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Reducing potassium leaching in peat soil using potassium zeolite-based fertilizer (ZEKA)

Eko Noviandi Ginting[1]*, Syaiful Anwar[2], Budi Nugroho[2], Suroso Rahutomo[1]

[1] Department of Soil Science and Agronomy, Indonesian Oil Palm Research Institute (IOPRI), North Sumatra, Medan, 20158, Indonesia
[2] Department of Soil Sciences and Land Resources, IPB University, Bogor, 16680, Indonesia

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* *Corresponding Author*
Email address: *eko.novandy@gmail.com*

ABSTRACT

Using peat soils for agricultural purposes is challenged by low fertilizer efficiency, especially potassium chloride (KCl). On the other hand, zeolite is a potential material to produce slow-release fertilizers to improve fertilizer efficiency. This study aims to evaluate and compare potassium leaching from a conventional potassium fertilizer, KCl, and a zeolite-based potassium fertilizer, ZEKA, on peat soil columns. The ZEKA fertilizer was produced using two different zeolite particle sizes: coarse zeolite (ZC) and fine zeolite (ZF). The K leached from the fertilizers was measured in a peat soil column. Three zeolite-based potassium fertilizers were formulated: (1) 40% potassium-impregnated zeolite and 60% KCl; (2) 50% potassium-impregnated zeolite and 50% KCl; and (3) 60% potassium-impregnated zeolite and 40% KCl. Since two different sizes of zeolite were used in this study—coarse zeolite (ZC) and fine zeolite (ZF)—the results of the formulation are referred to as follows: ZC-1, ZC-2, ZC-3, ZF-1, ZF-2, and ZF-3. The experiment was completely randomized with eight treatments and three replications. The treatments were as follows: (1) control, (2) KCl, (3) ZC-1, (4) ZC-2, (5) ZC-3, (6) ZF-1, (7) ZF-2, and (8) ZF-3. The findings revealed that ZC-1 and ZF-1 were the most effective ZEKA fertilizer formulations, with total potassium leached of 1.84 grams and 1.05 grams, respectively. Furthermore, the results showed that the total potassium leached from ZEKA fertilizer was 1.71 grams, while the total potassium leached from KCl fertilizer was 2.83 grams. The results showed that ZEKA fertilizer reduced potassium leaching by around 40% compared to KCl fertilizer. Furthermore, the results of this study can be used to improve the efficiency of potassium fertilizer, particularly in agricultural practices on the peatlands.

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1. INTRODUCTION

The growth of the world's population and the need for food have led to massive extensification of agricultural land, making the use of sub-optimal land inevitable. Peatlands are one of the sub-optimal lands currently utilized as agricultural land, including plantations. The utilization of peatlands for agriculture faces various challenges regarding the peat's physical, chemical, and biological properties. Azis et al. (2022) state that peatlands have low productivity because the availability of macro- and micronutrients in peatlands is low. Reeza et al. (2021) also argue that some peatlands have low availability of macronutrients, especially potassium, calcium, and magnesium. This condition is a natural feature of peat because peat is formed from organic matter with high acidity levels and low nutrient content, and it is dominated by macropores that facilitate water movement (Cole et al., 2022; Kurnianto et al., 2019; Mustamo et al., 2016). Therefore, the fulfilment of plant nutrient needs in peatlands is highly dependent on fertilization.

To meet the potassium requirements of plants, farmers commonly apply fertilizer in the form of potassium chloride (KCl) or muriate of potash (MoP). However, KCl has a high solubility, which can result in the leaching of potassium (K) out of peat soil due to the porous nature of peat and the high rainfall levels. Therefore, this research explores the use of zeolite as a material to produce potash fertilizer with slow-release properties to increase potash fertilizer efficiency, especially on peatlands. There have been numerous studies on the enhancement of fertilizer efficiency in peatlands through the incorporation of diverse ameliorants to improve the capacity of peat soil to retain nutrients (Fatimah et al.,

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2024; Tandiono et al., 2025; Utami et al., 2024). Zeolite is a soil ameliorant widely employed in agricultural applications to improve soil conditions. Three unique properties of zeolites that have contributed to their extensive agricultural utilization include (1) high water holding capacity, (2) high cation exchange capacity, and (3) high adsorption capacity. Cataldo et al. (2021) further asserted that zeolite is a highly effective ion exchange material due to its considerable internal surface area within its pores and channels. In addition to their high cation exchange capacity, zeolites exhibit high cation selectivity, particularly for ammonium and potassium (Bhattacharyya et al., 2015).

Plants need at least seventeen essential nutrients to grow and produce optimally (Kalsoom et al., 2020). Plants have an absolute requirement for potassium as an essential macronutrient. Binner et al. (2017) stated that plants need about 20–50 mg of potassium to form each gram of dry weight for optimal plant growth. Potassium is the second most abundant nutrient in leaves after N, contributing to various plant functions (Sardans & Peñuelas, 2021; Soumare et al., 2023). Several plant species require considerable amounts of potassium, especially when the plants are fruiting, because potassium helps to improve fruit quality (Muhammad et al., 2018; Ullah Khan et al., 2022). Numerous studies have shown that potassium has a vital function in plant photosynthesis (Tränkner et al., 2018), helps plants deal with stress (Dreyer et al., 2017; Jia et al., 2018), and participates in controlling plant metabolic systems (Cuin et al., 2018). In addition, Sustr et al. (2019) reported that plants that get an adequate supply of potassium can increase photosynthetic assimilation and improve nutrient absorption.

In mineral soils, the availability of potassium may be less of a concern due to the potential for the weathering of rocks and soil minerals to provide potassium (Sarkkola et al., 2016). However, the potassium content of peat soils is low due to the low mineral content and the ease with which potassium is lost through leaching. The high porosity of peat and the high rainfall in tropical regions such as Indonesia facilitate potassium leaching. Azis et al. (2022) observed that peat's horizontal conductivity is significantly higher than vertical. This condition can accelerate nutrient leaching, particularly in high rainfall (Widiarso et al., 2020). Consequently, in addition to reducing fertilization efficiency, the leached nutrients have the potential to cause environmental pollution problems, which can result in the contamination of waterways and the degradation of soil quality (Bagheri et al., 2021; Hashim et al., 2019; Messiga et al., 2020).

