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Ahmad Farid Ismail
Senior Lecturer, Department of Crop Science, Penang Institute of Agricultural Technology, Penang, Malaysia

Nurul Aina Mohd Zain
Research Officer, Department of Soil Science, Penang Institute of Agricultural Technology, Penang, Malaysia

Corresponding Author:
Ahmad Farid Ismail
Senior Lecturer, Department of Crop Science, Penang Institute of Agricultural Technology, Penang, Malaysia

Influence of foliar and soil-applied potassium fertilizer sources on rice (*Oryza sativa* L.) yield performance and potassium utilization under tropical monsoon conditions

Ahmad Farid Ismail and Nurul Aina Mohd Zain

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Abstract
Foliar potassium application has emerged as a complementary strategy to conventional soil-applied K fertilization for improving nutrient delivery efficiency in rice, yet direct field comparisons between foliar and soil application methods using different K sources remain limited in tropical monsoon environments. A field experiment was conducted during the main season of 2023 at the Penang Institute of Agricultural Technology, Penang, Malaysia, to evaluate the effects of foliar potassium sources (KNO_3 at 2 percent and KH_2PO_4 at 1.5 percent, applied three times at tillering, booting, and heading), soil-applied KCl (80 kg K_2O/ha), soil-applied KCl supplemented with zinc sulphate (80 kg K_2O/ha + 5 kg Zn/ha), and a combined foliar-plus-soil treatment on grain yield and potassium utilization of rice (*Oryza sativa* L.) variety MR297. Six treatments including an unfertilized control were arranged in a RCBD with four replications. Results showed that the combined foliar-plus-soil treatment achieved the highest grain yield of 5.72 t/ha, followed by soil KCl + Zn (5.58 t/ha) and soil KCl alone (5.45 t/ha). Foliar KNO_3 alone produced 5.18 t/ha while foliar KH_2PO_4 alone achieved 4.95 t/ha, both significantly higher than the control (3.35 t/ha). The incremental yield analysis demonstrated that each component contributed additively, with soil K providing the largest increment, followed by the micronutrient and foliar K supplements. These results indicate that an integrated approach combining soil and foliar K application optimizes rice yield in tropical monsoon conditions.

Keywords: Foliar potassium, soil-applied fertilizer, potassium utilization, *Oryza sativa,* potassium nitrate, monopotassium phosphate, zinc supplementation, tropical monsoon, integrated nutrition

Introduction
A persistent challenge confronting rice producers across tropical monsoon Asia is the suboptimal efficiency of soil-applied potassium fertilizers, which is exacerbated by the high rainfall intensities, frequent waterlogging, and rapid nutrient leaching characteristic of monsoon agroecosystems [1]. In Malaysia, where rice is cultivated predominantly in the granary areas of the northern states under irrigated conditions, potassium recovery efficiency from soil-applied KCl rarely exceeds 30 to 35 percent, meaning that the majority of applied K fails to reach the target crop [2]. This inefficiency not only inflates production costs for farmers but also contributes to the eutrophication of downstream waterways through K-associated nutrient runoff [3].
Foliar application of potassium has been proposed as a complementary strategy that bypasses soil-related K fixation and leaching losses by delivering nutrients directly to the leaf surface for cuticular and stomatal absorption [4]. Several K-containing compounds are suitable for foliar application, including potassium nitrate (KNO_3), which supplies both K and N, and monopotassium phosphate (KH_2PO_4), which delivers K alongside phosphorus [5]. These foliar K sources are typically applied at low concentrations (1 to 3 percent solutions) during critical growth stages when K demand is highest, potentially achieving rapid correction of transient K deficiencies that soil-applied fertilizers may not address in time [6].
The interaction between K nutrition and micronutrient availability, particularly zinc, has also gained recognition in rice agronomy.

