20 g of compound NPK 30:1:32 |
| SF | Standard pineapple fertilization for tropical peat soils (positive control): 20 g of compound NPK 30:1:32 |
| NC | Untreated peat soil (negative control) |

**Soil sampling and exchangeable potassium measurement**

Throughout the MD2 pineapple growth and development for each season, peat soil samples were obtained thirty days after fertilization during the vegetative (three and six months of pineapple growth) and flower induction (nine months of pineapple growth) stages. For each treatment (**Table 2**), peat soil sampling was carried out at 10 points within the aerobic horizons (pineapple root areas above the water table) using the zigzag technique at two soil depths (0–20 cm and 20–40 cm), giving a total of 120 soil samples per block. Soil exchangeable $K^+$ was extracted using the Mehlich 3 solution (Mehlich, 1984) after which the extracted $K^+$ was determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP–OES, Perkin Elmer Optima 8000). Peat soil pH in ratios of 1:5 soil to water suspension was measured utilizing a benchtop pH meter (Cyberscan pH 1500).

**MD2 pineapple growth, potassium uptake and use efficiency, yield and fruit attributes**

For each MD2 pineapple season, plant growth variable, particularly plant height was recorded at three, six, and nine months after planting. Heights of the MD2 plants were determined from the base of the pineapple stem to the top of the tallest pineapple leaf using a measuring tape. MD2 fresh fruit pineapples were harvested at 12 months after planting (maturity index 1) in January and December 2024, respectively for the first and second planting season. Harvested pineapple plants were divided into roots, stems, and leaves. Afterward, these plant parts were oven dried at 60 °C, pulverized, and determined for total K. The dry ashing method was used to extract K from the pineapple plant parts (Miller, 1998), after which the extracts were analyzed for K using ICP–OES (Perkin Elmer Optima 8000). Potassium uptake of the MD2 pineapple plants were determined by multiplying the dry weight of roots, stems, and leaves with the concentrations of K in their respective plant parts. Potassium use efficiency of MD2 pineapples were determined using the method of Pomares–Garcia and Pratt (1978). The MD2 fresh fruit weight was determined using an electronic weighing scale (EK-15KL, A&D Company, Toshima-ku, Tokyo, Japan), whereas pineapple fruit yield was calculated according to the average fresh fruit weight and planting density of the MD2 pineapples (Liu *et al.,* 2013). Fresh MD2 fruits with similar ripening attributes (maturity index 5: 50% ripe) were selected and determined for total soluble solids (TSS) using the method of Siti Rashima *et al.* (2019), whereas titratable acidity (TA) was measured using the technique by Hajar *et al.* (2012).

**Laboratory soil potassium leaching experiment**

Laboratory soil column studies (Owen and Johnson, 1996) were conducted to determine the leaching and retention of exchangeable $K^+$ in sapric soils treated with clinoptilolite in the wet and dry seasons. The field fertilization treatments outlined in **Table 2** was also evaluated in the laboratory leaching experiment. The experimental design used in the laboratory study was a completely randomized design with five replications. For this experiment, acrylic cylinder-shaped soil columns were utilized measuring 0.05 m in diameter and 0.9 m in height. Each soil column was attached with stainless steel mesh (0.001 m) to minimize soil loss. Sapric soils were filled into the columns according to their respective soil layers of 10–30 cm, 30–60 cm, and 60–90 cm, whereas treatment mixture comprising peat soils, clinoptilolite, and NPK fertilizers (**Table 2**) were placed into the soil column at depth of 0–10 cm. Peat soils in the soil columns were showered with approximately one-tenth pore volume of deionized water before beginning the leaching experiment. A total of 1175.5 mL and 586.7 mL of deionized water were utilized for the leaching experiment, respectively representing the wet (mean rainfall of 598.6 mm with 19 rainy days over a 30-day phase) and dry (mean rainfall of 298.8 mm with 9 rainy days over a 30-day phase) seasons. These water volumes were computed according to the rainfall data recorded at the study site in Saratok, Sarawak. For each season, soil leachates were collected and determined for $K^+$ using ICP–OES (Perkin Elmer Optima 8000) and pH utilizing a benchtop pH meter (Cyberscan pH 1500). At the end of the leaching study, peat samples in the soil columns at depths of 0–10 cm, 10–30 cm, 30–60 cm, and 60–90 cm were determined for pH and exchangeable $K^+$ according to the methods described previously.

**Statistical data analysis**

Statistical data analysis for this present study was carried out using the Statistical Analysis System (SAS) Version 9.1 software. Significant effects of the clinoptilolite fertilization treatments on sapric soil $K^+$ availability and MD2 pineapple fresh fruit yield, K uptake and use efficiency, and fruit quality attributes were assessed using analysis of variance (ANOVA), whereas Tukey's Multiple Range Test procedure at $P \leq 0.05$ was utilized to obtain treatments means deviating from the control treatments.

