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POTASSIUM EFFICIENCY IN OIL PALM SEEDLINGS: DOES IT MATTER?

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SUMMARY

Potassium (K) is an important macronutrient and plays a vital role in oil palm (*Elaeis guineensis*) growth and productivity; however, its availability is often lacking due to fixation and leaching in tropical soils. Improving potassium use efficiency via genotype selection is a crucial strategy to enhance sustainability in oil palm cultivation. The following study sought to determine the potassium use efficiency in six *Dura* × *Pisifera* oil palm (*Elaeis guineensis*) progenies under four K fertilizer levels (0%, 100%, 75%, and 50% of the recommended dose). The study used a split-plot design to assess the vegetative growth, dry biomass, and K uptake. Nutrient use efficiency indices, viz., agronomic efficiency (AE), recovery efficiency (RE), and internal efficiency (IE), entailed calculations. The results revealed genotypic effects on vegetative traits and potassium use efficiency parameters; however, the interaction effects between oil palm progenies and K doses were nonsignificant. Oil palm progenies P2 and P4 showed leading performance in vegetative growth, biomass production, K uptake, and multiple efficiency indices, indicating their potential as nutrient-efficient palms. Moderate K application (75%) performance emerged to be at par with full dose in some progenies. Early-stage screening proved feasible for identifying K-efficient oil palm genotypes, which offers a practical approach for breeding and nutrient management in sustainable oil palm systems.

Keywords: Early-stage screening, genotypic variations, growth traits, nutrient uptake, oil palm (*E. guineensis*), potassium use efficiency

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Key findings: The *Dura* × *Pisifera* oil palm (*E. guineensis*) progenies responded distinctively to various doses of potassium. The progenies P2 and P4 showed leading performance in vegetative growth, biomass production, K uptake, and multiple efficiency indices, indicating their potential as nutrient-efficient palms.

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is a key tropical crop with significant socioeconomic values, contributing to rural livelihoods, national income, and global energy security. Its strategic and considerable role in poverty reduction, as well as its alignment with several United Nations Sustainable Development Goals (SDGs), highlights its pivotal role in both local and global development strategies (Ningsih and Fitrisiah, 2020; Mardiharini *et al*., 2021; Sukiyono *et al*., 2022; Chiriacò *et al*., 2022). Nevertheless, like other input-intensive agricultural systems, oil palm cultivation also faces growing scrutiny due to its potential environmental effects from inefficient management of inputs, particularly fertilizers. Thus, sustainable oil palm production largely depends on optimizing input use efficiency, where fertilizers are the most influential and environmentally sensitive components.

Among the essential macronutrients, potassium (K) plays a crucial role in numerous physiological functions in plants, including enzyme activation, maintaining osmotic balance, regulating stomata, and responding to diverse environmental stress conditions (Khan *et al*., 2022). In oil palm, K is an essential nutrient for vegetative and generative growth; however, an abundance of K doses may lead to inefficiency (Lamade and Tcherkez, 2023). Potassium is also the second most concentrated nutrient in mature leaf tissues after nitrogen, accounting for approximately 1% of the leaf's dry weight (Ochs, 1965). Despite its physiological importance, its accessibility to crop plants is often scarce in tropical soil. This is because 90% of the soil's total potassium appears in non-exchangeable forms, becoming unavailable for the plant's uptake (Nigon and Bruulsema, 2023).

Furthermore, potassium fertilizers are prone to significant losses, with around 60% lost due to leaching and fixation, which not only diminishes nutrient use efficiency (NUE) but also elevates fertilizer costs and environmental risks. A recent study by Thompson-Morrison *et al*. (2024) investigated the chemical elements in *E. guineensis*, reporting the widespread K-deficiency symptoms in oil palm plantations across the Sumatra Region, Western Indonesia. A study of potassium in oil palms by Prabowo *et al*. (2023) underscores the urgent exigency for efficient management of potassium and its improved utilization strategies in oil palm systems.

In oil palms, enhancing potassium use efficiency (KUE) is a paramount strategy for achieving sustainable intensification through existing plantation systems. One promising avenue is the identification and selection of genotypes having significant nutrient uptake and utilization. Early-stage selection of such genotypes can reduce long-term fertilizer dependency and support more resilient cropping systems. The presented study aimed to determine the potassium use efficiency of six oil palm progenies under varying K fertilizer rates at the nursery stage. It integrates both vegetative growth parameters and K uptake measurements, alongside comprehensive NUE indices, including apparent recovery efficiency (RE), physiological efficiency (PE), internal efficiency (IE), and agronomic efficiency (AE). This research seeks to identify oil palm progenies with high potassium use efficiency potential. These findings will support breeding and plantation programs especially focused on nutrient-efficient genotypes, offering an early screening strategy to enhance sustainable fertilizer management in oil palm cultivation.

MATERIALS AND METHODS

This study utilized germinated seeds from six *Dura* × *Pisifera* (D × P) oil palm (*E. guineensis*) progenies, developed by crossing the l

Table 1. Fertilizer recommendations for oil palm seedlings.

Age (MAT)	Fertilizer (g)			
	N	P	K	Mg
1	1.13	1.13	0.45	0.30
2	2.63	2.63	1.05	0.70
3	2.40	2.40	3.40	1.70
4	2.40	2.40	3.40	1.70
5	3.60	3.60	5.10	2.55
6	3.60	3.60	5.10	2.55
7	4.80	4.80	6.80	3.40
8	4.80	4.80	6.80	3.40
9	6.00	6.00	8.50	3.60
Total	31.35	31.35	40.60	19.90

Legends: MAT: Month After Transplanting.