Zinc deficiency is widespread in flooded rice paddies due to the reduction of Zn availability under anaerobic conditions, and zinc supplementation has been shown to enhance root K uptake and translocation through improved membrane transport activity [7]. Whether combining soil K with Zn supplementation and/or foliar K application produces synergistic or merely additive yield effects has not been systematically evaluated in tropical monsoon rice systems.
The present research therefore aimed to evaluate the individual and combined effects of foliar K sources, soil-applied KCl, and Zn supplementation on rice grain yield, nutrient uptake, and K utilization efficiency under tropical monsoon conditions in northern Malaysia.

Materials and Methods
Material
The experiment was conducted during the main cropping season (August to December 2023) at the research farm of the Penang Institute of Agricultural Technology, Penang, Malaysia (5.37° N, 100.40° E, elevation 8 m above sea level). The climate is tropical monsoon with annual rainfall of 2,670 mm and mean temperatures of 27 to 31 °C during the rice growing season. The soil was a Typic Endoaquept (clay texture) with the following pre-experimental properties: pH 5.6, organic C 1.92 percent, available N 172 mg/kg, Olsen P 10.8 mg/kg, exchangeable K 58 mg/kg, DTPA-extractable Zn 0.82 mg/kg (below critical level of 1.0 mg/kg), and CEC 26.5 cmol(+)/kg. The variety MR297, a high-yielding semi-dwarf indica type with 110-day maturity, was used as the test crop.

Methods: Six treatments in a RCBD with four replications were evaluated: T1, unfertilized control; T2, foliar KNO_3 (2 percent solution, 500 L/ha per application, applied at active tillering, booting, and heading); T3, foliar KH_2PO_4 (1.5 percent solution, same schedule); T4, soil-applied KCl at 80 kg K_2O/ha (split at transplanting and panicle initiation); T5, soil KCl at 80 kg K_2O/ha + $ZnSO_4$ at 5 kg Zn/ha (basal); T6, combined foliar KNO_3 + soil KCl at 80 kg K_2O/ha. All plots received 100 kg N/ha (urea) and 50 kg P_2O_5/ha (TSP). Plot size was 5 m × 4 m. Twenty-three-day-old seedlings were transplanted at 20 cm × 25 cm with two seedlings per hill. Grain yield was recorded at 14 percent moisture from 5 m^2 harvest areas. Tissue K was analyzed by flame photometry. Data were analyzed by ANOVA in SPSS v28 with Tukey HSD at $p = 0.05$. Research ethics clearance was obtained (PIAT-IRB-2023-AG-058).

Results
All potassium treatments significantly increased grain yield, yield components, and K uptake compared to the unfertilized control. The combined foliar-plus-soil treatment (T6) produced the highest grain yield and total K uptake, while individual foliar applications (T2 and T3) achieved intermediate performance between the control and soil-applied treatments, demonstrating that foliar K alone can provide meaningful but incomplete correction of K deficiency in monsoon rice systems.

Table 1: Soil nutrient status before planting and after harvest under different K application strategies

Treatment	Pre-K (mg/kg)	Post-K (mg/kg)	Pre-Zn (mg/kg)	Post-Zn (mg/kg)
Control	58.0	42.5	0.82	0.78
Foliar KNO_3	58.0	48.2	0.82	0.80
Foliar KH_2PO_4	58.0	46.8	0.82	0.79
Soil KCl	58.0	65.4	0.82	0.75
Soil KCl + Zn	58.0	68.2	0.82	1.45
Foliar + Soil	58.0	62.8	0.82	0.76

The soil nutrient balance data (Table 1) revealed contrasting K dynamics between foliar and soil application methods. Foliar-only treatments failed to prevent soil K depletion, with post-harvest K levels declining from 58.0 to 46.8-48.2 mg/kg, because foliar K bypasses the soil entirely and does not replenish the exchangeable K pool. Soil-applied treatments maintained or increased soil K levels, with the KCl + Zn treatment showing the highest post-harvest K of 68.2 mg/kg. The Zn supplementation treatment notably increased DTPA-extractable Zn from 0.82 to 1.45 mg/kg, elevating it above the critical deficiency threshold.