## RESULTS AND DISCUSSION

**Effect of clinoptilolite zeolite on sapric soil potassium availability in MD2 pineapple cultivation**

Throughout the MD2 pineapple vegetative phase and growth, the ion exchange and morphological features of natural zeolite of the clinoptilolite species are instrumental in improving $K^+$ availability via sapric soil amelioration through monthly pineapple fertilization. The incorporation of clinoptilolite zeolite (T1 to T4) in the MD2 pineapple fertilization regime at three, six, and nine months of plant growth significantly influenced sapric soil pH and exchangeable $K^+$ availability. Irrespective of MD2 plant growth and development, sapric soils amended with clinoptilolite zeolite (T1 to T4) demonstrated higher exchangeable $K^+$ compared to that of NPK fertilized soil (SF) and non-treated soils (NC) throughout the MD2 pineapple planting seasons (**Figures 2** and **3**). The effectiveness of clinoptilolite zeolite in retaining exchangeable $K^+$ throughout the MD2 pineapple growth demonstrates the ability of this zeolite mineral to adsorb $K^+$ ions onto its active-charged lattices via ion exchange (Sangeetha and Baskar, 2016; Uzuno and Mikosch, 2013; Jakkula and Wani, 2018). Also, the alkaline nature of the clinoptilolite (pH 8.77) improved exchangeable $K^+$ retention by reducing sapric soil acidity. This could be associated with the slow accumulation of the clinoptilolite at the aerobic horizon (0-20 cm) because clinoptilolite does not weather and disintegrate rapidly (Nur Aainaa *et al.,* 2018). As the clinoptilolite's lattices gradually turns more negatively charged with increasing soil pH, this process increases the affinity of clinoptilolite for exchangeable $K^+$ adsorption via ion exchange. This observation is consistent with the higher pH of the sapric soil which was ameliorated with clinoptilolite (T1 to T4) (pH range: 4.27 to 5.62) compared with NPK fertilization and untreated soils (pH range: 3.38 to 4.04) (**Table 3**). Although the clinoptilolite mineral has a high affinity for $K^+$ ions (Mumpton, 1999), the retention of exchangeable $K^+$ following clinoptilolite zeolite fertilization varied with the amount of clinoptilolite used (T1 to T4) and soil depths throughout the pineapple growth phases and planting seasons (**Figure 3**). The basis for this observation relates to the competing interactions between $K^+$ and other soil cations or anions, for example $Ca^{2+}$, $Al^{3+}$, $Fe^{3+}$, $Mg^{2+}$, $Na^+$, ammonium, nitrate, phosphate, and or organic acids onto the active charged lattices of clinoptilolite. This action reduced the temporary adsorption of $K^+$ ions because the limited unoccupied channels of clinoptilolite are not adequate to adsorb $K^+$, cations, anions, and peat organic acids concurrently. Regardless of the pineapple planting seasons (first and second cycles: January 2023 to December 2024), clinoptilolite treated soils in T4 (20 g/plant) constantly demonstrated higher exchangeable $K^+$ relative to other treatments (except T1 and T2 in the first season and T1 in the second season) including controls (**Figure 2**). The higher amount of clinoptilolite increased the number of negatively charged lattices for $K^+$ adsorption through ion exchange. Moreover, the high CEC of the clinoptilolite (103.8 $cmol_{(+)}$/kg) coupled with this mineral's affinity for $K^+$ ions enabled the adsorption of $K^+$ onto clinoptilolite active charged lattices.

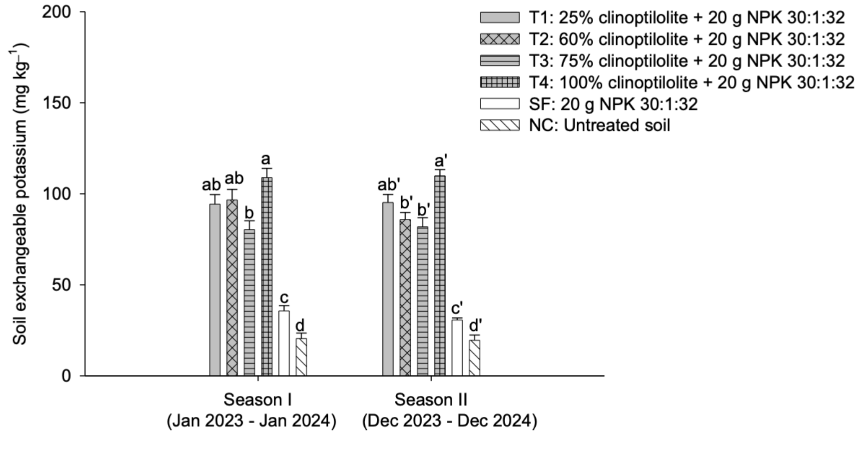



**Figure 2**. Mean amount of exchangeable potassium retained from a drained sapric soil cultivated with MD2 pineapple at different planting seasons. Error bars indicate the standard error of the mean. Means with different letters are significantly different by Tukey's Multiple Range Test at p ≤ 0.05. Letters with single prime denote mean soil exchangeable potassium retained in the second MD2 pineapple planting season.