Deli Dura and African Pisifera parental palms. Growing the seedlings used a two-stage nursery system. The pre-nursery (PN) phase established uniform seedlings and further prepared them for experimental treatments. No specific fertilizer application happened during this stage. After three months, the seedlings underwent transplanting into the main nursery (MN), where implementing different experimental variants occurred. Application of treatments ensued in the second stage because, after three months, the nutrient stock in the cotyledons had depleted, and the seedlings began to acquire nutrients from the rhizosphere. During the treatments, sanitation and weeding continued regularly while applying pesticides only when needed. Maintenance of all plants was according to the treatments until seeing and statistically detecting the treatments' effects, but not to the point of death. At the end of the experiments, harvesting the samples commenced before drying them destructively for biomass data.

The said experiment used a split-plot design with six replications, utilizing potassium (K) fertilizer application levels as the main plots and the oil palm progenies as the subplots. The K fertilizer application treatments comprised four different doses: F0 (0%), F1 (100%), F2 (75%), and F3 (50%) of the recommended K dose (Pangaribuan *et al*., 2025) (Table 1). The evaluated six oil palm progenies received designations as P1 through P6. Each treatment combination has replicates, with 30 seedlings per replicate, resulting in a robust experimental layout for comparative analysis.

Isolating the effect of potassium employed a minus-one nutrient approach. All the essential macronutrients bore uniform applications across treatments, except for K, which varied according to the indicated treatments. The different fertilizers used were urea (N-source), triple superphosphate–TSP (P-source), muriate of potash–KCl (K-source), and kieserite (Mg and Ca sources) based on recommended doses (Pangaribuan *et al.*, 2025). Fertilizers entailed manual application by broadcasting them evenly around the seedling base in polybags, once per month, and from four to 12 months after planting. During the pre-nursery stage at the age of 0–3 months, no fertilizer application transpired. At the age of three months, transplanting the seedlings succeeded in the main nursery, and the seedlings took one month to recover from transplanting stress. Therefore, recording of observations started at the fourth month before the treatment. The observations continued for the next nine months, in which the treatment started on the fifth month and went on until the 12th month after being transplanted to the main nursery (MAT).

Traits measurement

The data on growth parameters, plant height, number of leaves, and stem diameter attained monthly recording as indicators of vegetative performance. At the end of the experimental period, three seedlings from each treatment received random sampling to determine the total dry biomass and K content in plant tissues. These data served as the basis for calculating multiple indices of potassium use efficiency (KUE), which are essential for determining the genotypic differences in nutrient acquisition and utilization. Obtaining a comprehensive assessment of nutrient efficiency required the computation of four primary indices based on the framework as described by Dobermann (2007).

Apparent recovery efficiency (RE)

The apparent recovery efficiency (RE) represents the fraction of applied potassium that was taken up by the plants, indicating the plant's ability to absorb nutrients from fertilizer inputs, with the same calculation as:

$$RE = \frac{Uf - U0}{F}$$

Where Uf = K uptake (mg or g plant^{-1}) in the fertilized treatment, $U0$ = K uptake (mg or g plant^{-1}) in the unfertilized (control) treatment, and F = the amount of K fertilizer applied (mg or g plant^{-1}).

Physiological efficiency (PE)

The physiological efficiency (PE) measures how efficiently the absorbed potassium reached conversion into biomass. A higher PE indicates the plant used the absorbed nutrient more effectively for growth parameters:

$$PE = \frac{Yf - Y0}{Uf - U0}$$

Where Yf = dry biomass (g plant^{-1}) in the fertilized treatment, $Y0$ = dry biomass (g plant^{-1}) in the unfertilized (control) treatment, and $Uf - U0$ = difference in K uptake due to fertilizer application.

Internal efficiency (IE)

The internal efficiency (IE) indicates the amount of biomass produced per unit of potassium found in the plant. This reflects the plant's ability to utilize the internal nutrient reserves to support the growth traits:

$$IE = \frac{Y}{U}$$

Where Y = total dry biomass (g plant^{-1}) and U = total K content in the plant tissue (g or mg plant^{-1}).

Agronomic efficiency (AE)

Agronomic efficiency (AE) measures the increase in biomass yield per unit of fertilizer applied. It reflects the practical return (in terms of growth) on fertilizer investment:

$$AE = \frac{Yf - Y0}{F}$$

Where Yf = dry biomass (g plant^{-1}) in the fertilized treatment, $Y0$ = dry biomass (g plant^{-1}) in the unfertilized (control) treatment, and F = the amount of K fertilizer applied (g plant^{-1}).

Each index provides distinct and complementary information regarding the ability of oil palm progenies to acquire, utilize, and respond to potassium fertilizer's different doses. Together, these indices offer a robust framework for identifying the oil palm genotypes with superior KUE, which is critical for improving nutrient management efficiency and reducing fertilizer dependency in oil palm cultivation systems.

