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Maize nutrient translocation on artisanal gold mining soil ameliorated with EFB compost, clay, and lime

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ABSTRACT

Artisanal gold mining generally produces coarse-textured soils with low nutrient-holding capacity, which limit plant growth and productivity. Soil reclamation in these conditions necessitates not only improved soil quality but also effective nutrient uptake and allocation within the plant. This study aims to evaluate the effects of oil palm empty fruit bunch (EFB) compost, clay soil, and lime, used as soil conditioners, on the concentrations of N, P, and K in various maize organs grown in soil formerly used for artisanal gold mining. The study was conducted in experimental pots using a completely randomized factorial design (CRF) with three factors: A) EFB compost at 6, 12, and 18 t ha^{-1}; B) clay at 10 and 20%; and C) lime at 0.5 and 1.0 t ha^{-1}. After harvest, maize plants were separated into roots, stems, leaves, and grain, and tissue concentrations of N, P, and K were determined. The results showed clear organ-specific patterns of nutrient accumulation. The highest N concentration was found in the grain (1.95%), the highest P in the roots (0.37%), and the highest K in the leaves (3.07%), all under treatment A3B1C1 (18 t ha^{-1} of EFB compost, 10% clay, and 0.5 t ha^{-1} of lime). The findings suggest that using EFB compost, clay soil, and lime together can effectively improve nutrient availability, uptake, and partitioning in maize grown on post-gold mining soil. This strategy has the potential to support the productive reuse of degraded artisanal gold mining land.

Keywords: Clay soil, EFB compost, lime, maize, post artisanal gold mining soil

INTRODUCTION

Artisanal gold mining has far-reaching environmental consequences, including severe landscape disturbance and the formation of soils that are physically fragile, chemically degraded, and biologically impoverished. Following topsoil removal or intensive substrate mixing, the residual material is commonly coarse-textured, weakly structured, low in organic matter, low in cation exchange capacity, and poorly able to retain nutrients and support crop establishment (Timsina et al., 2022; Eludoyin et al., 2017). This issue is particularly relevant when researchers use maize as a test crop to evaluate nutrient translocation in reclaimed soils. Maize is a crop that requires a balanced supply of nutrients, such as nitrogen, phosphorus, and potassium, during its vegetative and reproductive growth (Rawal et al., 2022; Ciampitti et al., 2013; Kuunya et al., 2025). In reclaimed mining soils, maize performance reflects soil quality and productivity. Its response to soil amendments can indicate whether reclamation has improved nutrient availability. It can also indicate whether reclamation has improved soil–plant nutrient dynamics (Hu et al., 2021; Zhang et al., 2025; Fang et al., 2025; Kumari and Maiti, 2022).

Among the amendments available for post-mining soil rehabilitation, oil palm empty fruit bunch compost is particularly promising because it provides organic matter and nutrients while enhancing cation exchange capacity, pH, and biological activity (Neswati et al., 2022; Saidy et al., 2025). Two factors can further enhance the effectiveness of this method. First, the addition of clay soil improves nutrient retention through colloidal charge. Second, the addition of lime reduces acidity and increases the availability of phosphorus. Previous studies have demonstrated that EFB-based amendments and related organic materials can enhance nutrient availability, reduce acidity, and improve crop performance in degraded soils (Saidy et al., 2024; Dejene et al., 2023). However, there has been limited research on how these combined ameliorants affect nutrient levels in specific maize organs under artisanal ex-gold mining conditions.

The effects of EFB compost, clay soil, and lime on N, P, and K concentrations in maize roots, stems, leaves, and grain grown in soil from an artisanal ex-gold mining area are investigated in this study. The study aims to clarify how reclamation treatments influence not only soil nutrient availability but also nutrient uptake, translocation, and partitioning within the plant by focusing on organ-specific nutrient concentrations. This perspective is essential for developing reclamation strategies, which must be both agronomically effective and physiologically meaningful for the sustainable reuse of post-mining land.

MATERIALS AND METHODS

Study site

This research was conducted from January to July 2025. Maize cultivation was carried out on land belonging to the Bunga Tanjung agricultural group under the supervision of the Kuantan Singingi Regency Agricultural Crop Service in Riau.