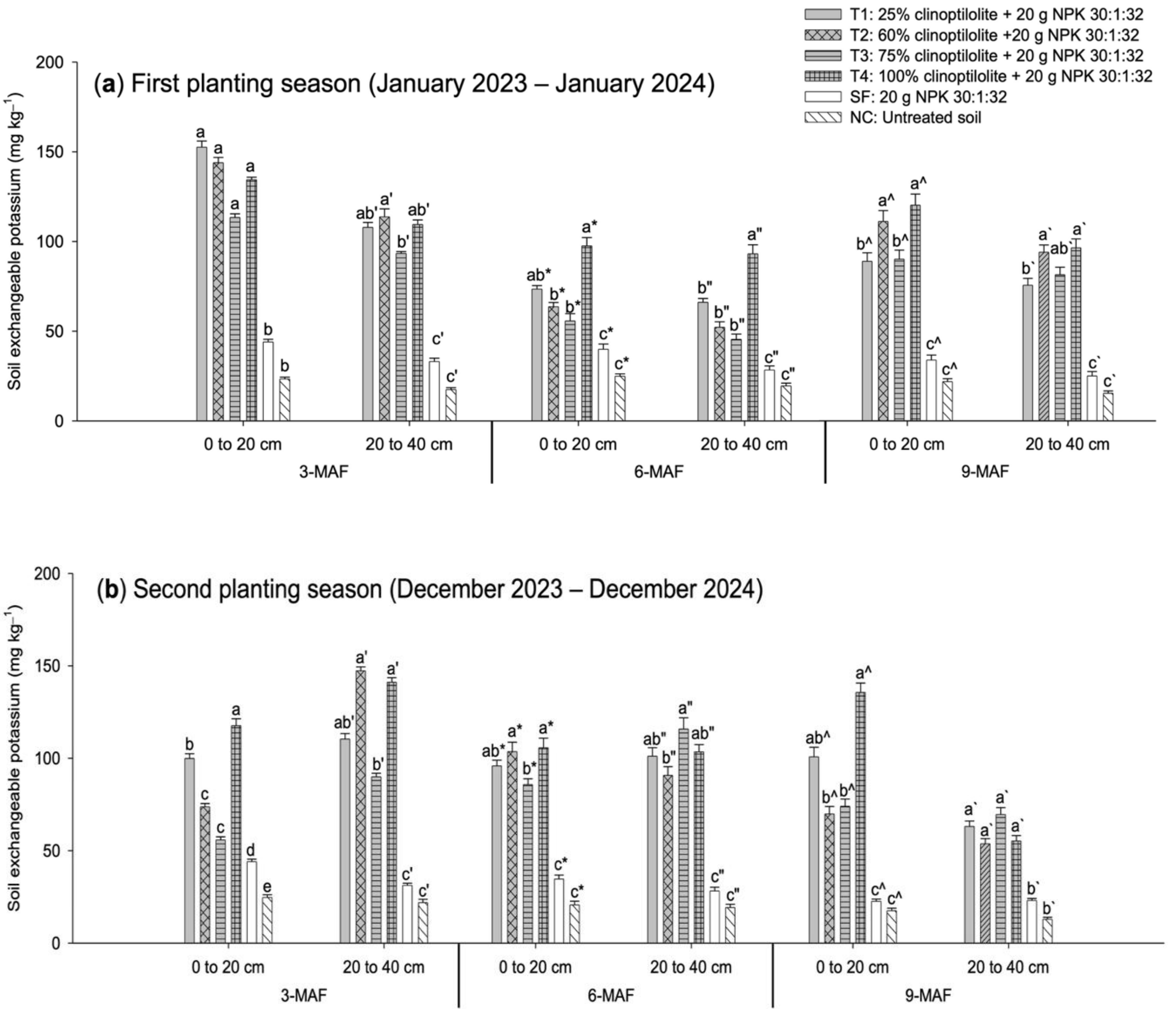



**Figure 3.** Mean amount of exchangeable potassium retained according to soil depth and growth phases throughout the MD2 planting seasons. Error bars indicate the standard error of the mean. Note: 3–MAF indicate 3 months after planting; 6–MAF indicate 6 months after planting; and 9–MAF indicate 9 months after planting. Means with different letters are significantly different by Tukey's Multiple Range Test at $p \leq 0.05$. Letters with single prime denote mean exchangeable potassium retained at 3 months of pineapple growth. Letters with asterisk and double prime denote mean exchangeable potassium retained at 6 months of pineapple growth. Letters with caret and backtick denote mean exchangeable potassium retained at 9 months of pineapple growth.

**Table 3.** Mean soil pH of sapric soils amended with clinoptilolite zeolite and NPK fertilizers cultivated with MD2 pineapples at different growth stages and soil depths for two planting seasons

| Treatments | Soil pH (Depth: 0 – 20 cm) | | | | | |
|---|---|---|---|---|---|---|
| | Season I (Pineapple growth period) | | | Season II (Pineapple growth period) | | |
| | 3 months | 6 months | 9 months | 3 months | 6 months | 9 months |
| T1 | $4.42^{a} \pm 0.13$ | $4.85^{a} \pm 0.04$ | $4.62^{a} \pm 0.05$ | $4.97^{b} \pm 0.02$ | $4.59^{a} \pm 0.07$ | $4.75^{ab} \pm 0.03$ |
| T2 | $4.31^{a} \pm 0.23$ | $4.36^{a} \pm 0.11$ | $4.45^{a} \pm 0.07$ | $5.62^{a} \pm 0.04$ | $4.76^{a} \pm 0.10$ | $4.51^{b} \pm 0.03$ |
| T3 | $4.91^{a} \pm 0.08$ | $4.78^{a} \pm 0.08$ | $4.87^{a} \pm 0.03$ | $4.58^{b} \pm 0.10$ | $4.75^{a} \pm 0.04$ | $4.94^{a} \pm 0.02$ |
| T4 | $4.49^{a} \pm 0.10$ | $4.42^{a} \pm 0.06$ | $4.54^{a} \pm 0.11$ | $5.16^{ab} \pm 0.06$ | $4.63^{a} \pm 0.03$ | $4.66^{b} \pm 0.08$ |
| SF | $3.52^{b} \pm 0.07$ | $3.46^{b} \pm 0.13$ | $3.48^{b} \pm 0.05$ | $4.18^{c} \pm 0.03$ | $3.98^{b} \pm 0.06$ | $4.04^{c} \pm 0.02$ |
| NC | $3.44^{b} \pm 0.05$ | $3.40^{b} \pm 0.14$ | $3.45^{b} \pm 0.06$ | $3.87^{c} \pm 0.05$ | $3.83^{b} \pm 0.10$ | $3.91^{c} \pm 0.03$ |
| | Soil pH (Depth: 20 – 40 cm) | | | | | |
| T1 | $4.39^{a} \pm 0.12$ | $4.47^{a} \pm 0.03$ | $4.51^{a} \pm 0.13$ | $4.60^{b} \pm 0.03$ | $4.32^{a} \pm 0.04$ | $4.68^{a} \pm 0.06$ |
| T2 | $4.27^{a} \pm 0.04$ | $4.33^{a} \pm 0.05$ | $4.39^{a} \pm 0.06$ | $5.03^{a} \pm 0.06$ | $4.44^{a} \pm 0.02$ | $4.47^{a} \pm 0.10$ |
| T3 | $4.86^{a} \pm 0.07$ | $4.76^{a} \pm 0.09$ | $4.97^{a} \pm 0.03$ | $4.48^{b} \pm 0.06$ | $4.35^{a} \pm 0.04$ | $4.86^{a} \pm 0.04$ |
| T4 | $4.51^{a} \pm 0.05$ | $4.59^{a} \pm 0.10$ | $4.54^{a} \pm 0.01$ | $4.61^{b} \pm 0.08$ | $4.44^{a} \pm 0.07$ | $4.57^{a} \pm 0.03$ |
| SF | $3.47^{b} \pm 0.14$ | $3.43^{b} \pm 0.07$ | $3.45^{b} \pm 0.04$ | $4.04^{c} \pm 0.07$ | $3.96^{b} \pm 0.05$ | $3.79^{b} \pm 0.05$ |
| NC | $3.49^{b} \pm 0.09$ | $3.38^{b} \pm 0.07$ | $3.42^{b} \pm 0.05$ | $3.77^{c} \pm 0.04$ | $3.79^{b} \pm 0.08$ | $3.84^{b} \pm 0.07$ |

Note: Means (value ± standard error) with different letters within the same column are significantly different by Tukey's test at $P \leq 0.05$.