Statistical analysis

The conducted analysis used R-Studio version 4.4.1. All the data assessment underwent analysis of variance (ANOVA), followed by the Duncan's multiple range test (DMRT) to assess the effect of oil palm genotypes and potassium

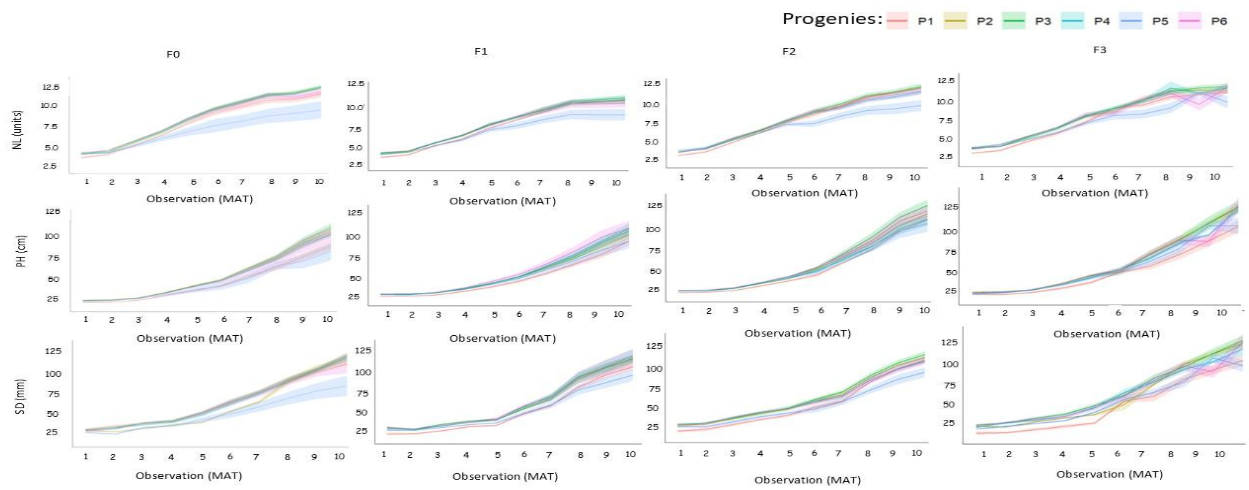

Figure 1. Morphological growth of oil palm seedlings in 10 months. Legend: Shadows indicate the standard deviation of the same color line; F0: 0% K, F1: 100% K, F2: 75% K, F3: 50% K.

fertilizer doses on the total potassium uptake and seedling dry weight. Employing the potassium utilization efficiency index helped identify the efficient genotypes, incorporating RE, AE, and IE. The RE determination proceeded by comparing potassium uptake at 75% and 50% dose relative to the 100% dose. The 0% K dose acted as a diminution factor in the formula; therefore, it had no evaluation. The AE calculation was the additional potassium absorbed per unit of potassium applied, while IE was the ratio of dry weight to potassium uptake. Normalizing all index values used min-max scaling to generate a combined efficiency score for each oil palm progeny.

RESULTS AND DISCUSSION

Morphological development with K levels

During the 10-month observation period in the main nursery, the oil palm (*E. guineensis*) progenies showed a general upward trend in vegetative growth, with increases in plant height, the number of leaves, and stem diameter across all potassium (K) fertilizer treatments (Figure 1). However, over time, the growth patterns varied, particularly with the lowest level of potassium (F3). In this treatment, inconsistencies in plant height and leaf number for the last three months suggested unstable growth in response to potassium limitation. Similarly, deviations in stem diameter development were evident as early as the fifth month. Among the oil palm progenies, P1 displayed the most consistent vegetative response across different potassium levels, while P5 was notably sensitive to K reduction, exhibiting the poorest growth performance. The shuffling in growth rate could have resulted from the change of metabolism due to the lack of K, which was vital for enzyme activities, homeostasis, and ATP production (Zhao *et al*., 2020). However, the K-efficient plant, at a certain level, can replace the cation K starvation with osmoticum metabolites and other cations to maintain the cation-anion balance.

The results further revealed potassium availability plays a primary role in managing the vegetative growth and development in oil palm seedlings, and the genotypic variations considerably influenced the plants' response to K fertilizer application. Overall, the oil palm progenies exhibited an upward trend in growth; however, the growth pattern with the lowest K level (F3) was irregular and reduced, particularly beyond the seventh month after transplanting. The observations implied prolonged K deprivation does not halt growth entirely, however, it disrupts its consistency

Table 2. Analysis of variance for oil palm vegetative response to potassium application at 10 MAT (α = 0.5).

Source of Variation	df	Mean of Squares		
		PH	NL	SD
Replication	5	42.71*	0.30	4.56
Fertilizer	3	96.09*	0.36*	5.46
Error (a)	15	8.48	0.11	1.58
Progenies	5	225.54*	3.17*	21.97*
Fertilizer x Progenies	15	13.79	0.09	2.74*
Error (b)	75	18.19	0.10	1.44

Legends: d.f.: degree of freedom, PH: plant height; NL: number of leaves; SD: stem diameter; ns: nonsignificant; *: significant; **: highly significant.

and efficiency. These growth symptoms were consistent with the known physiological role of potassium in enzyme activation, carbohydrate translocation, and regulation of turgor pressure processes that underpin photosynthetic efficiency and vegetative expansion (Fontana *et al*., 2020; Xu *et al*., 2020).

In this context, in oil palm progeny P1, the early decline in stem diameter growth emerged at four MAT, ahead of other progenies, further suggesting high sensitivity to K stress. Reports of similar observations have also appeared in basil (*Ocimum basilicum* L.) (Attia *et al*., 2022)*.* Reversely, Kusumiyati *et al*.'s (2022) findings revealed less K doses affect the lowest stem diameter in red chili (*Capsicum annuum* L.). Although Zhang *et al*. (2021) reported in tomato, the trend changed with time. In the early stage, the K accumulation was more in the roots and stems; however, by the time K deficiency continued, the K concentration was higher in the leaves than in the stems and roots. A confirmation also stated that responses to K availability were unique for every plant, as influenced by some conditions, such as the levels and duration of K scarcity and the plant's growth phase. The results enunciated that all oil palm progenies have their own specific behaviour to the K levels. The oil palm progeny P1 maintained relatively stable growth dynamics, and its overall performance for biomass and efficiency indices was low, suggesting growth stability alone was not a sufficient indicator of nutrient efficiency.