Experimental Design

The study was conducted using experimental pots to evaluate land reclamation strategies for former artisanal gold mines. The soil used in this study was collected from a land-typology H gold mine located along the Singingi River in Riau Province, as previously characterized by Okalia *et al.* (2025). The experiment was designed using a completely randomized factorial (CRF) design with three factors (A, B, and C) at various levels, each replicated three times. Three ameliorants were used: A (EFB compost), B (clay soil), and C (lime). EFB compost (A) was applied at doses of 6, 12, and 18 t ha^{-1} (144, 288, and 432 g pot^{-1}), clay soil (B) at 10% and 20% (4.8 and 9.6 kg pot^{-1}), and lime (C) at 0.5 and 1.0 t ha^{-1} (12 and 24 g pot^{-1}), respectively. The clay soil used in this study belongs to the Ultisol order, with a clay content of 40%, and the lime used is $CaCO_3$. Maize grains of Pioneer P32 were planted at a distance of 70 cm apart in a 50×50 cm pot (equivalent to 48 kg of dry soil weight) and fertilized with 3.1 g of N, 1 g of P_2O_5 and 1.3 g of K_2O pot^{-1}.

Research procedure

After harvesting maize biomass (100 days after planting), plant tissue samples were obtained by separating roots, stems, leaves, and grain. The samples were dried in an oven at 70 °C, and their dry weights were measured. Next, the dried samples were ground using a mechanical grinder equipped with a 0.5-mm mesh filter. The macronutrients nitrogen (N), phosphorus (P), and potassium (K) were determined using the wet combustion method with H_2SO_4 and H_2O_2 . Total N concentration was measured using the Kjeldahl method, P using a spectrophotometer at a wavelength of 693 nm, and K concentration was measured using an atomic absorption spectrophotometer (AAS). All chemical analysis methods are as described in Eviati et al. (2023).

Statistical Analysis

The collected data were analyzed using Analysis of Variance (ANOVA) to detect significant differences between treatment groups at a 5% significance level. If significant differences were detected ($p < 0.05$), a post hoc analysis was conducted. Tukey's test was used to identify the specific treatment combinations responsible for the differences. Pearson correlation analysis was performed to assess relationships among nutrient concentrations in maize organs, and the results were visualized as a heatmap. RStudio 4.5.2 was used for all data analysis, and the results were presented in both tabular and graphical formats in Origin Pro Learning Edition.

RESULTS AND DISCUSSION

Effects of EFB Compost, Clay Soil, and Lime on N, P, and K Nutrient Concentration in Maize Roots

The effect of EFB compost, clay soil, and lime significantly increased the nutrient concentration of N, P, and K in maize roots. Based on the results of the Tukey 5% post-hoc test, there was an EFB compost, clay soil, and lime interaction (AxBxC) in the N and P nutrient concentration in maize roots, as shown in Table 1.

Treatment A3B2C2 had the highest nitrogen concentration at 0.72%, while A1B1C1 had the lowest at 0.27%, which is a difference of 0.45%. The study revealed an intriguing finding: treatments A3B2C2, A3B1C1, and A3B1C2 with a high EFB

Table 1. Effect of the EFB compost, clay soil, and lime interactions (A×B×C) on the N and P nutrient concentration in maize roots.

Treatment	N concentration (%)	P concentration (%)
A1B1C1 (6 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.27 ± 0.001 ^{h}	0.14 ± 0.028 ^{e}
A1B1C2 (6 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.47 ± 0.019 ^{fg}	0.18 ± 0.020 ^{de}
A1B2C1 (6 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.42 ± 0.036 ^{g}	0.25 ± 0.023 ^{c}
A1B2C2 (6 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.55 ± 0.035 ^{cd}	0.23 ± 0.023 ^{cd}
A2B1C1 (12 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.67 ± 0.044 ^{ab}	0.25 ± 0.005 ^{c}
A2B1C2 (12 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.64 ± 0.003 ^{bc}	0.24 ± 0.001 ^{c}
A2B2C1 (12 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.60 ± 0.023 ^{cd}	0.25 ± 0.024 ^{c}
A2B2C2 (12 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.52 ± 0.029 ^{ef}	0.24 ± 0.016 ^{c}
A3B1C1 (18 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.65 ± 0.022 ^{abc}	0.37 ± 0.005 ^{a}
A3B1C2 (18 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.67 ± 0.022 ^{abc}	0.32 ± 0.018 ^{b}
A3B2C1 (18 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.52 ± 0.022 ^{ef}	0.24 ± 0.009 ^{c}
A3B2C2 (18 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.72 ± 0.006 ^{a}	0.34 ± 0.002 ^{ab}

compost dose (A3) increased nitrogen (N) concentration. Moreover, combining high EFB compost (A3) with different clay soils (B1 and B2) and lime doses (C1 and C2) further increased nitrogen availability. The root nitrogen concentration in soil from reclaimed mine sites treated with soil amendments in this study was approximately 0.27–0.72%; however, it can vary by soil type. The result is consistent with the study by Castellano *et al.* (2021), which examined root nitrogen concentration in maize across several soil types. The lowest root nitrogen concentration was around 0.70%. The average whole-root nitrogen concentration increased with nitrogen fertilization rate: 1.1% for zero N, 1.2% for middle N, and 1.3% for excess N.