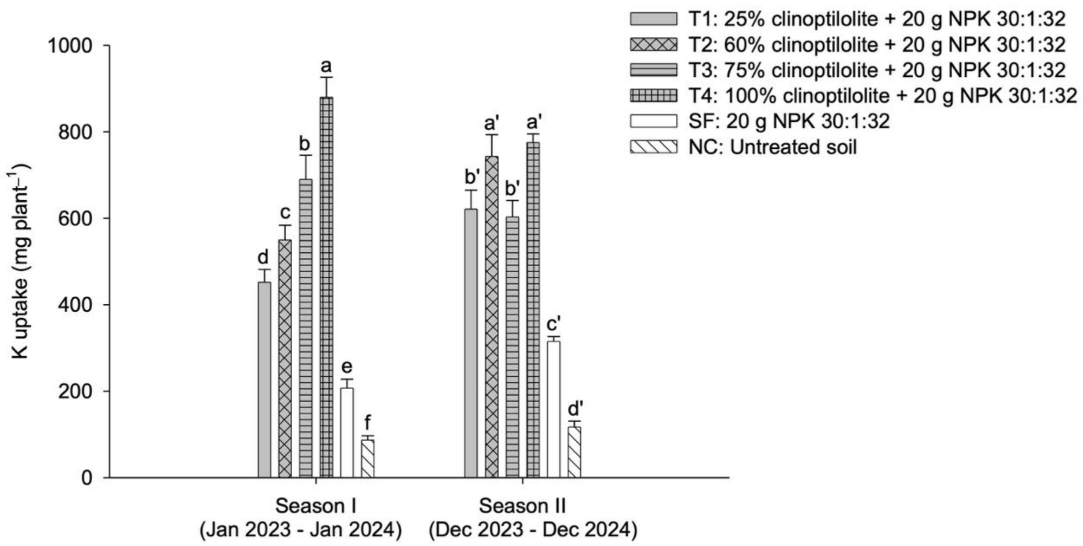
Throughout the MD2 pineapple planting cycles and growth phases (**Figure 3**), the differences in exchangeable $K^+$ availability following NPK fertilization in sapric soils amended with clinoptilolite may possibly have been affected by the formation of the pineapple root structure and movement of nutrients into the pineapple rooting area via mass flow, which incidentally influence the uptake of $K^+$ ions by the MD2 pineapple roots (Dotaniya and Meena, 2015; Xiong *et al.,* 2021). Furthermore, these processes are influenced by water table fluctuation and preferential flow of the peat soil water under high and low rainfall environment (Sapek *et al.,* 2007; Liu and Lennartz, 2019). Lateral movement of peat water and penetrating rainwater affect $K^+$ ions movement along the preferential pathway, hence leading to changes in the availability of exchangeable $K^+$ ions in the peat soil solution for sorption by clinoptilolite at different vegetative phase of the MD2 pineapple plants. Likewise, the different contents of exchangeable $K^+$ at different soil depths (0-20 cm and 20-40 cm) relates to the diffusion of clinoptilolite minerals through sapric pore spaces in the presence of water throughout the wet and dry periods of 2023 to 2024, which might have affected the sorption of $K^+$ ions at different soil layers (Sapek *et al.,* 2007; Liu and Lennartz, 2019).

Irrespective of the planting seasons and during the growth and development of the MD2 pineapples plants, the low exchangeable $K^+$ in the control treatments (NPK fertilization and untreated soils) could be attributed to the functional groups of the humic compounds in sapric soils, namely phenols, carboxyl, and hydroxyl that do not establish coordination bonds with exchangeable $K^+$ ions despite the high CEC values of the peat soils (Ahmed *et al.,* 2013; Maftu'ah *et al.,* 2014). In addition, the low clay content coupled with nonexistence mineral matter in sapric spoils causes the $K^+$ ions to be easily leached, especially during heavy rainfall (Ahmed *et al.,* 2013).

**Clinoptilolite fertilization effect on the growth, potassium uptake and use efficiency, yield, and fruit quality of MD2 pineapples**

Compared with NPK fertilization (SF) and untreated soils (NC), clinoptilolite fertilization (T1 to T4) significantly increased uptake and use efficiency of K by the MD2 pineapple plants regardless of the pineapple planting seasons (**Figure 4**). These findings buttress the ability of the clinoptilolite mineral to adsorb and regulate exchangeable $K^+$ in sapric soils. The gradual release of $K^+$ ions by clinoptilolite via diffusion according to the MD2 pineapple plant requirements resulted in the significant uptake and use efficiency of K. Also, the ability of the clinoptilolite in improving K uptake and use efficiency relates to the alkaline nature of the zeolite mineral, which increases sapric soil pH. Increasing soil pH leads to the lattices and frameworks of the clinoptilolite to be more negatively charged. This action increases the affinity of the clinoptilolite for $K^+$ sorption and thereby increases the availability of $K^+$ for MD2 plant uptake throughout the vegetative growth phases of the pineapple plants (Pegoraro *et al.,* 2014; Ramadhani and Nuraini, 2018). This observation is consistent with the higher sapric soil pH treated with clinoptilolite (pH range between 4.27 and 5.62) compared with the controls (pH range between 3.38 and 4.18) (**Table 3**). However, clinoptilolite application (T1 to T4) did not significantly affect MD2 plant height compared with NPK fertilization (SF) irrespective of MD2 growth phases and planting seasons (**Table 4**). This observation was unexpected, but it is possible that the competing interactions between exchangeable $K^+$ and other nutrients for sorption onto clinoptilolite's lattices and framework affected the zeolite's ability to gradually desorb nutrients for plant uptake. This process is influenced by the preferential flow of the peat soil water, which indirectly affect the mobilization of exchangeable $K^+$ into the pineapple rooting zone for plant use (Dotaniya and Meena, 2015; Liu and Lennartz, 2019; Xiong *et al.,* 2021). This might explain the ineffectiveness of the clinoptilolite in improving pineapple plant heights compared with that of standard NPK fertilization.