The analysis of variance disclosed a significant interaction between fertilizer and progeny in the stem diameter parameter (Table 2). It displayed the treatments significantly affected all morphological aspects, while the interaction between fertilizer and progenies only substantially altered the stem diameter growth. Nonetheless, the progeny identity had a remarkable effect on the measured vegetative parameters at 10 months after transplanting. Potassium application levels significantly influenced the number of leaves and stem diameter, whereas replication modified plant height. The mean performance of the oil palm progenies revealed progenies P3 and P6 recorded the highest average plant height across treatments, although they were not considerably different from P2 and P4. In contrast, P5 consistently showed the lowest values (Table 3). This trend was also evident in leaf number and stem diameter, further highlighting the superior performance of progeny P3 and the consistently poor response of oil palm progeny P5. Interestingly, potassium application at 75% of the recommended rate frequently yielded growth outcomes that were at par and even better than the full dose (100% K) (Table 3). This indicates certain progenies may possess greater efficiency in utilizing potassium under limited supply conditions.

Table 3. Mean performance of oil palm progenies under potassium doses for various morphological traits at 10 MAT (DMRT α = 0.05).

Progenies	Fertilizer				Means
	F0	F1	F2	F3	
Plant height (cm)					
P1	39.14	37.81	42.72	39.37	39.76b
P2	46.96	42.62	47.21	47.98	46.19a
P3	47.76	44.11	50.47	47.98	47.58a
P4	45.43	44.69	45.17	45.30	45.15a
P5	38.71	40.87	45.05	43.60	42.05b
P6	45.47	46.72	49.07	46.40	46.92a
Mean	43.91	42.81	46.62	45.10	
Number of leaves (unit)					
P1	6.78	6.62	6.9o	6.68	6.74
P2	7.30	6.94	7.13	7.19	7.14
P3	7.21	6.95	7.20	7.19	7.14
P4	7.29	6.97	7.06	7.22	7.13
P5	5.99	6.15	6.33	6.47	6.23
P6	7.21	6.92	7.12	6.97	7.06
Mean	6.96	6.76	6.96	6.95	
Stem diameter (mm)					
P1	9.68	9.23	9.76	9.29	9.49b
P2	11.50	10.46	10.82	11.04	10.96a
P3	11.49	10.76	11.17	11.74	11.29a
P4	13.80	10.62	10.70	11.20	11.58a
P5	8.95	9.18	9.43	10.09	9.41b
P6	11.12	10.67	11.86	11.24	11.22a
Mean	11.09	10.15	10.62	10.77	

Numbers followed by the same letter are not significantly different in the DMRT test at the 0.05 level, F0: 0% K, F1: 100% K, F2: 75% K, and F3: 50% K.

Biomass response to K levels

The harvesting of oil palm progenies continued at 10 months after transplanting (MAT). It was evident in all progenies; the dry biomass of F0 was consistently the lowest. However, in F1, F2, and F3, most progenies exhibited slight differences, except for P4, which had the highest dry biomass in F2. For the R:S ratio of biomass, in all progenies, the biomass of F0concentrated in the roots (indicated by a high R:S ratio). Each progeny displayed a different pattern in K content distribution. P1, P2, and P3 showed more K deposited in the roots in the lower K treatments (F0, F2, and F3), whereas in the full-dose K treatment (F1), more K was prevalent in the shoot. The other three progenies had a different pattern. In P4, accumulation of K in the root resulted in F0 and F2. In P5 accumulation, K in the root appeared in F0 and F3; meanwhile, in P6, the highest K in the root was in F2 (Figure 2). Nevertheless, considerable genotypic differences were noticeable. The progenies played an important role both in the total biomass accumulation and biomass allocation patterns, particularly the root-to-shoot (R:S) ratio, including in the K translocation and accumulation.

Contrary to expectations, the full dose of potassium (F1) did not consistently lead to superior growth and biomass accumulation in oil palm seedlings. Potassium (K), often considered a luxury nutrient, is generally non-toxic to plants; however, its effects vary depending on species and developmental stage. Both deficiency and excess of K can alter nitrogen (N) and carbon (C) metabolic processes, thereby reducing nitrogen metabolism (Xu *et al*., 2020). Moreover, inappropriate K supply may induce secondary nutrient imbalances, such as magnesium (Mg)