Peat soil widely utilized in agricultural development. One of the major constraints in peat soil cultivation is the high rate of potassium (K) leaching. Conventional potassium fertilizers, such as potassium chloride (KCl), are highly soluble and susceptible to leaching, resulting in poor nutrient use efficiency and increased environmental risks. Zeolite has been widely studied as a soil amendment due to its high cation exchange capacity, water retention, and ion adsorption properties. While many studies have explored its use to improve soil fertility or as a carrier for nitrogen and phosphorus fertilizers (Lateef et al., 2016; Nakhli et al., 2017; Rameshaiah et al., 2015), very limited research has focused on the specific application of zeolite as a carrier material for potassium-based slow-release fertilizers in peat soils. Given that potassium is particularly prone to leaching in peat, this represents a critical research gap. The effectiveness of zeolite in retaining potassium in such highly leachable soil environments remains underexplored, especially in formulations designed for controlled nutrient release. To address these gaps, this study introduces a novel formulation of a zeolite-based potassium fertilizer (ZEKA) designed to act as a slow-release fertilizer for peat soils.

The aim of this study is to evaluate and compare potassium leaching from conventional potassium fertilizer, KCl, and zeolite-based potassium fertilizer, ZEKA, on peat soil columns.

2. MATERIAL AND METHODS

The research was carried out from October 2022 to October 2023 in the Indonesian Oil Palm Research Institute's (IOPRI) laboratory and greenhouse in Medan, North Sumatra, Indonesia.

2.1. Materials

The materials used in this study included commercial natural zeolite in powder form, KCl fertilizer, and undisturbed peat soil samples. The soil sampling location was the Sei Meranti oil palm plantation of PT Perkebunan Nusantara IV, which is located in Labuhan Batu Regency, North Sumatra.

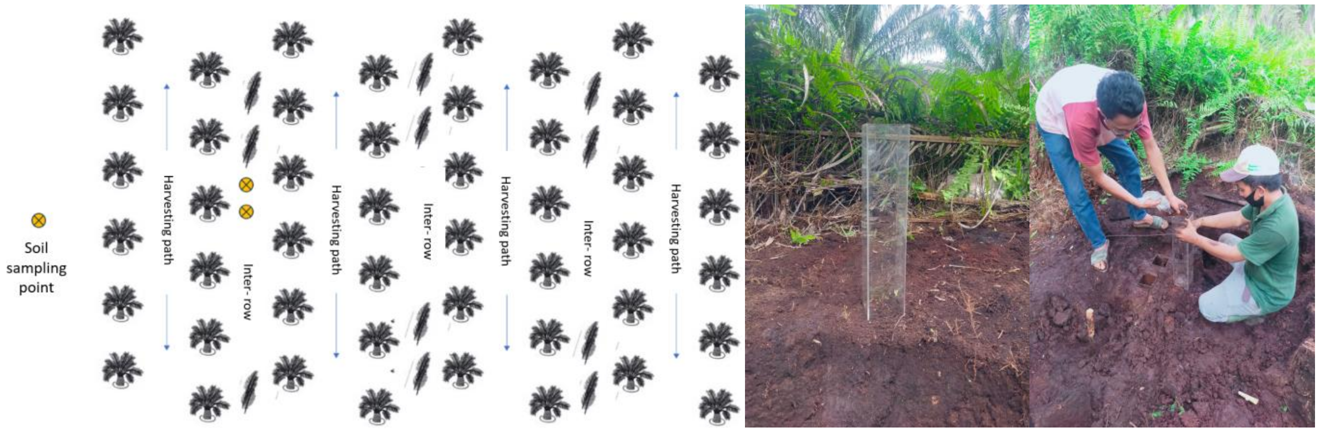


Figure 1. Soil sampling point at the inter-row of oil palm.

Table 1. Formulation and K_2O content of each ZEKA fertilizer

ZEKA's Formula	Granulation composition*	K_2O (%)
ZC-1	40% potassium-impregnated Coarse-zeolite + 60% KCl	29.36
ZC-2	50% potassium-impregnated Coarse-zeolite + 50% KCl	26.11
ZC-3	60% potassium-impregnated Coarse-zeolite + 40% KCl	29.42
ZF-1	40% potassium-impregnated Fine-zeolite + 60% KCl	26.87
ZF-2	50% potassium-impregnated Fine -zeolite + 50% KCl	33.04
ZF-3	60% potassium-impregnated Fine -zeolite + 40% KCl	36.15

Remarks: *) composition by weight; ZC-1 = ZEKA- Coarse formula-1; ZC-2 = ZEKA- Coarse formula-2; ZC-3 = ZEKA- Coarse formula-3; ZF-1 = ZEKA- Fine formula-1; ZF-2 = ZEKA- Fine formula-2; ZF-3 = ZEKA- Fine formula-3.

Table 2. Fertilizer dosage on each treatment

Treatment	Fertilizer dosage (g)	K_2O (g)
Control	-	-
KCl	8.17	4.90
ZC-1	18.24	4.90
ZC-2	14.48	4.90
ZC-3	13.56	4.90
ZF-1	16.70	4.90
ZF-2	18.77	4.90
ZF-3	16.66	4.90

Remarks: *) composition by weight; ZC-1 = ZEKA- Coarse formula-1; ZC-2 = ZEKA- Coarse formula-2; ZC-3 = ZEKA- Coarse formula-3; ZF-1 = ZEKA- Fine formula-1; ZF-2 = ZEKA- Fine formula-2; ZF-3 = ZEKA- Fine formula-3.

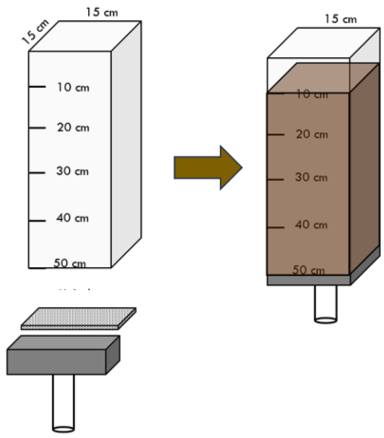


Figure 2. Acrylic soil column illustration for undisturbed soil sampling

2.2. Tools

The equipment included an oven, digital balance for weighing, shaker, pH meter for measuring soil pH, high energy ball mill Emax Retsch-Alle Germany (planetary ball mill) for grounding of zeolite, furnace for activated the zeolite, AAS (atomic absorption spectrophotometer), and soil columns for soil sampling. This research consists of (1) the preparation and formulation of zeolite-based potassium fertilizer and (2) a potassium leaching experiment of formulated zeolite-based potassium fertilizer on peat soil columns.