Table 1 shows that the highest P concentration (0.37%) was found in A3B1C1, while the lowest (0.14%) was in A1B1C1, resulting in a 0.23% difference. The results of the study indicate that a combination of high-dose EFB compost, clay soil, and lime, applied at optimal doses, improves phosphorus availability by increasing soil pH and phosphate solubility. Castaned *et al.* (2018) reported that P nutrient concentration in corn roots is influenced by the availability of P in the soil.

Furthermore, regarding potassium concentration in maize roots, based on the results of the Tukey 5% post-hoc test, the concentration of the K nutrient was influenced by the interactions between the treatments of EFB compost (A) and clay (B), EFB compost (A) and lime (C), and clay (B) and lime (C) (Figure 1).

In the A×B interaction (Figure 1a), treatments A3B1 and A3B2 resulted in the highest potassium concentration, which was not significantly different from each other at 1.31%. Figure 1a shows an inverse relationship in treatment A1B1 (6 t ha^{-1} EFB compost and 10% clay soil), where the potassium concentration was the lowest at 0.41%. Figure 1b also illustrates an A×C interaction; treatment A3C2 resulted in a potassium concentration of 1.32%, which was not significantly different from A3C1 (18 t ha^{-1} EFB compost and 0.5 t ha^{-1} lime), with a concentration of 1.31%. It suggests that increasing the lime dose from 0.5 t ha^{-1} (C1) to 1 t ha^{-1} (C2) does not significantly change soil potassium concentration. Treatment A1C1 showed the lowest potassium concentration, at 0.44%. In Figure 1c, the B×C interaction is shown; B2C2 exhibits a potassium concentration of 1.06%, slightly higher than that of B1C2 (0.88%). This indicates that A×B and A×C have higher K concentration than B×C. Amri (2018) reported that potassium supply from EFB compost and the lime-regulated soil chemistry work together to improve potassium uptake.

Effects of EFB Compost, Clay Soil, and Lime on N, P, and K Concentration in Maize Stems

Soil amelioration significantly affected all parameters, N, P, and K, in maize stems (Figure 2 and Table 2). Based on Figure 2a, for the EFB compost and clay interaction (AxB), treatment A3B1 showed the highest nitrogen concentration at 0.29%,

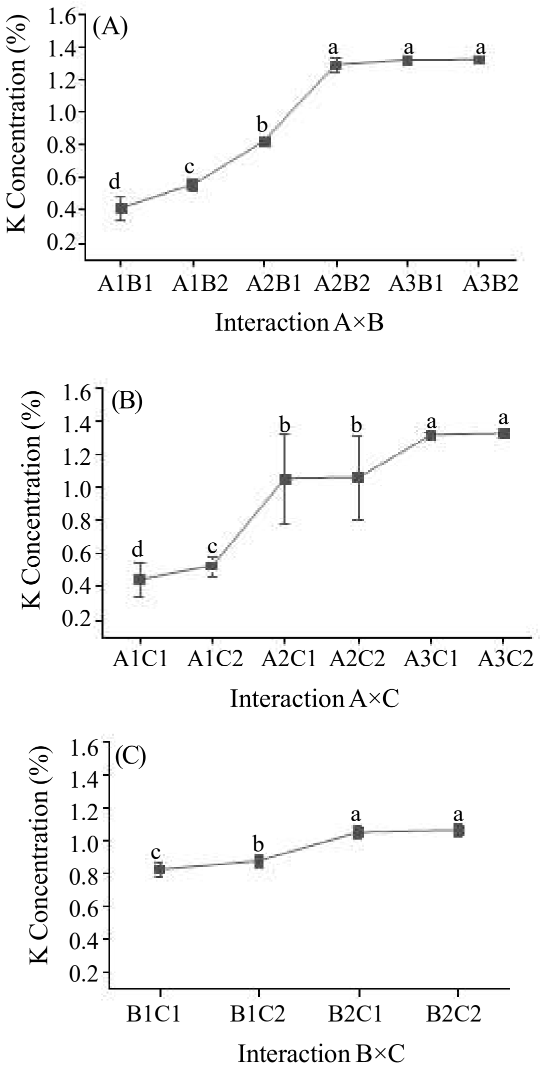

Figure 1. The effect of EFB compost (A) x clay soil (B) (1a), EFB compost (A) x lime (C) (1b), and clay soil (B) x lime (C) (1c) interactions on the K concentration in maize roots. Means above a bar of each sample, superscripted with different lowercase letters, are significantly different according to the Tukey test ($p<0.05$). Notes : A1: 6 t ha^{-1}, A2: 12 t ha^{-1} and A3: 18 t ha^{-1} of EFB compost; B1: 10% and B2: 20% clay; C1: 0.5 t ha^{-1} and C2: 1.0 t ha^{-1} of lime.