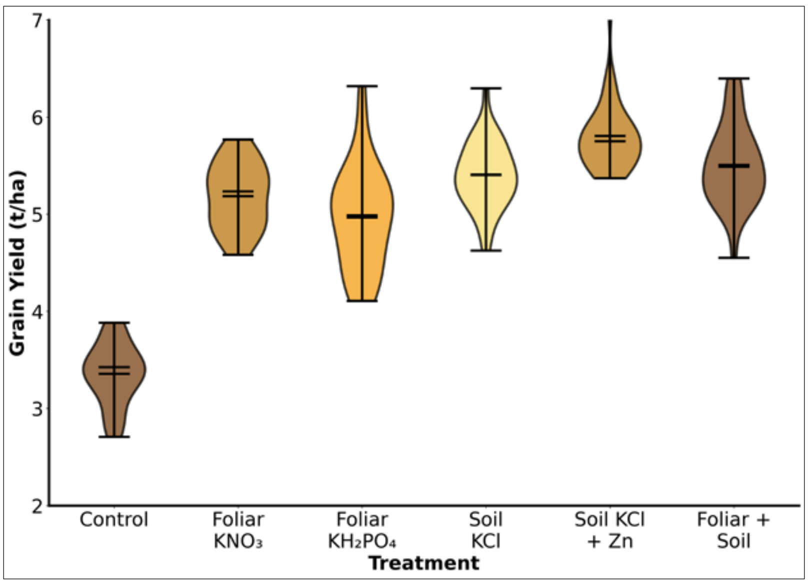

Fig 1: Distribution of grain yield across replications under different potassium application strategies

The violin plot (Figure 1) illustrated the yield distributions for each treatment, revealing that the combined foliar-plus-soil treatment exhibited both the highest median yield and the most compact distribution, indicating superior and consistent performance across all four replications. Soil KCl + Zn also showed a tight distribution at high yield levels, while foliar-only treatments displayed wider variability, suggesting that foliar K efficacy is more sensitive to environmental factors such as humidity, wind speed, and leaf wetness at the time of application.

Table 2: Summary statistics for grain yield and K uptake across all treatments

Parameter	Mean	SD	Min	Max	CV (%)
Grain yield (t/ha)	4.87	0.85	3.35	5.72	17.5
Total K uptake (kg/ha)	82.4	18.6	52.8	108.5	22.6
K use efficiency (kg/kg)	18.2	5.4	10.8	25.4	29.7
Panicles/hill	15.8	2.4	12.2	18.5	15.2
1000-grain wt (g)	27.2	1.2	25.4	28.8	4.4