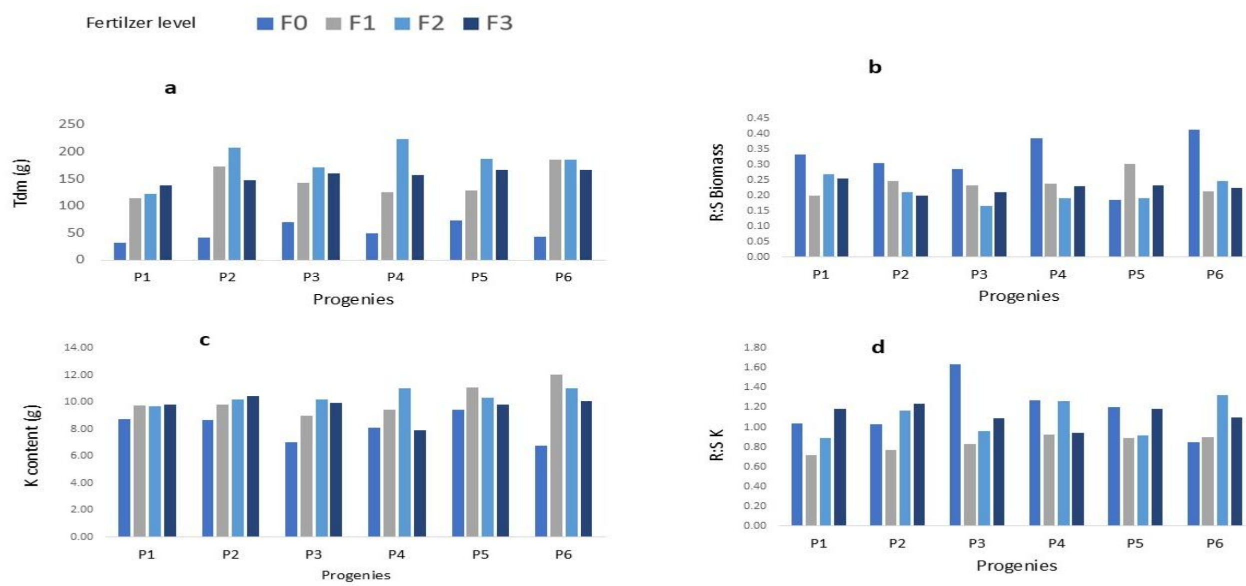

Figure 2. The impact of potassium on the distribution of oil palm seedling productivity. a) total dry biomass; b) distribution of dry biomass presented in R:S biomass ratio; c) total K content; d) distribution of K presented in R:S K ratio. Legend: Tdm: Total dry biomass, R:S Biomass: ratio biomass in root respective to shoot, K content: total K in the plant, R:S K: ratio of K content in root respective to shoot, F0: 0% K, F1: 100% K, F2: 75% K, and F3: 50% K.

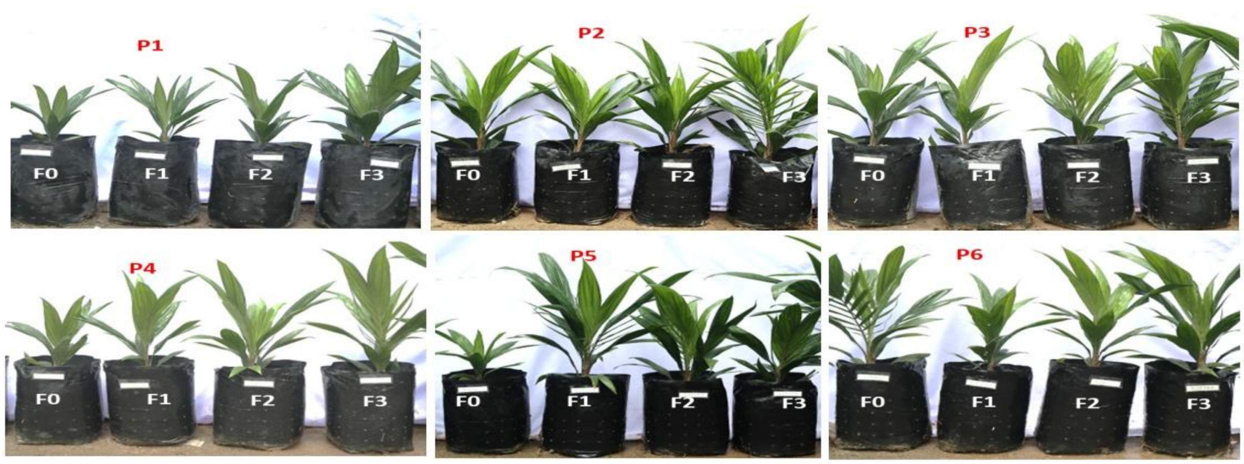

Figure 3. Performance of the oil palm seedlings at 10 MATs under various K doses.
Legends: F0: 0% K, F1: 100% K, F2: 75% K, and F3: 50% K.

deficiency (Xie *et al.*, 2021). Therefore, a proper K dose is crucial for maintaining optimal plant growth. In this experiment, the 75% potassium dose (F2) produced comparable and even better results in several progenies, supporting the hypothesis that certain genotypes may possess enhanced potassium uptake and utilization efficiency under moderate nutrient supply. Visual comparison and the biomass data further confirmed the relationship between K dose and vegetative growth was not linear (Figure 3). These results align with the concept of luxury consumption, where increased nutrient supply does not necessarily translate into proportional biomass gain (Marschner and Rengel, 2023). It suggests moderate K inputs may be more optimal for oil palm genotypes with superior nutrient efficiency traits.

The root-to-shoot (R:S) biomass ratio offers additional insight into plants' adaptive strategies under nutrient stress conditions. A high R:S ratio is often an interpretation of a response to resource limitation, reflecting the plant's prioritization of nutrient acquisition over shoot development (Kurepa and Smalle, 2022). Conversely, Lopez *et al*. (2023) reported that, although it was not significant, the lack of K caused a reduction in root diameter and the R:S biomass ratio, as well as in root apparatus such as root hairs (Templalexis *et al*., 2022). In this study, the control treatments (F0) displayed a high R:S ratio; however, this ratio has no accompanying high total biomass and potassium use efficiency. Still, the highest biomass, potassium content, and potassium uptake mostly occurred in the F2 level of potassium, particularly in oil palm progeny P4. The results suggested a large investment in root growth may benefit survival in stress conditions; yet it does not necessarily enhance nutrient conversion efficiency or productivity. Instead, the F2 and F3 variants of potassium exhibited relatively balanced R:S ratios and produced the highest shoot biomass and potassium uptake, alongside high agronomic and recovery efficiency indices. He *et al*. (2022) reported that the maize and wheat biomass in their experiment was increasing along with the rise of K dose, up until when the dose was too high; the increment was not significant. On the other side, the recovery efficiency decreased following K dose escalation because the plants stopped absorbing the excessive K.