2.3. Soil Sampling

Soil sampling was done in the inter-row of oil palms, which are populated by *Nephrolepis biserrata* (Fig. 1). This area is free from worker activities and minimum disturbance is caused by human activity and vehicle traffic, so it does not have any compaction. Soil samples were taken at a depth of 0-40 cm using an acrylic soil column. First, the soil surface was cleared of vegetation. Then, a soil column (15 cm length, 15 cm width, and 50 cm high) was placed on the cleaned soil surface and gently pressed to a depth of 40 cm. Finally, the soil at the bottom of the soil column was cut and covered using column cover.

2.4. Preparation and Formulation of Zeolite-based Potassium Fertilizer

Two zeolite particle sizes are used to manufacture zeolite-based potash fertilizer: Coarse-zeolite and Fine-zeolite. Coarse-zeolite refers to zeolite with a particle size of ±0.147 mm, and Fine-zeolite refers to zeolite with a particle size of ±500 nm. Before use, the zeolite was activated using an acidic solution of 1.75 N HCl with a ratio of zeolite to HCl solution of 1:5. Furthermore, filtering was carried out using Whatman filter paper 42 to separate zeolite solids from the solution. The activated zeolite was then rinsed using distilled water until pH 7, and then the zeolite was placed in a furnace at 400^0C for 1 hour. The activated zeolite was then soaked in KCl solution at a concentration of 25,000 ppm for 17 days (Jaskūnas et al., 2015). The solution was filtered to separate the filtrate from the solid, and then the impregnated solid was used as the base material for the manufacture of zeolite-based potassium fertilizer.

The formulation of zeolite-based potassium fertilizer involved granulating each potassium-impregnated Coarse-zeolite and Fine-zeolite with KCl fertilizer in several ratios. In this study, three formulations of zeolite-based potassium fertilizer were carried out, namely: (i) Formula-1 (40% potassium-impregnated zeolite: 60% KCl fertilizer); (ii) Formula-2 (50% potassium-impregnated zeolite: 50% KCl fertilizer); and (iii) Formula-3 (60% potassium impregnated zeolite: 40% KCl fertilizer). The results of these formulations are from now on referred to as (a) ZEKA-Coarse-1, (b) ZEKA-Coarse -2, (c) ZEKA- Coarse -3, (d) ZEKA-Fine-1, (e) ZEKA- Fine -2 and (f) ZEKA- Fine -3. ZEKA-Coarse is a zeolite-based potassium fertilizer with a particle size of ±0.147 mm, granulated with KCl fertilizer in three formulations. Meanwhile, ZEKA-Fine is a zeolite-based potassium fertilizer with a particle size of ± 500 nm, granulated with KCl fertilizer and available in three formulations. This study abbreviates the ZEKA-Coarse as ZC and ZEKA-Fine as ZF. The potassium content of each ZEKA fertilizer formulation is presented in Table 1.

2.5. Potassium Leaching Experimental Design

The potassium leaching experiment on peat soil columns was designed as a completely randomized design (CRD) with eight treatments and three replications. The treatments were: (1) control/no fertilizer, (2) KCl fertilizer, (3) ZC-1, (4) ZC-2, (5) ZC-3, (6) ZF-1, (7) ZF-2 and (8) ZF-3. Each treatment was applied to the soil column surface with equal amounts of potassium nutrient conversion (Table 2). Potassium leaching experiments were conducted using peat soil columns. The acrylic soil column used was cube-shaped with dimensions of 15 cm × 15 cm × 50 cm (Fig. 2). The peat soil samples used were undisturbed peat samples taken from the area between rows of oil palms. In taking soil samples using acrylic, the soil was only taken to a depth of ± 40 cm, while the remaining ± 10 cm was left as space for treatment and watering. The following methods were used to analyze the soil: the potentiometric method for measuring pH, the volumetric NaCl-10% method for cation exchange capacity, atomic absorption spectroscopy (AAS) with ammonium acetate 1N for exchangeable bases, the spectrophotometric method for C-organic using $K_2Cr_2O_7$ 1N, and the Kjeldahl method for N-total. The soil column was then placed on a shelf in the greenhouse. Before treatment, undisturbed peat soil samples were saturated with water and left for one week. Then, each treatment was applied to the surface of the soil column and watered until it reached the top of the soil column. The wash water (filtrate) from each soil column was collected weekly for ten weeks. The potassium concentration of the wash water from each soil column was analyzed using AAS in the laboratory. The total K-leached was calculated using Equation 1. At the end of the study, the soil in the soil column was taken apart and composited for analysis.

K-Lch(g) = C-Lch × V-per .... [1]

where, K-Lch = the amount of potassium leached in leachate (g); C-Lch = concentration of potassium in percolated water (ppm); Vper = percolated water volume (l).

2.6. Statistical analysis

The data were analyzed using an analysis of variance (ANOVA) followed by Duncan's multiple range test at a confidence level of 95%.

3. RESULTS

3.1. Peat Characteristics

The characteristics of the peat soil before treatment application are presented in Table 3. The maturity level of the peat was hemic-sapric, with a pH of 4.3, a C/N ratio of 4.6, and an exchangeable K content of 1.37 cmol kg^{-1}. The Cation Exchange Capacity (CEC) is high at 121.44 cmol kg^{-1}. Meanwhile, the bulk density of the soil is 0.32 g cm^{-3}, with a particle density value of 1.22 g cm^{-3}. The porosity of the peat was measured at 74.02% with a permeability of 2 × 10-6 m s^{-1}. The results showed changes in several soil properties after the treatment (Table 4). Changes in soil properties occurred with increased soil pH and cation exchange capacity. The initial pH value of the soil was < 4, but after treatment, the pH increased to > 4. In this study, the highest pH was obtained in the ZF-2 treatment, namely 4.9 and the lowest in the control treatment, namely 4.10 (Fig. 3). The results showed that at the end of the study, the highest soil CEC was obtained in the ZF-2 treatment with 183.78 cmol kg^{-1}, which was the lowest in the KCl and control treatments, with 96.60 cmol kg^{-1} and 108 cmol kg^{-1}, respectively. Figure 4 shows that the ZEKA fertilizer treatment produced a higher CEC than the KCl treatment. In addition to soil pH, cation exchange capacity (CEC) was slightly higher in ZEKA than in control and KCl treatments (Fig. 4). The results showed that at the end of the study, the highest soil CEC was obtained in the ZF-2 treatment, with 183.78 cmol kg^{-1}, which was the lowest in the KCl and control treatments, with 96.60 cmol kg^{-1} and 108 cmol kg^{-1}, respectively. Figure 3 shows that the ZEKA fertilizer treatment produced a higher CEC than the KCl treatment.

