Synergistic Effects of Mineral and Bio-Potassium Fertilization on Yield, Fruit Quality, and Potassium Use Efficiency in Baladi Orange

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Abstract: *The experiment evaluated the effects of mineral potassium and bio-potassium fertilizers on 20-year-old Baladi orange trees over two growing seasons in Ismailia. Using a randomized complete block design, various treatments were tested, including a control and bio-fertilizer (Potassiomag), along with different potassium sulfate and feldspar levels. Key measures included potassium content, fruit yield, quality, and vitamin C levels. Results showed significant improvements in yield and quality with bio-mineral combinations, particularly the 100 units treatment, which consistently outperformed others. Principal component analysis indicated that treatment variability was primarily linked to productivity and nutrient efficiency. The study concluded that mineral supply is crucial for crop production, with bio-fertilization enhancing, rather than replacing, mineral inputs. The most effective treatment combined optimal minerals with bio-fertilizer, achieving superior fruit quality and potassium accumulation.*

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Treatments were clustered into high, intermediate, and low performers, with high yields associated with balanced nutrient management. A strategy integrating full mineral supply with bio-inputs is recommended for optimal productivity in orange cultivation

Keywords: *Mineral, Bio-potassium, Orange fruit, Fruit juice, PCA*

Introduction

Egypt's most commercially significant fruit crop is citrus, which is essential to both agricultural exports and the country's food security. Citrus cultivation encompasses more than 0.52 million feddan, with a fruiting area above 0.48 million feddan and an annual production reaching 5.1 million tons in recent seasons, according to the Ministry of Agriculture and Land Reclamation's Annual Reports of the Economic Affairs Sector. During the 2024 and 2025 production years, orange yields remained the dominant contributor to total citrus output, reflecting both sustained domestic demand and export stability. Due to its capacity to adapt to a variety of soil conditions, consumer choice in local markets and consistent productivity under Egyptian agro-climatic conditions, Balady orange continues to be one of the most extensively grown local cultivars of oranges. Maintaining citrus productivity and fruit quality requires balanced mineral nutrition, especially in newly reclaimed areas with sandy soil. For optimum development, output, and fruit quality, citrus trees need at least sixteen key mineral elements; macronutrients are crucial in determining productivity (Ouaggio et al., 2002).

Potassium (K) is equally important because it is involved in protein synthesis, carbohydrate metabolism, enzyme activation, osmoregulation, and the translocation of photo assimilates from leaves to developing fruits, even though nitrogen is the main factor driving vegetative growth and yield formation (Srivastava, 2012; Shaaban and Abdel-Ati, 2025). Improved orange fruit size, peel color, juice content, total soluble solids, and overall marketability are all closely correlated with adequate potassium nutrition. Despite its significance, Egyptian soils still have low potassium usage efficiency, especially in sandy and calcareous soils where applied mineral K fertilizers are prone to fixation or leaching, which lowers their bioavailability to plants. Over the past few decades, an over-reliance on conventional mineral fertilizers has led to environmental contamination, nutritional imbalance, and soil degradation. With nutrient application rates per cultivated unit significantly higher than global averages, Egypt has long struggled with fertilizer overuse. This has resulted in decreased fertilizer efficiency, declining soil fertility, and increased risks to human and environmental health (FAO, 1994; Alalaf et al., 2023; Cano-Castro et al., 2024). Potassium availability in soil may decrease to less than 10% of total K content in such circumstances, limiting its physiological efficacy even with large application rates (Kucey et al., 1989; Miller et al., 1990).