This counterintuitive relationship suggested higher K accumulation in shoot tissues may not always indicate efficient utilization but may reflect possible luxury uptake and storage without proportional biomass gain. A report of similar findings appeared in past studies distinguishing the nutrient acquisition efficiency (ENA) and utilization efficiency (ENU) (Santa-Maria *et al*., 2015). This study's results suggested some progenies may accumulate K effectively but lack the physiological mechanisms to use it efficiently for biomass production. For example, the IE tended to be high when plants produced more biomass per unit of K absorbed, but excessive K stored in shoots may dilute this efficiency metric. Genotypes with the highest internal K efficiency seemed to translocate nutrients more effectively from roots to aboveground plant parts (Nieves-Cordones *et al*., 2020), although such translocation must require a match of active metabolic use to contribute meaningfully to growth. These contrasting profiles revealed that the most efficient genotypes were not necessarily those with the most pronounced stress responses, but rather those that optimize both acquisition and utilization pathways.

Identification of efficient progenies

Further evaluation of potassium-use efficiency (KUE), based on agronomic efficiency (AE), internal efficiency (IE), apparent recovery efficiency (RE), and other supporting parameters, such as nutrient uptake and potassium sequestration, revealed not a single oil palm progeny consistently excelled across all indices (Table 4). For instance, progeny P1 exhibited the highest R:S biomass ratio and ranked poorly in most efficiency-related metrics. In contrast, progeny P4 revealed higher values in most KUE parameters, such as in RE and AE (in F2) and IE (in F3), while the oil palm progenies P2, P3, and P6 were higher in individual parameters. None of the progeny demonstrated dominance across all efficiency dimensions. However, by combining all parameters produced, the progeny P4 ranked first, followed by oil palm progeny P2 (Figure 4a). The progenies P4 and P2 emerged better in KUE in different ways. The diversity of efficiency responses among the progenies disclosed that each genotype may adopt distinct physiological mechanisms in coping with varying levels of potassium.

The said comparison highlighted oil palm progenies P2 and P4 under various K regimes, occurring consistently superior for vegetative growth and biomass accumulation.

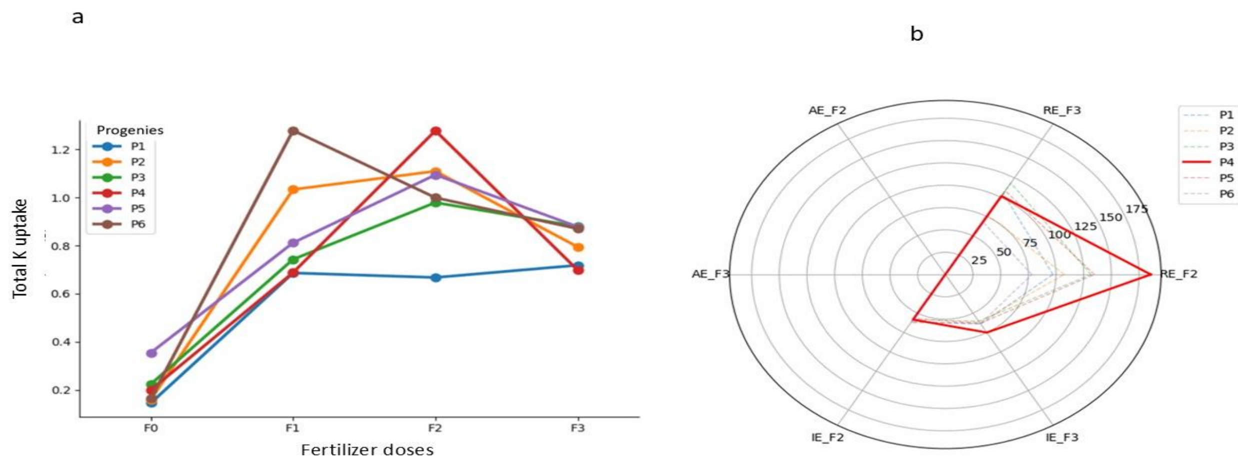

Figure 4. KUE parameters to assess K efficient progeny. a) Interaction in line graph demonstrated the best interaction between progenies and K dose for K uptake, and b) Radar chart assess P4 as the progeny with the largest score area of various NUE parameters.

Conversely, progeny P5 displayed the lowest responsiveness to increasing potassium availability, regardless of the fertilizer dose applied. Collectively, these results reinforce the feasibility of early-stage screening to identify the oil palm progenies with superior potassium use traits, particularly under suboptimal nutrient conditions. The K-efficient plants not only exhibited qualification in K acquisition but also in translocation to other organs and maintained the K cytosolic (Deng *et al*., 2021). Furthermore, the better K maintenance referred to plant vigor via sugar production and translocation (Cui *et al*., 2020; Imtiaz *et al*., 2023) and even to stress resistance (Singhal *et al*., 2023).