Table 3. Peat soil characteristics (before treatments)

Description	Value
Peat thickness (m)	> 3
Decomposition level	Hemic-Sapric
Soil sample depth (cm)	± 40
pH (H_2O)	3.9
C (%)	43.81
N (%)	1.24
C/N	46
P (ppm)	16.95
K cmol kg^{-1}	1.37
Ca cmol kg^{-1}	14.78
Mg cmol kg^{-1}	9.54
CEC cmol kg^{-1}	121.44
Bulk density g cm^{-3}	0.32
Particle density g cm^{-3}	1.22
Porosity (%)	74.02
Permeability m s^{-1}	2 x 10^{-6}

Remarks: CEC = cation exchange capacity (volumetric NaCl-10%); pH (1:2,5) potentiometric, C-organic (total) spectrophotometric/$K_2Cr_2O_7$ 1N, Nitrogen- Kjeldahl, P- bray 2, K, Ca, Mg ammonium acetate 1N

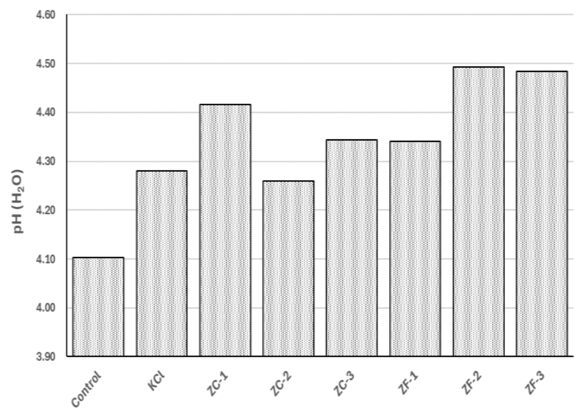


Figure 3. Soil pH on each treatment at the end of the study

3.2. Potassium Leaching

The analysis of variance showed a significant difference between the treatments regarding the amount of leached potassium. The potassium leached in the first week of the KCl treatment was 409.79 mg L^{-1}, the highest potassium leached compared to other treatments (Fig. 5).

Table 4. Peat soil properties on each treatment (after treatments)

Treatments	pH (H_2O)	C (%)	N (%)	C/N	P mg kg^{-1}	K	Ca	Mg	CEC
						cmol kg^{-1}			
Control	4.10	51.81	0.95	56.01	26.95	0.51	8.08	7.90	108.00
KCl	4.28	53.21	0.96	53.97	191.40	1.27	18.95	10.89	96.60
ZC-1	4.42	52.91	0.99	53.27	74.07	1.55	12.28	9.85	170.61
ZC-2	4.26	52.29	0.87	60.11	64.78	1.64	9.35	7.96	114.19
ZC-3	4.34	36.04	0.64	56.60	54.77	1.58	11.85	6.63	137.57
ZF-1	4.34	52.17	0.87	60.19	68.35	0.51	10.66	9.58	147.91
ZF-2	4.49	50.75	0.79	64.51	108.64	1.27	12.63	6.80	183.78
ZF-3	4.48	50.00	0.77	64.94	72.60	1.66	10.00	7.70	116.60

Remarks: CEC = cation exchange capacity (volumetric NaCl-10%); pH (1:2,5) potentiometric, C-organic (total) spectrophotometric/$K_2Cr_2O_7$ 1N, Nitrogen- Kjeldahl, P- Bray 2, K, Ca, Mg ammonium acetate 1N; ZC-1 = ZEKA- Coarse formula-1; ZC-2 = ZEKA- Coarse formula-2; ZC-3 = ZEKA- Coarse formula-3; ZF-1 = ZEKA- Fine formula-1; ZF-2 = ZEKA- Fine formula-2; ZF-3 = ZEKA- Fine formula-3.

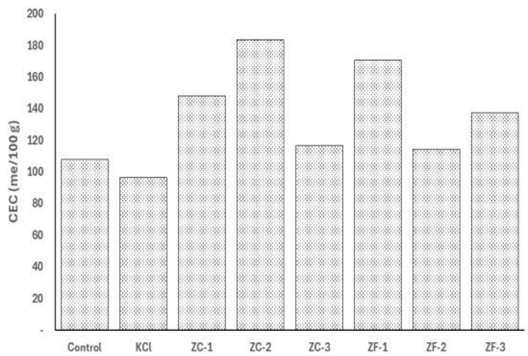


Figure 4. Soil cation exchange capacity on each treatment

Furthermore, from the second week to the fourth week, the leached potassium in the KCl treatment was 244.45 mg L^{-1}, 261.95 mg L^{-1}, and 398.43 mg L^{-1}, respectively, and was stable in the following weeks. Overall, the average leached potassium in the KCl treatment was 167.56 mg L^{-1}. Meanwhile, in the ZF-1 treatment, which was the treatment with the least leached potassium, the amount of leached potassium in the first week was 45.59 mg L^{-1}, then increased in the second week to 228.29 mg L^{-1}, fell back to 84.65 mg L^{-1} in the third week and was relatively stable in the following weeks with an average leached potassium of 74.46 mg L^{-1}.