(**a**)




(**b**)

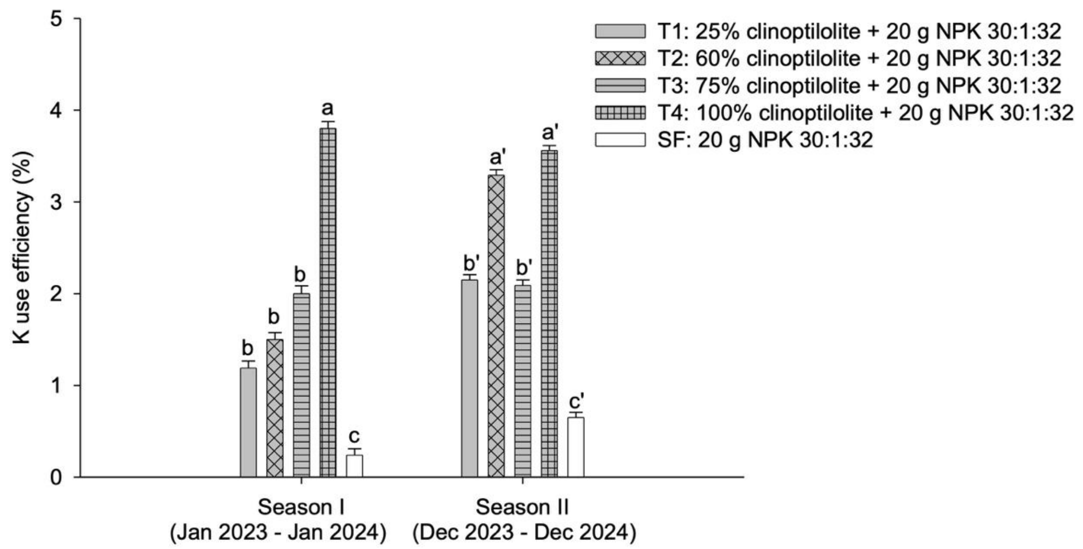



**Figure 4**. Effects of clinoptilolite and NPK fertilization on (**a**) total potassium uptake and (**b**) potassium use efficiency of MD2 pineapples for two planting seasons. Error bars indicate the standard error of the mean. Means with different letters are significantly different by Tukey's Multiple Range Test at $p \leq 0.05$.

**Table 4.** Mean height of MD2 pineapple plants cultivated on sapric soils amended with clinoptilolite and NPK fertilizers at different vegetative phase for two planting seasons

| Treatments | Plant height (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Season I (Pineapple growth period) | | | Season II (Pineapple growth period) | | |
| | 3 months | 6 months | 9 months | 3 months | 6 months | 9 months |
| T1 | $62.75^a \pm 5.63$ | $85.25^a \pm 4.17$ | $95.37^a \pm 2.36$ | $30.31^a \pm 0.55$ | $48.13^a \pm 1.16$ | $59.43^a \pm 0.99$ |
| T2 | $61.00^a \pm 4.14$ | $86.25^a \pm 3.64$ | $90.26^a \pm 4.07$ | $33.94^a \pm 1.04$ | $46.31^a \pm 1.25$ | $59.77^a \pm 2.13$ |
| T3 | $63.75^a \pm 2.81$ | $82.75^a \pm 3.84$ | $89.49^a \pm 2.15$ | $31.47^a \pm 0.77$ | $47.53^a \pm 0.31$ | $57.09^a \pm 1.22$ |
| T4 | $57.00^a \pm 2.68$ | $84.00^a \pm 3.37$ | $91.43^a \pm 3.61$ | $31.55^a \pm 0.69$ | $49.29^a \pm 1.47$ | $58.38^a \pm 0.74$ |
| SF | $59.50^a \pm 2.99$ | $81.75^a \pm 2.49$ | $89.13^a \pm 2.89$ | $27.69^a \pm 0.87$ | $40.50^a \pm 0.63$ | $55.67^a \pm 1.63$ |
| NC | $48.76^b \pm 1.85$ | $63.93^b \pm 1.61$ | $70.74^b \pm 2.38$ | $25.13^a \pm 0.71$ | $32.59^b \pm 0.58$ | $44.53^b \pm 0.96$ |

Note: Means (value ± standard error) with different letters within the same column are significantly different by Tukey's test at $P \leq 0.05$.

Ananas comosus L. Merr var. MD2 has a standard fruit weight of approximately 1.5 kg/fruit to 2.5 kg/fruit (Thalip *et al.,* 2015). Therefore, the higher MD2 pineapple fresh fruit weight with clinoptilolite zeolite treatments (2.42 to 2.66 kg/fruit) demonstrates acceptable fruit yield compared with the standard agronomic practices utilizing compound NPK 30:1:32 fertilizers (1.50 to 1.76 kg/fruit) (**Table 5**). The higher MD2 pineapple fruit weight with clinoptilolite treatments (T1 to T4) relates to the adequate availability of exchangeable $K^+$ in the sapric soil. This also explain the increased in MD2 fruit yield (t/ha) with clinoptilolite fertilization irrespective of planting seasons. Compared with NPK fertilization, the increase in MD2 pineapple fresh fruit weigh and yield are consistent with the higher retention of exchangeable $K^+$ in the clinoptilolite amended sapric soils throughout the pineapple planting seasons. These findings substantiate the importance of $K^+$ in the production of superior pineapple yields and further demonstrate the ability of clinoptilolite to adsorb and regulate soil $K^+$ for plant uptake. Although clinoptilolite fertilization improved pineapple fruit weight and yield, this mineral had no significant effect toward MD2 fruit quality traits (fruit sweetness and acidity) compared with that of NPK fertilization (**Table 5**). Moreover, the amount of clinoptilolite utilized (T1 to T4: 5 g to 20 g/plant) in the pineapple fertilization regime showed similar effects on MD2 fresh fruit weight and yield. The reason for these abnormal observations could be attributed to the competing interactions for $K^+$ sorption onto the charged zeolite frameworks between nutrients, ions, and organic acids, which indirectly may have affected the utilization, translocation, and assimilation of K for MD2 fruit development (Tewodros *et al.,* 2018). Irrespective of the pineapple planting seasons, the use of standard NPK fertilization were ineffective to increase K uptake and use efficiency, and MD2 fruit yields not only because of the acidity of the sapric soil and lower contents of peat exchangeable $K^+$, but also because of the leaching of K.