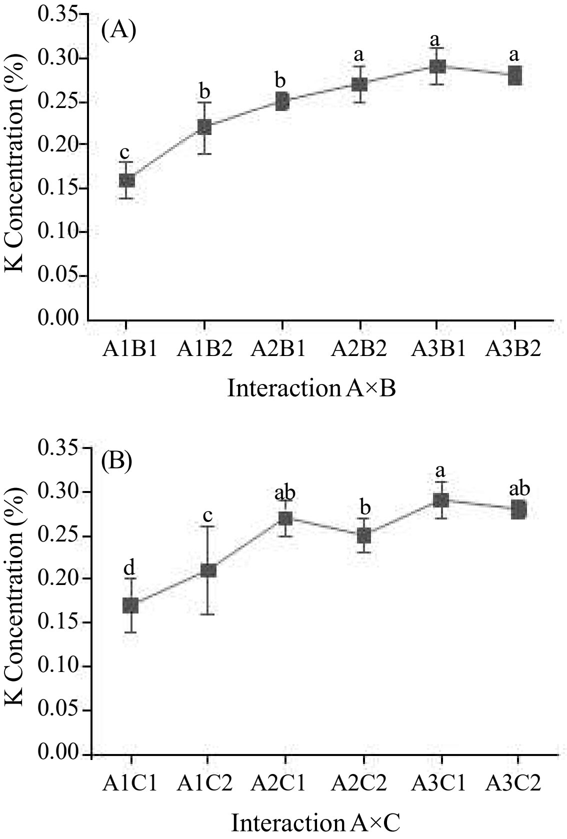

Figure 2. Effect of the EFB compost (A) x clay soil (B) (2a) and EFB compost (A) x lime (C) (2b) interactions on nitrogen concentration in maize stems. Means above a bar of each sample, superscripted with different lowercase letters, are significantly different according to the Tukey test ($p<0.05$). Note : A1: 6 t ha^{-1}, A2: 12 t ha^{-1} and A3: 18 t ha^{-1} of EFB compost; B1: 10% and B2: 20% clay; C1: 0.5 t ha^{-1} and C2: 1.0 t ha^{-1} of lime.

followed by treatment A3B1 at 0.25%. There was an interaction between EFB compost (A) and clay soil (B) and EFB compost (A) and lime (C) in terms of N concentration in stems (Figure 2).

Based on Figure 2a, for the AxB interaction, treatment A3B1 showed the highest nitrogen concentration at 0.29%, followed by treatment A3B1 at 0.25%. Increasing the compost application rate from 6 t ha^{-1} (A1) to 18 t ha^{-1} (A3) resulted in a significant increase in nitrogen concentration, with a difference of 0.13% between A1B1 (0.16%) and A3B1 (0.29%). The A3B1 treatment yielded the highest nitrogen concentration, while in A1B1 it was 0.16%, the lowest

Figure 2b shows that the AxC interaction, the A3C1 treatment (18 t ha^{-1} EFB compost and 0.5 t ha^{-1} lime) yielded the highest nitrogen concentration, at 0.29%, followed by A2C1 with a concentration of 0.27%. The addition of lime (C1) increased the nitrogen availability required by maize plants; however, the change from C1 to C2 (1.0 t ha^{-1} of lime) did not show a significant difference in N concentration. In A1C1, the N concentration was recorded at 0.17%, which was lower than in A3C1, indicating that a higher compost dose combined with a 0.5 t ha^{-1} lime dose was more effective in increasing nitrogen availability. In addition, compared to the nitrogen concentration in the roots, the nitrogen concentration in the stems is lower (see Table 1). In maize, the distribution of nitrogen among roots, stems, leaves, and grain is dynamic and influenced by nutrient availability and management practices (Duan et al., 2023). Furthermore, the P and K concentration of maize stems is significantly influenced by the A×B×C interaction shown in Table2.