The use of biofertilizers has emerged as a sustainable approach to overcome these problems and to enhance the bioavailability of nutrients and fertilizer use efficiency. It has been shown that potassium-solubilizing microbes and biofertilizers that fix nitrogen and mobilize nutrients can convert the forms of K in the soil from unavailable to plant-available, thus improving nutrient uptake and crop performance. Bioavailable potassium sources have been consistently reported in recent studies to improve vegetative growth, leaf mineral composition, yield and fruit quality of citrus trees, while improving soil biological activity and organic matter status (El-Khwaga and Maklad, 2013; El-Badawy, 2017; Fatma and Ahmed, 2020; Akalaa et al., 2022; Pérez-Piqueres et al., 2025; Semalulu et al., 2025). The combination of mineral fertilizers and biofertilizers was proved to be effective in reducing the loss of nutrients, increasing the efficiency of potassium uptake, and improving the tolerance to biotic and abiotic stresses in Balady citrus and other orange cultivars. Such integrated nutrient management approaches are being recognized as essential tools for sustaining citrus productivity under the increasing constraints of climate variability and decline in soil fertility experienced during recent production seasons (Wang et al., 2022; Hu et al., 2023; Fatima and Al-Hadethi, 2024).

Hence, the present investigation was conducted to study the impact of the combined application of mineral potassium fertilizers and bioavailable potassium sources on the yield performance, leaf mineral status, fruit quality and yield attributes of Balady orange trees under sandy soil conditions during the 2024 and 2025 growing seasons. The study also, aims to evaluate the potential of bioavailable potassium inputs to improve potassium use efficiency and minimize reliance on traditional mineral fertilization and therefore promote more sustainable citrus production systems in Egypt.

Materials and Methods

Experimental site and seasons

The experiment was conducted during two successive growing seasons of 2024 and 2025, at the Wadi El-Mollak region, Ismailia governorate (30° 44′ 47.6″ N, 32° 0′ 16.16″ E). The physical and chemical analysis of soils are shown in Table (1).

Table 1. Analysis of the orchard soils of both locations

Physical properties	**Organic matter (%)**		**1.2**
	Textural class		Loamy Sand
Chemical properties			
pH			8.4
Electric conductivity E.C. (ds/m)			0.4
$CaCO_3$			0
CEC (meq/100g) soil			4.65
Soluble ions, meq / L	Soluble anions	HCO_3^-	1.77
		CL^-	1.43
		SO_4^{-2}	1.17
	Soluble cations	Ca^{+2}	1.77
		K^+	0.56
		Na+	1.71

Each tree was planted in a 5 × 4 m with a drip irrigation system to study the impact of mineral K sources and bio-potassium (potasiomag) fertilization on 20-year-old Baladi orange (*Citrus sinensis*, L.) trees budded on Bitter orange (*Citrus aurantium*, L.) rootstock. The trees were selected as uniform as possible in growth, vigor, fruiting, and free from any disease. Standard cultural practices recommended for the orange including fertilizer (except potassium), pruning, irrigation, and pest control were uniformly applied throughout the experiment, except for the imposed fertilization treatments.

Experimental design: The experiment was laid out in a randomized complete block (RCBD) design with three replicates in each season (Table 2).

Table 2. Experiment scheme

	T0	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**
Units	NNon	100	100	100	100	100	100	50	50	50	50	50	50
Mineral Source	NNon	K	F	50%(K+F)	K	F	50%(K+F)	K	F	50%(K+F)	K	F	50%(K+F)
Bio treatment	NNon	NNon	nNon	NNon	BBio	BBio	BBio	NNon	NNon	NNon	BBio	BBio	BBio

Bio-fertilizer treatments: Two bio-fertilizer levels were tested:
Without bio-fertilizer (Non-bio)
With bio-fertilizer (Potassiomag 5 g tree^{-1} per application**)**
Potassium sulfate (K) (From Feb. to Oct.)
50 units: 64 g tree^{-1} month^{-1}, equivalent to 571 g tree^{-1} year^{-1}
100 units: 127 g tree^{-1} month^{-1}, equivalent to 1142 **g** tree^{-1} year^{-1}
K was split monthly from Feb. to October
Feldspars (F)
50 units: 2550 g tree^{-1} year^{-1}
100 units: 5100 g tree^{-1} year^{-1}
Applied once annually without monthly splitting
50% K +50% F
50 units: 285+1275 g tree^{-1} year^{-1}
100 units: 571+2550 g tree^{-1} year^{-1}
Bio potassium (Potassiomag)
Applied as described under bio-fertilizer treatments

Potassiomag: is a commercial potassium bio-fertilizer contains special bacteria (*Bacillus circulars*) which releasing the potassium in available form. Bio-fertilizer was soil added (15cm depth) in twice equal doses during the growing season, in February and June, at a rate of 5 g tree^{-1} per application.
Potassiomag, were obtained from the Department of Microbiology, Agricultural Research Centre, Giza, Egypt.