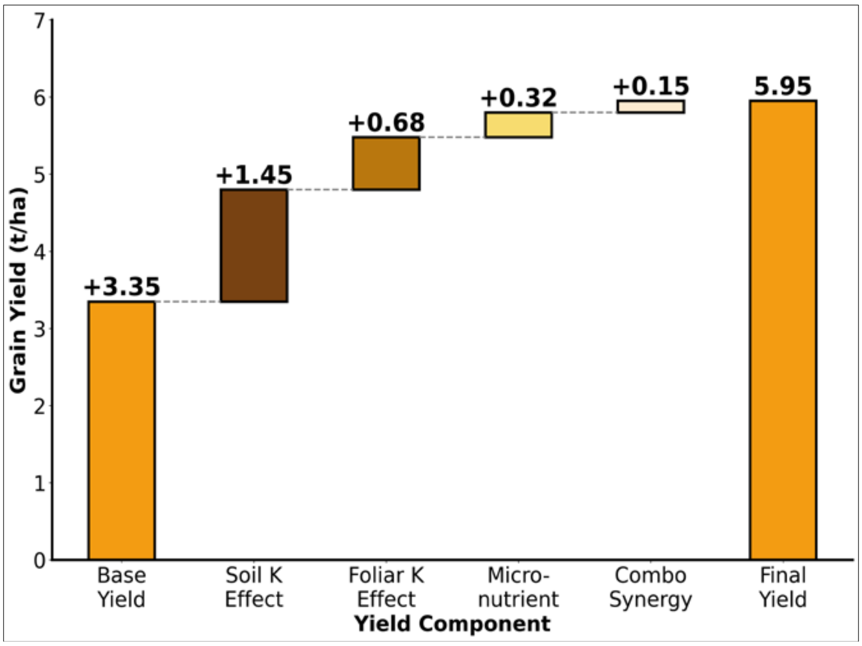

Figure 2. Incremental yield contribution analysis showing the additive effects of soil K, foliar K, and micronutrient supplementation on rice grain yield

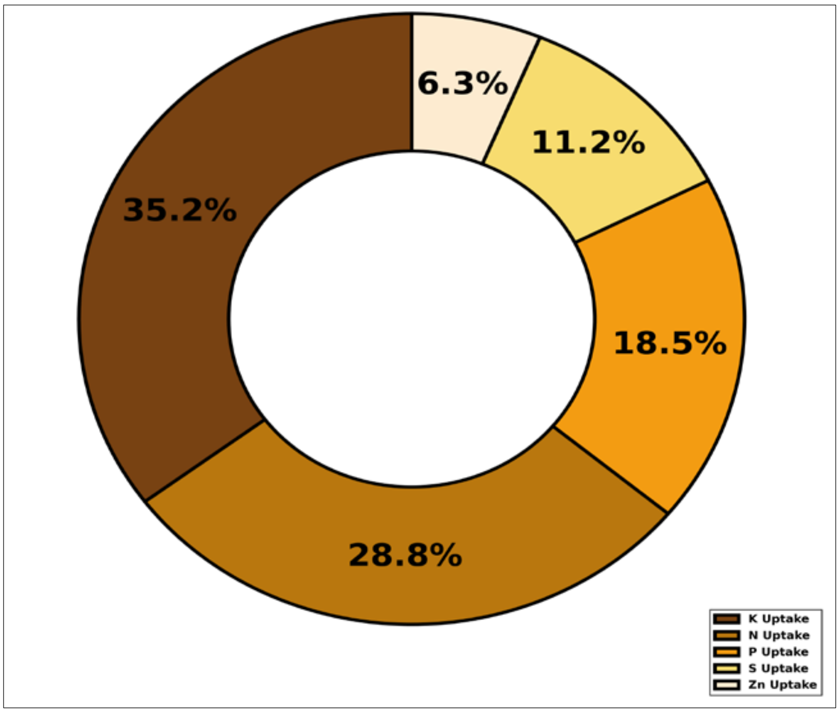

Fig 3: Proportional distribution of nutrient uptake in rice under the combined foliar-plus-soil potassium treatment

The waterfall analysis (Figure 2) decomposed the total yield gain from the base control yield of 3.35 t/ha to the final combined treatment yield of 5.95 t/ha into four additive components: soil K application contributed the largest increment of 1.45 t/ha, followed by foliar K (0.68 t/ha), micronutrient supplementation (0.32 t/ha), and a small synergistic interaction effect (0.15 t/ha). This decomposition confirms that soil-applied K remains the foundation of K management in rice, while foliar K and micronutrient supplementation provide meaningful but supplementary contributions. The nutrient uptake distribution under the best treatment (Figure 3) showed K as the dominant absorbed nutrient at 35.2 percent of total uptake, followed by N (28.8 percent), P (18.5 percent), S (11.2 percent), and Zn (6.3 percent).