Table 2 shows the effect of the A×B×C interaction on P and K concentration in maize stems. The highest P concentration was observed in treatment A2B2C1 at 0.22%, while the lowest was in treatments A3B2C1 and A2B2C2, both at 0.05%, a difference of 0.17%. The phosphorus concentration in the roots is approximately 0.05-0.22%, which is lower than the range of approximately 0.14-0.37%. Holz et al. (2024) stated that the distribution of phosphorus within plants is such that only about 60% of the absorbed P reaches the upper parts of the plant, while approximately 40% remains in the growing root tips of both lateral and primary roots. This suggests that the root growth zone has a very high phosphorus requirement. For potassium, the highest concentration was recorded in A3B2C2 (1.93%), which was not different from that in A3B1C1. While the lowest was observed in A1B1C1, the difference in potassium concentration between treatments ranged from 0.17% to 1.21%. In contrast to the phosphorus concentration, the potassium concentration in the corn stalk (0.72-1.93%) is higher than in the roots (0.41-1.31%). Daher *et al.* (2010) and Ozpinar (2016) reported that potassium concentration in maize stems is generally higher than in roots, indicating greater potassium accumulation in aboveground tissues than in belowground tissues.

Effects of EFB Compost, Clay Soil, and Lime on N, P, and K Concentration in Maize Leaves

Amelioration of EFB compost, clay soil, and lime significantly affected the nutrient concentration of N, P, and K in leaves. The effects of EFB (A) and clay soil (B) on the nitrogen concentration of maize leaves are shown in Table 3.

According to Table 3, the increase in leaf nitrogen concentration with higher EFB compost rates suggests that the amount of compost applied was the main factor controlling nitrogen availability in maize. Treatment A3 (18 t ha^{-1}) led to the highest N value (0.73%), indicating that increasing the compost supply increased organic N, thereby enhancing nutrient mineralization, retention, and uptake. Recent studies also indicate that the addition of compost and other organic matter to soil significantly increases the concentration of nitrogen (N) in maize, enhances its uptake, and improves its overall nutrient efficiency. This enhancement is achieved by improving the soil's chemical properties and promoting more sustained N release (Nigussie

Table 2. Effect of the EFB compost, clay soil, and lime interactions (A×B×C) on the P and K nutrient concentration in maize stems.

Treatment	P concentration (%)	K concentration (%)
A1B1C1 (6 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.17 ± 0.0019 ^{d}	0.72 ± 0.026 ^{f}
A1B1C2 (6 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.18 ± 0.0010 ^{cd}	0.77 ± 0.035 ^{f}
A1B2C1 (6 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.07 ± 0.0017 ^{g}	1.02 ± 0.032 ^{de}
A1B2C2 (6 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.18 ± 0.0060 ^{bc}	1.08 ± 0.031 ^{d}
A2B1C1 (12 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.19 ± 0.0035 ^{b}	0.99 ± 0.015 ^{e}
A2B1C2 (12 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.09 ± 0.0035 ^{e}	1.26 ± 0.016 ^{c}
A2B2C1 (12 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.22 ± 0.0017 ^{a}	1.36 ± 0.030 ^{b}
A2B2C2 (12 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.05 ± 0.0071 ^{h}	1.38 ± 0.039 ^{b}
A3B1C1 (18 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.07 ± 0.0025 ^{g}	1.92 ± 0.028 ^{a}
A3B1C2 (18 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.08 ± 0.0030 ^{ef}	1.89 ± 0.029 ^{a}
A3B2C1 (18 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.05 ± 0.0026 ^{h}	1.91 ± 0.034 ^{a}
A3B2C2 (18 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.08 ± 0.0040 f^{g}	1.93 ± 0.018 ^{a}

Note: Numbers followed by the same letter in the same column are not significantly different according to Tukey's test at the 5% level.

Table 3. Effects of EFB compost (A) and clay soil (B) on the nitrogen concentration of maize leaves.

Factor	Treatment level	N concentration (%)
EFB (A)	A1 (6 t ha^{-1})	0.59±0.03 ^{c}
	A2 (12 t ha^{-1})	0.65±0.04 ^{b}
	A3 (18 t ha^{-1})	0.73±0.04 ^{a}
Clay soil (B)	B1 (10%)	0.64±0.07 ^{b}
	B2 (20%)	0.67±0.07 ^{a}

Note: Numbers followed by the same letter in the same column are not significantly different according to Tukey's test at the 5% level.

et al., 2021; Toth and Toth, 2024; Wang et al., 2024). By contrast, clay had a relatively small effect, as B2 (20% clay) increased leaf N only slightly compared with B1 (10% clay). This indicates that clay mainly improved the medium's capacity to retain water and available N rather than acting as a major source of N itself. Recent findings suggest that the positive effects of soil amendments on maize are most evident when they enhance nutrient conservation and root zone conditions. However, leaf nitrogen (N) levels remain a reliable indicator of enhanced physiological N status (Brodowska and Wyszkowski, 2022; Liang et al., 2024).