The accumulation of potassium leaching in each treatment is presented in Figure 6. It can be seen in Figure 6 that the accumulation of potassium leaching in the KCl fertilizer treatment increases sharply from the first week of leaching to the fourth week before gradually slowing down in the following weeks. In contrast, the accumulation of potassium leaching in the ZEKA fertilizer treatment was slow throughout the entire leaching period. The zeolite content of the ZEKA fertilizer reduces the accumulation of potassium leaching from the peat soil. The highest accumulation of potassium leaching was observed in the KCl treatment, with 31% of potassium leached from a total of 4.90 g of potassium applied in the first week, and this continued to increase until the last week of observation, when the total was approximately 84%. In contrast, the ZC-1 treatment was the fertilizer treatment with the lowest accumulation of leached potassium. In the initial week, 3% of the total potassium (4.90 g) was leached in the ZF-1 treatment, increased to 9% in the second week, and reached approximately 31% by the end of the observation period. The highest total leached potassium was obtained in the KCl treatment, which was 2.83 g and significantly different from all treatments. Meanwhile, in the zeolite-based potassium fertilizer treatment, ZEKA fertilizer, the total leached potassium was low, with the lowest value obtained in the ZF-1 treatment at 1.05 g (Fig. 7).

4. DISCUSSION

Nutrient leaching is the loss of nutrients when water percolates into the soil profile through the plant root zone, making it unavailable to the plant. This research simulates this condition in a peat soil column, where leached potassium is defined as potassium that moves with the water out of the soil column. In general, the potassium leaching pattern of all treatments was dynamic until the third week of observation, except for the KCl treatment, where there was an increase in potassium leaching in the fourth week, but it is not clearly caused by the sudden increase in leaching in the KCl. Finally, the potassium leaching in all treatments was similar in the fifth week of observation (Fig. 5). This phenomenon may be attributed to the elevated potassium levels in the soil during the initial weeks, which were a consequence of the application of potassium from all treatments. However, following the fourth week, the potassium content of the soil began to decline due to leaching during the early weeks. However, after the fourth week, the potassium content in the soil started to decrease due to leaching during the early weeks, resulting in a low amount of leached potassium in the following weeks.

The average leached potassium in the KCl fertilizer treatment was higher than in the ZEKA fertilizer treatment. The peak of potassium leaching in the KCl treatment occurred in the first week of observation. In contrast, the peak of potassium leaching in the ZEKA fertilizer treatment occurred in the second and third weeks of observation. KCl fertilizer is soluble, while peat has a low affinity for potassium, causing the potassium from KCl fertilizer to be washed away with the percolation water. ZEKA fertilizer, on the other hand, contains zeolite, which helps the peat soil retain potassium for a longer time. (Hashim et al., 2019) stated that peat has a high cation adsorption capacity, except for potassium.

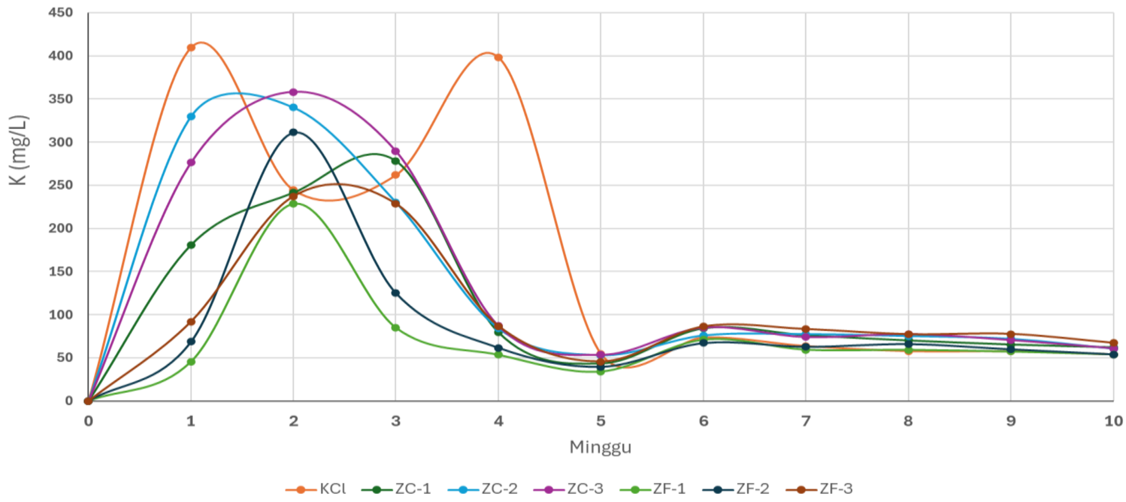


Figure 5. Potassium was leached weekly in each treatment

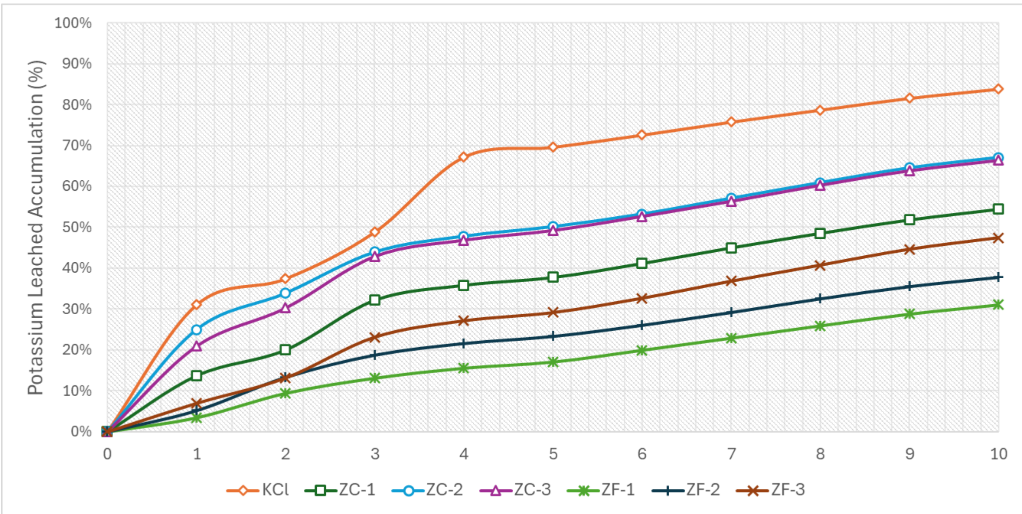
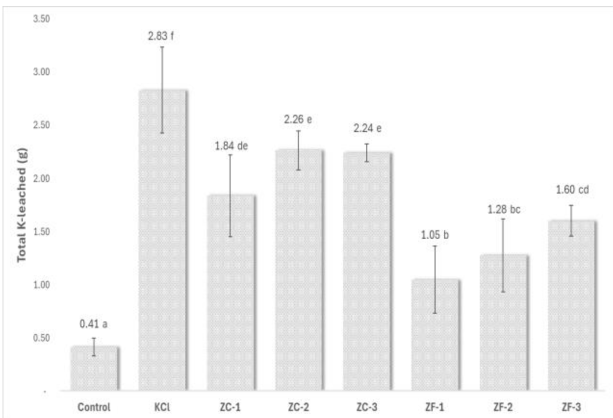