These relationships illustrated valuable insight into the differential nutrient allocation strategies among the evaluated oil palm progenies. Taken together, the results highlighted the importance of integrating multiple parameters, such as morphological, physiological, and efficiency-based, when assessing genotypic responses to potassium availability. The lack of a single progeny consistently outperforming other progenies across all traits underscores the complexity of nutrient use efficiency being a breeding target. The results confirmed each oil palm progeny possesses a unique behavioral response to potassium availability. The progeny P1 tends to be less responsive to potassium availability, while progeny P6 showed its best performance at optimum K level, and other progenies were best in the F2 potassium level. However, the promising performance of progenies P2 and P4, particularly under suboptimal K supply, suggested that early screening in the nursery can serve as an effective strategy for identifying the genotypes with superior nutrient use characteristics.

A final visual assessment of progeny performance across the potassium treatments is available in Figure 4b. The results expressed that oil palm progeny P4 has the greatest area of various efficiency variables. The latest results further confirmed higher K levels do not mean better performance in 10 MAT oil palm seedlings. These findings provide a basis for future breeding programs aimed at improving fertilizer efficiency and sustainability in oil palm production systems. Further validation under field conditions and different soil types would be necessary to confirm the stability and practical utility of these traits.

CONCLUSIONS

The results demonstrated significant genotypic variations in the oil palm (*E. guineensis*) progenies in response to potassium availability under nursery conditions. All oil palm progenies exhibited growth reduction under limited K supply, while the progenies P2 and P4 consistently showed superior vegetative performance, potassium uptake, and nutrient use efficiency indices. The results further suggested that early screening for potassium efficiency proved feasible and valuable for identifying genetically efficient oil palm planting materials, particularly in the context of sustainable fertilizer use.

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REFERENCES

Attia H, Rebah F, Ouhibi C, Saleh MA, Althobaiti AT, Alamer KH, Nasri MB, Lachaâl M (2022). Effect of potassium deficiency on physiological responses and anatomical structure of basil, *Ocimum basilicum* L. *Biology* 11(11): 1557. https://doi.org/10.3390/biology11111557.

Chiriacò MV, Bellotta M, Jusić J, Perugini L (2022). Palm oil's contribution to the United Nations sustainable development goals: Outcomes of a review of socio-economic aspects. *Environ. Res. Lett*. 17(6): 063007. https://doi.org/10.1088/1748-9326/ac6e77.

Cui J, Lamade E, Tcherkez G (2020). Potassium deficiency reconfigures sugar export and induces catecholamine accumulation in oil palm leaves. *Plant Sci.* 300: 110628. https://doi.org/10.1016/j.plantsci.2020.110628.

Deng Z, Yang J, Chen Y, Han H, Liu X, Yi X, Wang J, Lyu C (2021). Screening high potassium efficiency potato genotypes and physiological responses at different potassium levels. *Not. Bot. Hortic. Agrobot. Cluj-Napoca* 49(1): 12190. https://doi.org/10.15835/nbha49112190.

Dobermann A (2007). Fertilizer best management practices: General principles and strategy for their adoption and voluntary initiatives vs. regulations. International Ferilizer Industry Association, Paris.

Fontana JE, Wang G, Sun R, Xue H, Li Q, Liu J, Davis KE, Thronburg TE, Zhang B, Zhang Z, Pan X (2020). Impact of potassium deficiency on cotton growth, development, and potential microRNA-mediated mechanism. *Plant Physiol. Biochem.* 153: 72–80. https://doi.org/10.1016/j.plaphy.2020.05.006.

He B, Xue C, Sun Z, Ji Q, Wei J, Ma W (2022). Effect of different long-term potassium dosages on crop yield and potassium use efficiency in the maize–wheat rotation system. *Agronomy* 12(10): 2565. https://doi.org/10.3390/agronomy12102565.

Imtiaz H, Mir AR, Corpas FJ, Hayat S (2023). Impact of potassium starvation on the uptake, transportation, photosynthesis, and abiotic stress tolerance. *Plant Growth Regul.* 99(3): 429–448. https://doi.org/10.1007/s10725-022-00925-7.

Khan MA, Adnan MA, Basir A, Fahad S, Hafeez A, Saleem MH, Ahmad M, Gul F, Durrishahwar, Subhan F, Alamri S, Hashem M, Rahman IU (2022). Impact of tillage and potassium levels and sources on growth, yield, and yield attributes of wheat. *Pak. J. Bot.* 55(1): 10-30848. http://doi.org/10.30848/PJB2023-1(30).

Kurepa J, Smalle JA (2022). Auxin/cytokinin antagonistic control of the shoot/root growth ratio and its relevance for adaptation to drought and nutrient deficiency stresses. *Int. J. Mol. Sci.* 23(4): 1933. https://doi.org/10.3390/ijms23041933.

Kusumiyati K, Syifa RJ, Farida F (2022). Effect of various varieties and dosage of potassium fertilizer on growth, yield and quality of red chili (*Capsicum annuum* L.). *Open Agriculture 7*(1): 948–961. https://doi.org/10.1515/opag-2022-0151.

Lamade E, Tcherkez G (2023). Revisiting foliar diagnosis for oil palm potassium nutrition. *Eur. J. Agron.* 143: 126694. https://doi.org/10.1016/j.eja.2022.126694.

Lopez G, Ahmadi SH, Amelung W, Athmann M, Ewert F, Gaiser T, Gocke MI, Kautz T, Postma J, Rachmilevitch S, Schaaf G, Schnepf A, Stoschus A, Watt M, Yu P, Seidel SJ (2023). Nutrient deficiency effects on root architecture and root-to-shoot ratio in arable crops. *Front. Plant Sci.* 13: 1067498. https://doi.org/10.3389/fpls.2022.1067498.