Data recorded: The following parameters were measured during the two growth seasons:
Leaf content of K: forty mature leaves of Spring growth cycle in the non-fruiting shoots (Summer, 1985) were randomly collected in end September from each replicate, cleaned, washed and oven dried at 70^{o}C to a constant weight, then ground and digested according to Evenhuis and DeWaard (1980) using sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) to determine K element in leaf using flame spectrophotometry (Brown and Lillelland, 1974).

Fruit yield traits: at harvesting time, in the end of December, the fruits were harvested from each tree and numbered, weighed as a whole, and recorded the number (NF) and fruit weight/ tree (Y, kg)

Fruit quality properties: twenty fruits were taken randomly from each tree (5 fruit/ each direction) to determine the fruit size (FS, cm^3), and fruits chemical properties (average juice volume/fruit, JV cm^3, fruit juice percentage (FJ%).

Titration acidity in fruit juice was determined as citric acid by titration against 0.1 N sodium hydroxide solution and the total acidity percentage was calculated by the following equation: Total acidity = [(NAOH × 0.1 × 0.064)/juice volume] × 100 (A.O.A.C., 1999)

Total soluble solids percentage (TSS %) was determined in fruit juice using a hand refractometer.

Vitamin C content as mg ascorbic acid/100 ml juice was determined by titration against 2, 6-dichlorophenol indophenol dye (AOAC, 2006).

Statistical analyses:
Collected data were subjected to statistical analysis of variance according to Gomez and Gomez (1984), for a complete randomized block design (CRBD) and

the means of the different treatments were compared by LSD (least significant difference at 0.05 level of probability using ***OPSTAT*** Software, as described by Sheoran et al. (1998).

A principal component analysis (PCA) based on the treatments effect on all studied traits (over seasons) was conducted in a biplot-style dispersion plot. PCA yielded eigenvalues, which were then used to ascertain the axes' and their corresponding characteristics' relative discriminative power (Pradhan et al., 2015). A bi-plot figure was used to classify the treatments and compare them using cluster analysis.

Results

In both seasons, all the studied traits were significantly ($P \leq 0.05$) affected by fertilization treatments confirming significant effects of mineral input level, nutrient balance, and bio-fertilizer integration. Seasonal variation (S1 vs. S2) was minor compared to treatment effects and treatment rankings were highly consistent, demonstrating robust responses under different growing conditions.

Performance for Yield Traits and K Status

Potassium content (K), number of fruits (NF), fruit size (FS) and yield (Y) were found to have a clear and consistent pattern across seasons (Table 3). In both seasons, T6 (100 units, 50% K + 50% F with bio) gave the highest values for all four traits and formed a statistically distinct group (a), significantly exceeding all other treatments based on LSD values. T4 and T3 were the second highest (b) and T5 and T1 were intermediate (c). The lowest registered values were observed in low-input non-bio treatments (T7–T9) and control (d–e).

Table 3. Effect of mineral and bio-fertilizer treatments on Yield traits and K status performance in two seasons (S1, S2)

Treatment	K (S1)	K (S2)	NF (S1)	NF (S2)	FS (S1)	FS (S2)	Y (S1)	Y (S2)
T0	$0.737^{g} \pm 0.038$	$0.780^{g} \pm 0.029$	$183^{e} \pm 2.517$	$188.67^{e} \pm 2.186$	$152.67^{e} \pm 3.18$	$159.67^{e} \pm 3.18$	$31.9^{e} \pm 0.601$	$33.8^{e} \pm 0.748$
T1	$1.810^{d} \pm 0.036$	$1.853^{d} \pm 0.032$	$331^{c} \pm 5.132$	$339^{c} \pm 4.726$	$228^{c} \pm 1.732$	$236^{c} \pm 1.528$	$78.4^{c} \pm 2.553$	$82.6^{c} \pm 2.434$