Figure 6. Accumulation of leached potassium in each treatment

As a result, potassium is easily washed away, so its availability for plants is low. Furthermore, Rosenani et al. (2016) also stated that potassium is soluble and exists in the soil solution as ions, so potassium can easily be leached out of the plant root zone.

The analysis of percolated water for each treatment shows that the lowest total leached potassium was obtained in the control (Fig. 7). These results confirm that, naturally, without the addition of fertilizer, the potassium content of peat soil is low. Figure 6 also shows that the highest total leached potassium was obtained in the KCl treatment. The high total potassium leached in the KCl treatment was caused by the easy dissolution of potassium from KCl and the low affinity of peat to potassium because no ameliorants helped hold potassium, so potassium in the soil solution was quickly washed away. On the other hand, the low total potassium leached in the ZEKA fertilizer treatment is due to the zeolite in the ZEKA fertilizer, which helps the peat soil retain potassium, thus reducing the amount leached. ZEKA contains K on the outer surface and inside the pores of the zeolites. The release process of potassium on the outer surface is relatively easy.

In contrast, releasing potassium from the zeolite pores is more complex and takes a long time. As a result, the release of potassium in ZEKA fertilizers is slower than in KCl fertilizers. Mondal et al. (2021) reported that zeolite has selectivity for major essential nutrients, including potassium, in its unique porous structure, which reduces nutrient leaching. Furthermore, Jakkula and Wani (2018) also stated that zeolites can increase the soil retention capacity of nutrients so that plants can absorb more nutrients.



Remarks: The same notation on the bar indicates not significantly different based on Duncan's range test at the 5% level

Figure 7. Total potassium leached in each treatment

The average potassium leached in the ZC treatment was approximately 62% greater than that observed in the ZF treatment. These findings are believed to be due to fine-zeolite particles having a larger specific surface area than coarse-zeolite particles. The larger specific surface means the zeolite becomes more charged, increasing potassium absorption. Consequently, potassium is less susceptible to washing away and remains available to plants longer. These findings are consistent with the findings of Adam et al. (2020), who asserted that particle size plays a pivotal role in the properties and performance of an adsorbent. In addition, Santi et al. (2021) reported in their research that reducing the size of zeolite particles from 60-80 mesh to 100-150 mesh increased the surface area and improved physical and chemical reactions. The CEC of zeolite increased by approximately 55% from 70.35 cmol kg^{-1} to 126.45 cmol kg^{-1}. Furthermore, Kumar et al. (2019) also indicated that particles with smaller sizes have a high surface area, resulting in many active sides of the particles.

In Figure 2, the pH of all ZEKA fertilizer treatments is generally higher than that of the KCl treatment. These results indicate that the zeolites in the ZEKA fertilizer treatment contributed to the increase in soil pH. The results of this study align with the results of the research of Krishnan et al. (2021), which also revealed that zeolite application on peat soil can increase the pH of peat soil 30 days after zeolite application. The results also showed that the ZEKA fertilizer treatment resulted in a higher CEC of the peat soil than the KCl fertilizer treatment. However, although previous studies have shown that zeolites can increase soil CEC through their negative charge contribution (Sindesi et al., 2022), this study suggests that the increase in CEC is the result of an increase in pH. This assumption is based on the small dose of zeolite used in this study, so it is unlikely to have any real effect on the increase in soil CEC. Peat soil contains humic materials rich in carboxyl and phenolic hydroxyl groups, which can dissociate or deprotonate depending on pH. As soil pH increases, dissociation of these groups will occur, increasing the negative charge of peat soil organic colloids. The increase in soil CEC seems to have implications for soil exchangeable K content, where the results of soil analysis at the end of the experiment showed the lowest soil exchangeable K content was obtained in the control treatment at 0.51 cmol kg^{-1}, followed by the KCl fertilizer treatment at 1.27 cmol kg^{-1}. In comparison, the highest soil exchangeable K content was obtained in the ZF-1 treatment at 1.66 cmol kg^{-1} (Table 4). Table 4 shows that the soil exchangeable K content in the ZEKA fertilizer treatment is higher than in the KCl treatment. Assuming that the amount of potassium in each soil column is the same, except for the control, the soil exchangeable K content is the residue of the initial potassium amount minus the leached potassium amount. Overall, the results show that ZEKA fertilizer can increase the pH of peat soil, which has implications for increasing the soil CEC. Through this increase in CEC, the potassium that can be retained in the soil is higher than that of KCl fertilizer.

The findings of this study demonstrate that ZEKA can prevent potassium leaching in peat soils. However, this investigation was carried out utilizing the soil column approach in a highly controlled environment. In reality, numerous factors influence the amount of potassium leached from peat soil in a field. Therefore, further research is needed to study ZEKA's effectiveness in the field. The study demonstrated the effectiveness of ZEKA fertilizer in reducing the leaching of nutrients from peat soil columns.