Mardiharini M, Azahari DH, Chaidirsyah RM, Obaideen K (2021). Palm oil industry towards sustainable development goals (SDGs) achievements. *IOP Conf. Ser.: Earth Environ. Sci.* 892(1): 012068.

https://doi.org/10.1088/1755-1315/892/1/012068.

Marschner P, Rengel Z (2023). Nutrient availability in soils. In: Z. Rengel, I. Cakmak, and P.J. White (Eds.), Marschner's Mineral Nutrition of Plants. Academic Press, pp. 499–522.

Nieves-Cordones M, Rubio F, Santa-María GE (2020). Editorial: Nutrient use-efficiency in plants: An integrative approach. *Front. Plant Sci.* 11: 623976. https://doi.org/10.3389/fpls.2020.623976.

Nigon LL, Bruulsema T (2023). Assessing soil potassium: Basic principles and new developments. *Crops Soils Mag*. 56: 29–34. https://doi.org/10.1002/crso.20256.

Ningsih YS, Fitrisia A (2020). Perekonomian masyarakat perkebunan plasma kelapa sawit jorong jambak Kecamatan Luhak Nan Duo (2003–2019). *J. Kronologi* 2(3): 24–37. (In Indonesian).

Ochs R (1965). Fumure potassique du palmier à huile: Correction d'une déficience potassique (3ème partie). *Oléagineux* 20(8-9): 497–501. https://agritrop.cirad.fr/440273/. (In French).

Pangaribuan IF, Setiowati RD, Wening S, Pratiwi DR, Ginting EN, Mardiana C, Ernayunita (2025). Morphological response of oil palm seedlings to fertilizer application. *J. Penelit. Kelapa Sawit* 33(2): 105–120. https://doi.org/10.22302/iopri.jur.jpks.v33i2.294. (In Indonesian).

Prabowo NE, Foster HL, Nelson PN (2023). Potassium and magnesium uptake and fertilizer use efficiency by oil palm at contrasting sites in Sumatra, Indonesia. *Nutr. Cycl. Agroecosyst.* 126(2): 263–278. https://doi.org/10.1007/s10705-023-10289-7.

Santa-María GE, Moriconi JI, Oliferuk S (2015). Internal efficiency of nutrient utilization: What is it and how to measure it during vegetative plant growth? *J. Exp. Bot*. 66(11): 3011–3018. https://doi.org/10.1093/jxb/erv162.

Singhal RK, Fahad S, Kumar P, Choyal P, Javed T, Jinger D, Singh P, Saha D, Dharmappa PM, Bose B, Akash H, Gupta NK, Sodani R, Dev D, Suthar DL, Liu K, Harrison MT, Saud S, Shah AN, Nawaz T (2023). Beneficial elements: New players in improving nutrient use efficiency and abiotic stress tolerance. *Plant Growth Regul.* 100(2): 237–265. https://doi.org/10.1007/s10725-022-00843-8.

Sukiyono K, Romdhon MM, Mulyasari G, Yuliarso MZ, Nabiu M, Trisusilo A, Reflis, Napitupulu, DMT, Nugroho Y, Puspitasari MS, Sugiardi S, Arifudin, Masliani (2022). The contribution of oil palm smallholder farms to the implementation of the sustainable development goals-measurement attempt. *Sustainability* 14(11): 6843. https://doi.org/10.3390/su14116843.

Templalexis D, Tsitsekian D, Liu C, Daras G, Šimura J, Moschous P, Ljung K, Hatzopoulos P, Rigas S (2022). Potassium transporter TRH1 / KUP4 contributes to distinct auxin-mediated root system architecture responses. *Plant Physiol.* 188(2): 1043–1060. https://doi.org/10.1093/plphys/kiab472.

Thompson-Morrison H, Ariantiningsih F, Arief SM, Gaw S, Robinson B (2024). Chemical elements in *Elaeis guineensis* materials and derived oil. *Sci. Rep.* 14(1): 1836. https://doi.org/10.1038/s41598-023-50492-8.

Xie K, Cakmak I, Wang S, Zhan F, Guo S (2021). Synergistic and antagonistic interactions between potassium and magnesium in higher plants. *Crop J.* 9(2): 249–256. https://doi.org/10.1016/j.cj.2020.10.005

Xu X, Du X, Wang F, Sha J, Chen Q, Tian G, Zhu Z, Ge S, Jiang Y (2020). Effects of potassium levels on plant growth, accumulation and distribution of carbon and nitrate metabolism in apple dwarf rootstock seedlings. *Front. Plant Sci.* 11: 904. https://doi.org/10.3389/fpls.2020.00904.

Zhang J, Jiao X, Du Q, Song X, Ding J, Li J (2021). Effects of vapor pressure deficit and potassium supply on root morphology, potassium uptake, and biomass allocation of tomato seedlings. *J. Plant Growth Regul.* 40(2): 509–518. https://doi.org/10.1007/s00344-020-10115-2.

Zhao Y, Sun R, Liu H, Liu X, Xu K, Xiao K, Zhang S, Yang X, Xue C (2020). Multi-omics analyses reveal the molecular mechanisms underlying the adaptation of wheat (*Triticum aestivum* L.) to potassium deprivation. *Front. Plant Sci.* 11, 588994. https://doi.org/10.3389/fpls.2020.588994.