**Table 5**. MD2 pineapple fruit, yield, and quality attributes cultivated on drained sapric soils amended with clinoptilolite zeolite and compound NPK 30:1:32 fertilizers

| Treatments | Fresh fruit weight (kg) | Yield (t/ha) | Total soluble solids (°Brix) | Titratable acidity (%) |
|---|---|---|---|---|
| **First planting season** | | | | |
| T1 | $2.59^a \pm 0.06$ | $98.42^a \pm 2.38$ | $12.01^a \pm 0.01$ | $0.56^{ab} \pm 0.02$ |
| T2 | $2.58^a \pm 0.02$ | $98.04^a \pm 0.63$ | $12.40^a \pm 0.02$ | $0.65^a \pm 0.05$ |
| T3 | $2.51^a \pm 0.02$ | $95.38^a \pm 0.65$ | $12.10^a \pm 0.01$ | $0.64^a \pm 0.04$ |
| T4 | $2.66^a \pm 0.06$ | $101.08^a \pm 2.44$ | $12.20^a \pm 0.02$ | $0.57^{ab} \pm 0.05$ |
| SF | $1.76^b \pm 0.05$ | $66.88^b \pm 1.76$ | $12.00^a \pm 0.01$ | $0.51^b \pm 0.03$ |
| NC | $1.60^b \pm 0.06$ | $60.98^b \pm 2.18$ | $11.90^a \pm 0.03$ | $0.48^b \pm 0.03$ |
| **Second planting season** | | | | |
| T1 | $2.53^a \pm 0.05$ | $96.14^a \pm 1.09$ | $12.00^a \pm 0.02$ | $0.54^b \pm 0.03$ |
| T2 | $2.46^a \pm 0.03$ | $93.48^a \pm 2.45$ | $12.00^a \pm 0.02$ | $0.61^{ab} \pm 0.07$ |
| T3 | $2.42^a \pm 0.08$ | $91.96^a \pm 3.24$ | $12.10^a \pm 0.02$ | $0.75^a \pm 0.04$ |
| T4 | $2.46^a \pm 0.08$ | $93.48^a \pm 3.64$ | $12.10^a \pm 0.03$ | $0.77^a \pm 0.05$ |
| SF | $1.50^b \pm 0.05$ | $57.00^b \pm 2.85$ | $11.96^a \pm 0.03$ | $0.61^{ab} \pm 0.07$ |
| NC | $1.41^b \pm 0.01$ | $53.58^b \pm 4.21$ | $11.90^a \pm 0.01$ | $0.48^c \pm 0.02$ |

Note: Mean values (± standard error) with different letters in the same column are significantly different by Tukey's Multiple Range Test at $p \leq 0.05$.

In this present study, because all the clinoptilolite treatments (T1 to T4) demonstrated similar effect on MD2 pineapple yield and considering the current worldwide increase in fertilizer cost and farm operational expenditure, it therefore appears reasonably economical to recommend that monthly fertilization with co-application of clinoptilolite at a rate of 5 g/plant (25%) and compound NPK 30:1:32 fertilizer (20 g/plant) at the vegetative (3 and 6 months plant age) and flower induction phase (9 months plant age) should be cost effective in increasing MD2 pineapple yield besides improving peat exchangeable $K^+$ availability. This alternative pineapple agronomic practice could be embraced by farmers to sustainably cultivate pineapples on drained tropical peat soils.

**Sapric peat soil potassium availability under wet and dry conditions – a laboratory experiment**

Clinoptilolite zeolite application significantly influenced exchangeable $K^+$ availability in sapric soils under controlled laboratory conditions. The leaching and retention of $K^+$ varied depending on the amount of clinoptilolite used (T1 to T4: 5 g to 20 g), seasons (wet and dry conditions), and soil depths (aerobic and anaerobic zone). Sapric soils treated with clinoptilolite (T1 to T4) were effective in controlling $K^+$ loss and demonstrated higher exchangeable $K^+$ compared with NPK fertilization (SF) irrespective of season and soil depth (**Figures 5** and **6**). The effectiveness of clinoptilolite in controlling the loss of $K^+$ and improving exchangeable $K^+$ retention buttresses the ability of this zeolite mineral to adsorb $K^+$ ions onto the lattices and surface framework of the clinoptilolite via ion exchange (Sangeetha and Baskar, 2016; Jakkula and Wani, 2018). Among the zeolite treatments, application of clinoptilolite at a rate of 20 g (T4) was more effective in retaining exchangeable $K^+$ irrespective of season and soil depth (**Figures 5** and **6**). The higher amount of clinoptilolite in T4 increased the number of lattices and surface frameworks of clinoptilolite for exchangeable $K^+$ adsorption through ion exchange (Murkani *et al.,* 2015). This is because of the high CEC of the clinoptilolite and its preference for $K^+$ ions compared with other nutrients such as potassium, ammonium, and nitrate (Mumpton, 1999; Jha and Hayashi, 2009). Moreover, this finding concurs with the increase in sapric soil pH, whose soils were treated with clinoptilolite (T1 to T4: pH range of 4.58 to 6.67) (**Table 6**) throughout the dry and wet seasons, which decreases sapric soil acidity. The lattices and surface frameworks of the clinoptilolite becomes more negatively charged with increasing soil pH and this action subsequently increases the affinity of clinoptilolite for exchangeable $K^+$ adsorption.