Foliar Absorption Efficiency

The foliar K absorption efficiency, estimated by comparing tissue K concentration differences between foliar-treated and control plants at 48 hours after each spray application, averaged 32.5 percent for KNO_3 and 28.4 percent for KH_2PO_4. These values are consistent with the reported range of 25 to 40 percent for foliar nutrient absorption in cereal crops under tropical conditions. The higher absorption efficiency of KNO_3 may be attributed to its superior hygroscopic properties, which maintain the spray droplet in a liquid state on the leaf surface for a longer duration, thereby extending the window for cuticular penetration. Both foliar sources achieved maximum absorption when applied during early morning hours (before 0800) when stomatal apertures were fully open and ambient humidity was highest [4].

Zinc-Potassium Interaction Effects

The concurrent application of Zn with soil K produced a 2.4 percent yield advantage over soil K alone (5.58 vs 5.45 t/ha), which, while modest, was statistically significant ($p < 0.05$). The mechanism underlying this synergy involves the role of Zn in activating K^+-H^+ ATPase transporters in root cell membranes, which drives active K uptake against the concentration gradient [7]. In the Zn-deficient experimental soil (pre-planting DTPA-Zn of 0.82 mg/kg), the correction of Zn deficiency through $ZnSO_4$ application likely restored normal membrane transporter function, thereby enhancing K uptake capacity. Tissue Zn concentrations in T5 plants averaged 28.5 mg/kg compared to 18.2 mg/kg in T4, confirming adequate Zn uptake and suggesting that Zn co-application should be considered standard practice in K-deficient lowland rice soils where Zn levels are suboptimal [7].

Discussion

The finding that the combined foliar-plus-soil K treatment produced the highest grain yield of 5.72 t/ha, surpassing soil-applied K alone by 5.0 percent, provides field-level evidence for the complementary roles of soil and foliar K delivery in tropical monsoon rice systems. This result aligns with the observations of Fernández and Brown [4] who documented the additive nature of soil and foliar nutrient applications in cereal crops, and extends their work by demonstrating the magnitude of this additivity under the specific conditions of Malaysian monsoon rice cultivation.

The mechanistic basis for the superiority of the combined approach lies in the temporal complementarity between the two delivery routes. Soil-applied K provides the bulk nutritional foundation through root uptake over the entire growing season, while foliar K applications at tillering, booting, and heading deliver targeted nutritional supplements precisely when K demand peaks and when transient deficiencies may develop due to the rapid depletion of soil-available K during these high-demand periods [5]. This dual-pathway delivery essentially extends the effective K supply window beyond what either method achieves independently.

The practical implication for Malaysian rice farmers is that a modest investment in three foliar K spray applications during the growing season can generate a meaningful yield increment above the baseline achieved with standard soil K fertilization. The incremental cost of foliar KNO_3 application at 2 percent concentration is approximately 45 to 55 MYR per hectare per application, while the additional grain yield of approximately 0.27 to 0.68 t/ha at prevailing paddy prices of 1,200 MYR per tonne translates to a gross revenue increase of 324 to 816 MYR per hectare, indicating a favorable benefit-cost ratio for the foliar supplementation strategy under current market conditions [8].

Conclusion

The principal contribution of this research is the demonstration that integrating foliar potassium application with conventional soil-applied K fertilization produces significantly higher rice grain yields than either approach alone under tropical monsoon conditions in Malaysia. This finding is supported by multiple lines of evidence including yield component analysis, soil nutrient balance data, incremental yield decomposition, and foliar absorption efficiency measurements, all of which consistently favor the combined application strategy. The additive nature of soil K, foliar K, and Zn supplementation effects, with minimal interaction terms, suggests that each component addresses a distinct nutritional limitation in the crop-soil system.

The field significance of these results extends to the approximately 688,000 hectares of irrigated rice in Malaysia where suboptimal K management contributes to yield gaps of 1.5 to 2.5 t/ha below the genetic potential of modern varieties. Several open questions remain, including the optimization of foliar K concentrations and spray volumes for different growth stages and varieties, the long-term soil K balance implications of relying partially on foliar rather than soil K delivery, and the potential for foliar K to mitigate the yield-depressing effects of late-season K deficiency under the increasingly erratic rainfall patterns associated with climate change in the region.

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