Furthermore, A×B×C interactions were observed in the P and K parameters of maize leaves. For P concentration, treatment A3B1C1 yielded the highest, at 0.27%, followed by A3B2C1 at 0.27%. The EFB compost, clay soil, and lime interaction (A×B×C) on P and K concentration in maize leaves is shown in Table 4.

Table 4 shows the effect of the AxBxC interaction on the phosphorus (P) and potassium (K) concentration of maize leaves. Treatment A3B1C1 had the highest phosphorus concentration at 0.27%, while A1B1C1 had the lowest at 0.12%, representing a 0.15% difference. For potassium, the highest concentration was recorded in A3B1C1 (3.07%), while the lowest potassium concentration was observed in A1B1C1 (1.13%). The difference in potassium concentration between treatments ranged from 0.04 % to 1.94%.

The relationship between EFB, clay soil, and lime with P and K concentrations in maize leaves lies in their complementary roles. These roles

Table 4. Effect of EFB compost, clay soil, and lime interactions (A×B×C) on P and K nutrient concentration in maize leaves.

Treatment	P concentration (%)	K concentration (%)
A1B1C1 (6 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.12 ± 0.007 ^{c}	1.13 ± 0.06 ^{f}
A1B1C2 (6 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.13 ± 0.007 ^{c}	1.37± 0.05 ^{f}
A1B2C1 (6 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.13 ± 0.022 ^{c}	1.64 ± 0.06 ^{e}
A1B2C2 (6 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.23 ± 0.034 ^{ab}	1.92 ± 0.01 ^{d}
A2B1C1 (12 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.13 ± 0.003 ^{c}	2.66 ± 0.08 ^{bc}
A2B1C2 (12 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.17 ± 0.027 ^{bc}	2.09 ± 0.08 ^{d}
A2B2C1 (12 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.21 ± 0.020 ^{ab}	2.71 ± 0.01 ^{b}
A2B2C2 (12 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.22 ± 0.035 ^{ab}	2.42 ± 0.09 ^{c}
A3B1C1 (18 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.27 ± 0.010 ^{a}	3.07± 0.12 ^{a}
A3B1C2 (18 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	0.21 ± 0.016 ^{ab}	2.53± 0.10 ^{bc}
A3B2C1 (18 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	0.27 ± 0.024 ^{a}	2.55 ± 0.11 ^{cd}
A3B2C2 (18 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	0.26 ± 0.049 ^{a}	3.03 ± 0.07 ^{a}

Note: Numbers followed by the same letter in the same column are not significantly different according to Tukey's test at the 5% level.

Table 5. Effect of EFB compost, clay soil, and lime interactions (AxBxC) on N and P nutrient concentration in maize grain.

Treatment	N concentration (%)	P concentration (%)
A1B1C1 (6 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	0.78 ± 0.02 ^{f}	0.23 ± 0.010 ^{e}
A1B1C2 (6 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	1.08 ± 0.02 ^{e}	0.23± 0.005 ^{de}
A1B2C1 (6 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	1.25 ± 0.02 ^{d}	0.26 ± 0.017 ^{cd}
A1B2C2 (6 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	1.23 ± 0.01 ^{d}	0.27 ± 0.003 ^{c}
A2B1C1 (12 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	1.30 ± 0.02 ^{cd}	0.28 ± 0.007 ^{c}
A2B1C2 (12 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	1.36 ± 0.01 ^{c}	0.35 ± 0.009 ^{a}
A2B2C1 (12 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	1.36 ± 0.01 ^{c}	0.35 ± 0.012 ^{ab}
A2B2C2 (12 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	1.59 ± 0.01 ^{b}	0.32 ± 0.012 ^{b}
A3B1C1 (18 t ha^{-1} EFB compost, 10% clay soil, 0.5 t ha^{-1} lime)	1.95 ± 0.05 ^{a}	0.35± 0.006 ^{ab}
A3B1C2 (18 t ha^{-1} EFB compost, 10% clay soil, 1.0 t ha^{-1} lime)	1.89 ± 0.07 ^{a}	0.35± 0.007 ^{a}
A3B2C1 (18 t ha^{-1} EFB compost, 20% clay soil, 0.5 t ha^{-1} lime)	1.91 ± 0.02 ^{a}	0.35 ± 0.015 ^{ab}
A3B2C2 (18 t ha^{-1} EFB compost, 20% clay soil, 1.0 t ha^{-1} lime)	1.94 ± 0.03 ^{a}	0.35 ± 0.009 ^{a}