(**a**) Wet season (**b**) Dry season

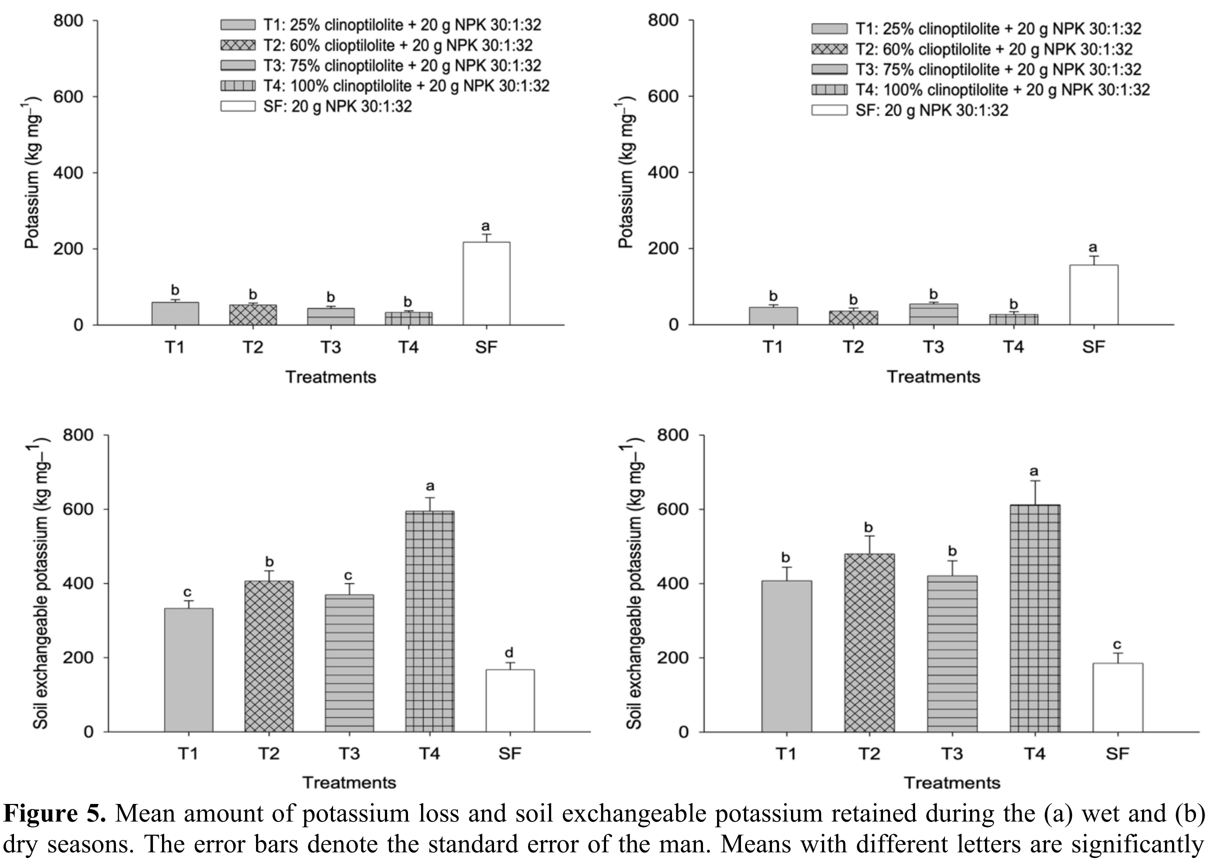



**Figure 5.** Mean amount of potassium loss and soil exchangeable potassium retained during the (a) wet and (b) dry seasons. The error bars denote the standard error of the man. Means with different letters are significantly different by Tukey's Multiple Range Test at p ≤ 0.05.

(**a**) Wet season

(**b**) Dry season

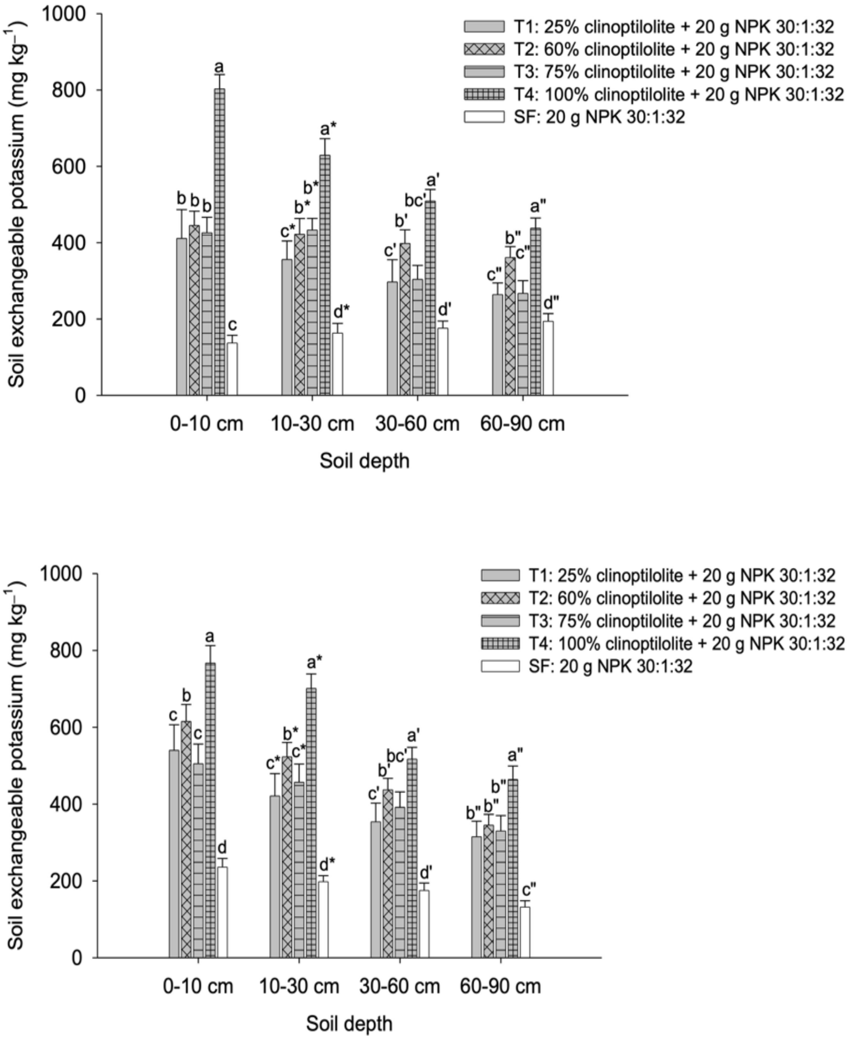



**Figure 6.** Mean sapric soil exchangeable potassium retained at different depths during the (a) wet and (b) dry seasons. The error bars denote the standard error of the man. Means with different letters are significantly different by Tukey's Multiple Range Test at $p \leq 0.05$. Letters with asterisk, single prime, and double prime denote peat horizons as 10 to 30 cm, 30 to 60 cm, and 60 to 90 cm, respectively.