5. CONCLUSION

The study demonstrated the effectiveness of ZEKA fertilizer in reducing the leaching of potassium from peat soil columns. Formulation-1 was the best formulation in ZC and ZF, resulting in the smallest leaching of potassium nutrients. Overall, the results showed that ZEKA fertilizer reduced potassium leaching in peat soil by about 40% compared to KCl fertilizer.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

Adam, M. R., Othman, M. H. D., Sheikh Abdul Kadir, S. H., Mohd Sokri, M. N., Tai, Z. S., Iwamoto, Y., . . . Jaafar, J. (2020). Influence of the Natural Zeolite Particle Size Toward the Ammonia Adsorption Activity in Ceramic Hollow Fiber Membrane. *Membranes*, *10*(4), 63. https://doi.org/10.3390/membranes10040063

Azis, A., Rauf, A., Hanum, H., & Agus, F. (2022). Dynamics of nutrition peat soil due the biochar of oil palm empty bunches application and nitrogen and kalium. *IOP Conference Series: Earth and Environmental Science*, *977*(1), 012097. https://doi.org/10.1088/1755-1315/977/1/012097

Bagheri, H., Zare Abyaneh, H., & Izady, A. (2021). Nutrient and colloid leaching from un-amended versus vermicompost-amended soil. *Soil and Tillage Research*, *213*, 105092. https://doi.org/10.1016/j.still.2021.105092

Bhattacharyya, T., Chandran, P., Ray, S., Pal, D., Mandal, C., & Mandal, D. (2015). Distribution of zeolitic soils in India. *Current Science*, *109*(7), 1305-1313. https://oar.icrisat.org/9106/1/ZEOLITE%20CURRENT%20SCIENCE%20PAPER%20.pdf

Binner, I., Dultz, S., Schellhorn, M., & Schenk, M. K. (2017). Potassium adsorption and release properties of clays in peat-based horticultural substrates for increasing the cultivation safety of plants. *Applied Clay Science*, *145*, 28-36. https://doi.org/10.1016/j.clay.2017.05.013

Cataldo, E., Salvi, L., Paoli, F., Fucile, M., Masciandaro, G., Manzi, D., . . . Mattii, G. B. (2021). Application of Zeolites in Agriculture and Other Potential Uses: A Review. *Agronomy*, *11*(8), 1547. https://doi.org/10.3390/agronomy11081547

Cole, L. E. S., Åkesson, C. M., Hapsari, K. A., Hawthorne, D., Roucoux, K. H., Girkin, N. T., . . . Thornton, S. A. (2022). Tropical peatlands in the anthropocene: Lessons from the past. *Anthropocene*, *37*, 100324. https://doi.org/10.1016/j.ancene.2022.100324

Cuin, T. A., Dreyer, I., & Michard, E. (2018). The Role of Potassium Channels in Arabidopsis thaliana Long Distance Electrical Signalling: AKT2 Modulates Tissue Excitability While GORK Shapes Action Potentials. *International Journal of Molecular Sciences*, *19*(4), 926. https://doi.org/10.3390/ijms19040926

Dreyer, I., Gomez-Porras, J. L., & Riedelsberger, J. (2017). The potassium battery: a mobile energy source for transport processes in plant vascular tissues. *New Phytologist*, *216*(4), 1049-1053. https://doi.org/10.1111/nph.14667

Fatimah, S., Noor, M., & Saputra, R. A. (2024). The Efficacy of Several Agricultural Wastes as Ameliorant for Peat Degraded Soil: The Case of Kalimantan. *Tropical Wetland Journal*, *10*(1), 39-45. https://doi.org/10.20527/twj.v10i1.131

Hashim, S. A., Teh, C. B. S., & Ahmed, O. H. (2019). Influence of Water Table Depths, Nutrients Leaching Losses, Subsidence of Tropical Peat Soil and Oil Palm (Elaeis guineensis Jacq.) Seedling Growth. *Malaysian Journal of Soil Science*, *23*, 13-30. https://www.msss.com.my/mjss/Full%20Text/vol23/V23_02.pdf

Jakkula, V. S., & Wani, S. P. (2018). Zeolites: Potential soil amendments for improving nutrient and water use efficiency and agriculture productivity. *Scientific Reviews & Chemical Communications*, *8*(1), 1-15. https://oar.icrisat.org/10768/1/Zeolites-Potential-soil-amendments-for-improving-nutrient-and-water-use-efficiency-and-agriculture-productivity.pdf

Jaskūnas, A., Subačius, B., & Šlinkštienė, R. (2015). Adsorption of potassium ions on natural zeolite: Kinetic and equilibrium studies. *Chemija*, *26*(2). https://doi.org/10.6001/chemija.2015.26.2.1

Jia, Q., Zheng, C., Sun, S., Amjad, H., Liang, K., & Lin, W. (2018). The role of plant cation/proton antiporter gene family in salt tolerance. *Biologia Plantarum*, *62*(4), 617-629. https://doi.org/10.1007/s10535-018-0801-8

Kalsoom, M., Ur Rehman, F., Shafique, T., Junaid, S., Khalid, N., Adnan, M., . . . Ali, H. (2020). Biological Importance Of Microbes In Agriculture, Food And Pharmaceutical Industry: A Review. *Innovare Journal of Life Sciences*, *8*(6), 1-4. https://doi.org/10.22159/ijls.2020.v8i6.39845

Krishnan, K., Ngerong, A. A., Ahim, K., Ahmed, O. H., Ali, M., Omar, L., & Musah, A. A. (2021). Mitigating Potassium Leaching from Muriate of Potash in a Tropical Peat Soil Using Clinoptilolite Zeolite, Forest Litter Compost, and Chicken Litter Biochar. *Agronomy*, *11*(10), 1900. https://doi.org/10.3390/agronomy11101900

Kumar, P. S., Korving, L., Keesman, K. J., van Loosdrecht, M. C. M., & Witkamp, G.-J. (2019). Effect of pore size distribution and particle size of porous metal oxides on phosphate adsorption capacity and kinetics. *Chemical Engineering Journal*, *358*, 160-169. https://doi.org/10.1016/j.cej.2018.09.202

Kurnianto, S., Selker, J., Boone Kauffman, J., Murdiyarso, D., & Peterson, J. T. (2019). The influence of land-cover changes on the variability of saturated hydraulic conductivity in tropical peatlands. *Mitigation and Adaptation Strategies for Global Change*, *24*(4), 535-555. https://doi.org/10.1007/s11027-018-9802-3

Lateef, A., Nazir, R., Jamil, N., Alam, S., Shah, R., Khan, M. N., & Saleem, M. (2016). Synthesis and characterization of zeolite based nano–composite: An environment friendly slow release fertilizer. *Microporous and Mesoporous Materials*, *232*, 174-183. https://doi.org/10.1016/j.micromeso.2016.06.020