Note: Numbers followed by the same letter in the same column are not significantly different according to Tukey's test at the 5% level.

improve nutrient availability and uptake. EFB gradually releases P and K while soil organic matter and cation exchange capacity are increased; clay colloids retain nutrients, and leaching is reduced; and soil pH is raised, acidity is reduced, and P availability is increased by lime. Together, these factors create a more favorable root environment. Thus, higher P and K concentrations in maize leaf tissue reflect improved nutrient release, retention, and translocation within the plant (Adu et al., 2022; Saidy et al., 2024; Blankson et al., 2025). Soil amendment had more effects and consistently improve soil chemical properties and maize yield (Nurida and Jubaedah 2019).

Effects of EFB Compost, Clay Soil, and Lime on N, P, and K Concentration in Maize Grain

Soil amelioration at former artisanal mining sites significantly affects the concentrations of N, P, and K in maize grain. Parameters showing EFB compost, clay soil, and lime interaction (A×B×C) were found in the N and P concentrations. Treatment A3B1C1 had the highest N concentration at 1.95%, which was not significantly different from A3B1C2, A3B2C1, and A3B2C2. Treatment A1B1C1 had the lowest N concentration (0.78%), indicating that a low compost dose is insufficient to provide optimal nitrogen. The EFB compost, clay soil, and lime interaction (A×B×C) of N and P nutrient concentration in the grain are shown in Table 5.

Based on Table 5, the phosphorus concentration in maize grain followed a pattern similar to that of nitrogen, with treatment A3B1C1 recording the highest value (0.35%). However, it was not significantly different from A3B1C2, A3B2C1, and A3B2C2. This suggests that the highest compost dose, combined with either 10% or 20% clay soil, and lime rates of 0.5 or 1.0 t ha^{-1} created similarly favorable conditions for P uptake and subsequent translocation to the grain during grain development. In maize, grain P concentration reflects not only the amount of available P in the soil but also the plant's capacity to absorb, remobilize, and allocate P to reproductive organs during grain filling. The role of EFB compost in this process is likely related to its contribution of organic matter and nutrients. At the same time, clay soil enhances P retention and lime improves P availability by reducing soil acidity and limiting P fixation. Studies have shown that the combined use of compost and lime can improve soil pH, available P, cation exchange capacity, and grain yield in maize, while integrated organic amendments can also increase nutrient uptake and transfer into economically important tissues (Dawid, 2021; Dejene et al., 2023; Matheus et al., 2023). In contrast, the lowest grain P concentration was found in A1B1C1 (0.23%), indicating that the lowest compost dose was insufficient to support optimum phosphorus accumulation in the grain.

The interaction between EFB compost (A) and clay soil (B) actually affects K concentration. The

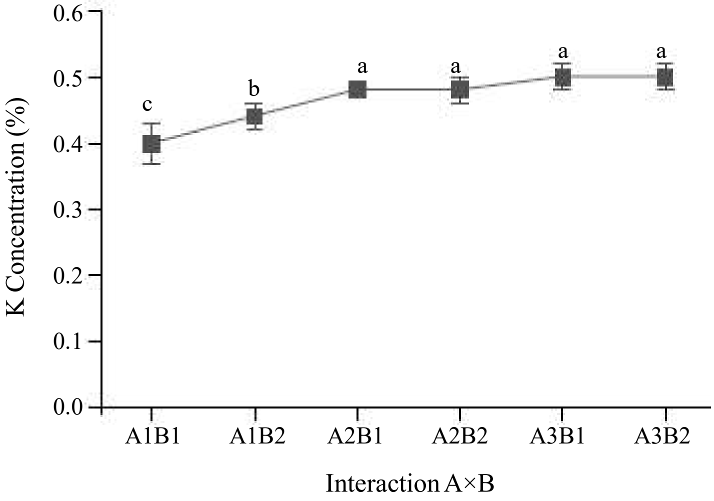

Figure 3. Effect of the EFB compost (A) x clay soil (B) interaction on K concentration in grain. Means above a bar of each sample, superscripted with different lowercase letters, are significantly different according to the Tukey test ($p<0.05$). Note : A1: 6 t ha^{-1}, A2: 12 t ha^{-1} and A3: 18 t ha^{-1} of EFB compost; B1: 10% and B2: 20% clay.

interaction between EFB compost (A) and clay soil (B) on K concentration in maize grain is shown in Figure 3.