The alkaline nature of the clinoptilolite mineral decreases soil acidity and this relatively explain the increase in soil pH under low and high rainfall conditions. This could be associated with the build-up of clinoptilolite at the aerobic layer, which reduces the acidity of the sapric soil. Conversely, the ineffectiveness of the zeolite in improving soil pH at the anaerobic layers (30 cm to 60 cm and 60 cm to 90 cm) could be attributed to the diffusive adhesion forces of the clinoptilolite which restrict the leaching of this mineral into the soil solution at the saturated soil depths (Hussain and Saiyudi, 2005). This process hinders the ability of the clinoptilolite to increase soil pH. The lower contents of exchangeable $K^+$ in the NPK fertilized sapric soils (SF: control) was presumed. The low soil pH with NPK amended soil (pH range: 3.94 to 4.41) explained the lower exchangeable $K^+$ in the sapric soil with this treatment. Similar to the field results, the control treatment in the laboratory leaching experiment did not improve exchangeable $K^+$ because $K^+$ ions do not establish coordination bonds with the organic acids of the humic compounds despite the high CEC of sapric soils (Ahmed *et al.,* 2013; Maftu'ah *et al.,* 2014). Based on the preceding discussion, results of the laboratory leaching experiment buttresses the ability of the clinoptilolite mineral to improve the availability of $K^+$ in drained sapric soils. The charged lattices and surface frameworks of clinoptilolite coupled with its high

CEC value played a crucial role in improving the retention of exchangeable $K^+$ besides controlling the leaching of this nutrient via ion exchange and mass transport. These results concur with the field observations and postulated hypothesis of the study.

**Table 6.** Mean pH of leachates and sapric peat soil in the dry and wet seasons

| Treatments | pH of leachates | Wet season | | | |
|---|---|---|---|---|---|
| | | Soil depth | | | |
| | | 0 cm to 10 cm | 10 cm to 30 cm | 30 cm to 60 cm | 60 cm to 90 cm |
| T1 | $5.27^b \pm 0.05$ | $5.65^b \pm 0.05$ | $5.13^a \pm 0.05$ | $4.78^a \pm 0.09$ | $4.64^a \pm 0.13$ |
| T2 | $5.59^b \pm 0.19$ | $5.48^b \pm 0.08$ | $5.29^a \pm 0.11$ | $4.61^a \pm 0.03$ | $4.58^a \pm 0.06$ |
| T3 | $5.84^b \pm 0.23$ | $5.74^b \pm 0.03$ | $5.51^a \pm 0.07$ | $4.93^a \pm 0.06$ | $4.77^a \pm 0.01$ |
| T4 | $6.31^a \pm 0.07$ | $6.03^a \pm 0.04$ | $5.86^a \pm 0.01$ | $4.97^a \pm 0.14$ | $4.81^a \pm 0.02$ |
| SF | $4.06^c \pm 0.04$ | $4.41^c \pm 0.01$ | $4.17^b \pm 0.04$ | $4.04^a \pm 0.05$ | $4.11^a \pm 0.01$ |
| | | Dry season | | | |
| T1 | $5.81^b \pm 0.13$ | $5.47^a \pm 0.05$ | $5.19^a \pm 0.02$ | $4.93^a \pm 0.13$ | $4.71^a \pm 0.01$ |
| T2 | $5.69^b \pm 0.08$ | $5.61^a \pm 0.07$ | $5.23^a \pm 0.03$ | $4.85^a \pm 0.07$ | $4.95^a \pm 0.04$ |
| T3 | $5.84^b \pm 0.03$ | $5.89^a \pm 0.04$ | $5.7^{5a} \pm 0.07$ | $4.89^a \pm 0.05$ | $4.67^a \pm 0.02$ |
| T4 | $6.67^a \pm 0.16$ | $5.91^a \pm 0.10$ | $5.84^a \pm 0.05$ | $4.77^a \pm 0.03$ | $4.63^a \pm 0.03$ |
| SF | $3.94^c \pm 0.14$ | $4.36^b \pm 0.02$ | $4.15^b \pm 0.01$ | $4.12^a \pm 0.02$ | $4.09^a \pm 0.05$ |

Note: Mean values (± standard error) with different letters in the same column are significantly different by Tukey's Multiple Range Test at $p \leq 0.05$.

## CONCLUSION

Co-application of clinoptilolite and compound NPK fertilizer improved $K^+$ availability in MD2 pineapple cultivation on a drained sapric soil. This amelioration strategy also improves pineapple K use efficiency besides increasing MD2 yield. The distinctive properties of the clinoptilolite with its structured lattices and open cavities, framework cations, and high CEC allows the adsorption of $K^+$ ions via ion exchange and diffusion in sapric soils. Availability of exchangeable $K^+$ ions differed with soil depth, and the mobilization of this macronutrient is influenced by the preferential flow of the peat soil water under high and low rainfall environment. The ability of the clinoptilolite to temporary entrap and release $K^+$ ions via diffusion according to the MD2 pineapple plant requirement resulted in the significant uptake and use efficiency of K. The alkaline nature of the clinoptilolite reduces sapric soil pH, thus reflecting the plausible use of this mineral as an alternative liming source on drained peat soils. Although results for the field observations (two planting cycles) and laboratory experiment demonstrated the co-application of clinoptilolite (5 to 20 g/plant) and compound NPK 30:1:32 fertilizer (20 g/plant) was effective in improving soil exchangeable K availability and pineapple productivity, it is reasonably economical to suggest that monthly fertilization with clinoptilolite (5 g/plant) and NPK 30:1:32 (20 g/plant) at the vegetative phase (3, 6, and 9 months after planting) should be cost effective not only in increasing MD2 pineapple yield but also to improve macronutrient availability in drained sapric soils, particularly exchangeable $K^+$ considering the importance of this nutrient for improving fruit yields and regulating plant photosynthesis. Comprehensive field testing for utilizing clinoptilolite zeolite as a prospective soil amendment for pineapple cultivation on drained tropical peat soils at a larger scale is currently carried out at farmers plot in Sarawak to increase agronomic efficiency, minimize farm operations cost, and improve farmers livelihood. This includes long-term observations to validate the effects of abiotic factors such as water table, peat preferential flow, temperature, and rainfall distribution on the sorption and availability of macronutrients in drained peat soils treated with clinoptilolite zeolite.

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