Messiga, A. J., Dyck, K., Ronda, K., van Baar, K., Haak, D., Yu, S., & Dorais, M. (2020). Nutrients Leaching in Response to Long-Term Fertigation and Broadcast Nitrogen in Blueberry Production. *Plants*, *9*(11), 1530. https://doi.org/10.3390/plants9111530

Mondal, M., Biswas, B., Garai, S., Sarkar, S., Banerjee, H., Brahmachari, K., . . . Hossain, A. (2021). Zeolites Enhance Soil Health, Crop Productivity and Environmental Safety. *Agronomy*, *11*(3), 448. https://doi.org/10.3390/agronomy11030448

Muhammad, S., Sanden, B. L., Saa, S., Lampinen, B. D., Smart, D. R., Shackel, K. A., . . . Brown, P. H. (2018). Optimization of nitrogen and potassium nutrition to improve yield and yield parameters of irrigated almond (Prunus dulcis (Mill.) D. A. webb). *Scientia Horticulturae*, *228*, 204-212. https://doi.org/10.1016/j.scienta.2017.10.024

Mustamo, P., Hyvärinen, M., Ronkanen, A.-K., & Kløve, B. (2016). Physical properties of peat soils under different land use options. *Soil Use and Management*, *32*(3), 400-410. https://doi.org/10.1111/sum.12272

Nakhli, S. A. A., Delkash, M., Bakhshayesh, B. E., & Kazemian, H. (2017). Application of Zeolites for Sustainable Agriculture: a Review on Water and Nutrient Retention. *Water, Air, & Soil Pollution*, *228*(12), 464. https://doi.org/10.1007/s11270-017-3649-1

Rameshaiah, G., Pallavi, J., & Shabnam, S. (2015). Nano fertilizers and nano sensors–an attempt for developing smart agriculture. *International Journal of Engineering Research and General Science*, *3*(1), 314-320. https://pnrsolution.org/Datacenter/Vol3/Issue1/40.pdf

Reeza, A. A., Hussin, A., & Ahmed, O. H. (2021). Comparison of the effectiveness of three extractants in extracting potassium, calcium and magnesium from tropical peat soils. *Mires and Peat*, *27*, 1-10. https://doi.org/10.19189/MaP.2019.OMB.StA.1833

Rosenani, A. B., Rabuni, W., Cheah, P., & Noraini, J. (2016). Mass loss and release of nutrient from empty fruit bunch of oil palm applied as mulch to newly transplanted oil palm. *Soil Research*, *54*(8), 985-996. https://doi.org/10.1071/SR15143

Santi, L. P., Goenadi, D. H., Sabiham, S., & Bindar, Y. (2021). The Use of Molecular-Sieving Materials as Ameliorant for Peat Degradation in the Tropics. *Journal of Minerals and Materials Characterization and*

Engineering, *9*(4), 362-374. https://doi.org/10.4236/jmmce.2021.94025

Sardans, J., & Peñuelas, J. (2021). Potassium Control of Plant Functions: Ecological and Agricultural Implications. *Plants*, *10*(2), 419. https://doi.org/10.3390/plants10020419

Sarkkola, S., Laiho, R., Ukonmaanaho, L., Nieminen, T., Laurén, A., Finér, L., . . . Nieminen, M. (2016). sufficiency of potassium (K) for wood production – long-term effects of forest management on the K-balance of drained boreal peatlands. Peatlands in harmony-agriculture, industry and nature: Proceedings of the 15th international peat congress, oral presentations, extended abstracts, 15th-19th August 2016, Kuching, Sarawak, Malaysia. https://peatlands.org/document/sufficiency-of-potassium-k-for-wood-production-long-term-effects-of-forest-management-on-the-k-balance-of-drained-boreal-peatlands/

Sindesi, O. A., Lewu, M. N., Ncube, B., Mulidzi, A., & Lewu, F. B. (2022). Residual effect of zeolite on soil exchangeable cations and cation exchange capacity in sandy soil cultivated with Swiss Chard. *35th Int'l Conference on Chemical, Biological and Environmental Engineering (ICCBEE-22) Nov. 28-29, 2022. Johannesburg (South Africa)*, 40-43.

Soumare, A., Sarr, D., & DiÉDhiou, A. G. (2023). Potassium sources, microorganisms and plant nutrition: Challenges and future research directions. *Pedosphere*, *33*(1), 105-115. https://doi.org/10.1016/j.pedsph.2022.06.025

Sustr, M., Soukup, A., & Tylova, E. (2019). Potassium in Root Growth and Development. *Plants*, *8*(10), 435. https://doi.org/10.3390/plants8100435

Tandiono, J., Thamrin, Hapsoh, & Warningsih, T. (2025). Impact of using Boiler Ash as Soil Ameliorant and Nitrogen Fertilizer on CO2 Emission in Oil Palm Plantations on Peat Soil. *Pertanika Journal of Tropical Agricultural Science*, *48*(2), 653-665. https://doi.org/10.47836/pjtas.48.2.18

Tränkner, M., Tavakol, E., & Jákli, B. (2018). Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. *Physiologia Plantarum*, *163*(3), 414-431. https://doi.org/10.1111/ppl.12747

Ullah Khan, S., Ahmad Alizai, A., Ahmed, N., Sayed, S., Junaid, M., Kanwal, M., . . . Ali, E. F. (2022). Investigating the role of potassium and urea to control fruit drop and to improve fruit quality of "Dhakki" date palm. *Saudi Journal of Biological Sciences*, *29*(5), 3806-3814. https://doi.org/10.1016/j.sjbs.2022.02.060

Utami, S. N. H., Kusumawardani, P. N., Maftu'ah, E., Noor, M., Masganti, Wakhid, N., . . . Karolinoerita, V. (2024). Empty Fruit Bunch Oil Palm Ash and Biochar Improved Peat Soil Properties, NPK Status on Leaves, and the Growth of Immature Oil Palm Plantations. *Applied and Environmental Soil Science*, *2024*(1), 1133527. https://doi.org/10.1155/aess/1133527

Widiarso, B., Minardi, S., Komariah, K., Chandra, T. O., Elmahdi, M. A., & Senge, M. (2020). Predicting peatland groundwater table and soil moisture dynamics affected by drainage level. *Sains Tanah Journal of Soil Science and Agroclimatology*, *17*(1), 8. https://doi.org/10.20961/stjssa.v17i1.38459