Figure 3 shows that the interaction between EFB compost and clay soil significantly increased potassium concentration in maize. The highest value was recorded in A3B2 (0.50%). However, it did not differ significantly from A3B1, A2B2, and A2B1, indicating that moderate-to-high compost rates under clay soil conditions were sufficient to stabilize K availability and support similar plant uptake. This effect likely arose from the complementary roles of both factors: EFB compost increased exchangeable K and soil organic matter, whereas clay enhanced

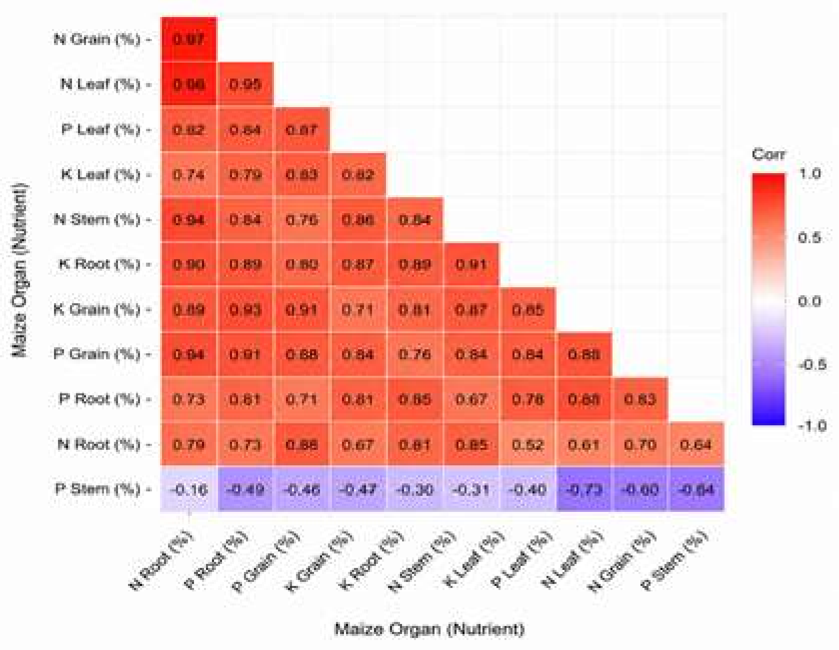

Figure 4. Heatmap of Pearson correlation coefficients (r) among N, P, and K concentrations in maize organs after harvest.

K retention through its colloidal surface and reduced leaching losses. Alayya et al. (2026) reported that ameliorants can reduce nutrient losses. Consequently, the lower K concentration in A1B1 (0.40%) suggests that the lowest compost rate could not maintain adequate K supply. In comparison, the 0.10% increase between A1B1 and A3B1 confirms that raising the compost rate from 6 to 18 t ha^{-1} significantly improved potassium status in maize by increasing available K and preserving it in plant-accessible form (El-awady and El-naqma, 2023; Hakimi et al., 2024; Bao et al., 2024; Teressa et al., 2024; Khairo et al., 2025).

Relationships of Nutrient Concentrations Among Maize Organs After Harvest

The results indicate element-specific nutrient accumulation patterns in maize organs after harvest. Nitrogen (N) reached the highest concentration in the grains (1.95%); phosphorus (P) was highest in the roots (0.37%); and potassium (K) peaked in the leaves (3.07%). The correlation results are presented as a heatmap (Figure 4), in which Pearson correlation coefficients (r) indicate the strength and direction of relationships among maize organs.

The correlation heatmap (Figure 4) illustrates that leaf and stem N are highly correlated with grain N (r = 0.96-0.86), indicating efficient remobilization to reproductive organs. Root P shows moderate correlations with leaf and grain P (r = 0.84-0.88), while stem and leaf K positively correlate with grain K (r = 0.82-0.91). During the reproductive phase, nitrogen (N) and phosphorus (P) are actively translocated to the reproductive organs, contributing significantly to the nutrient content of maize grain (Ray et al., 2020). A portion of P and K remains retained in roots and leaves for metabolic functions (Yuhui et al., 2019; Sun et al., 2023). These findings highlight that integrated soil amendments not only enhance nutrient availability but also support optimal nutrient allocation to grains, thereby improving maize productivity on post-artisanal gold-mining soils.

CONCLUSIONS

Nitrogen, phosphorus, and potassium exhibited distinct organ-specific translocation patterns in maize, with the highest accumulation concentrations recorded in the grain (1.95% N), roots (0.37% P), and leaves (3.07% K), respectively, under treatment A3B1C1. The application of 18 t ha^{-1} EFB compost, combined with 10% clay soil and 0.5 t ha^{-1} lime, represented the most effective amelioration strategy for improving nutrient availability, uptake, and partitioning in maize grown on post-artisanal gold-mining soil.

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