T2	1.533^{e} ± 0.049	1.590^{e} ± 0.046	269.33^{d} ± 3.179	276^{d} ± 3.606	199.67^{d} ± 3.48	212^{d} ± 2.082	57.2^{d} ± 1.032	60.7^{d} ± 1.275
T3	1.877^{c} ± 0.064	1.927^{c} ± 0.054	368^{b} ± 3.055	376.67^{b} ± 2.849	248^{b} ± 0.577	255^{b} ± 1.528	92.5^{b} ± 1.918	97.7^{b} ± 1.739
T4	1.960^{b} ± 0.025	2.037^{b} ± 0.034	400^{b} ± 3.464	409^{b} ± 4.359	258.33^{b} ± 1.452	264.33^{b} ± 1.855	105.7^{b} ± 0.926	109.9^{b} ± 1.069
T5	1.830^{cd} ± 0.023	1.877^{cd} ± 0.027	355.33^{c} ± 4.176	363.33^{c} ± 3.179	240^{c} ± 3.215	245^{c} ± 2.309	86.3^{c} ± 1.551	90.7^{c} ±1.092
T6	2.257^{a} ± 0.186	2.327^{a} ± 0.173	416.67^{a} ± 1.857	427.67^{a} ± 2.334	267.33^{a} ± 1.201	275^{a} ± 2.082	112.4^{a} ± 0.846	118.8^{a} ± 1.342
T7	1.137^{f} ± 0.076	1.197^{f} ± 0.080	228^{d} ± 3.464	237.33^{d} ± 3.48	176.67^{d} ± 4.055	188.33^{d} ± 3.93	44.2^{d} ± 1.063	47.9^{d} ± 1.335
T8	0.793^{g} ± 0.038	0.840^{g} ± 0.044	193.67^{e} ± 1.201	202.33^{e} ± 2.848	167^{e} ± 3.512	173.67^{e} ± 4.702	35.0^{e} ± 0.345	38.0^{e} ± 0.741
T9	0.950^{fg} ± 0.038	1.010^{fg} ± 0.023	213.67^{e} ± 3.283	220.67^{e} ± 3.18	171.67^{e} ± 2.027	180^{e} ± 2.082	39.8^{e} ± 1.302	43.1^{e} ± 1.459
T10	1.663^{de} ± 0.064	1.717^{de} ± 0.058	290.67^{c} ± 4.256	298.67^{c} ± 4.808	210.67^{c} ± 1.764	220.33^{c} ± 1.453	63.7^{c} ± 1.359	67.6^{c} ± 1.52
T11	1.277^{f} ± 0.049	1.343^{f} ± 0.064	244.67^{d} ± 3.18	252.67^{d} ± 2.728	191^{d} ± 3.606	200^{d} ± 4.583	49.2^{d} ± 1.263	52.9^{d} ± 0.773
T12	1.743^{d} ± 0.137	1.807^{d} ± 0.142	306.67^{c} ± 5.696	316.33^{c} ± 5.897	221.33^{c} ± 3.383	229.67^{c} ± 2.333	68.8^{c} ± 1.715	74.3^{c} ± 2.068
LSD	0.235	0.224	7.539	6.914	7.507	6.935	2.966	2.742

Values are **means ± S.E., Within each column and season, means followed by the same superscript letter are not significantly different at P ≤ 0.05 according to LSD.**

NF & FS ranked consistently as: T6[a] > T4[b] > T3[c] > T5[cd] > T1[d] > T12[de] > T10[e] > T2[f] > T11[g] > T7[h] > T9[i] > T8[j] No overlap beyond LSD limits occurred between the top three treatments (T6, T4, T3) and all others in both seasons, **Y (Yield):** T6[a] > T4[b] > T3[c] > T5[d] > T1[e] > others (f–j)

Physical and chemical quality of the fruit

Total soluble solids (TSS) exhibited moderate but significant increases, especially under high mineral treatments (Table 4). T6 and T4 showed the highest TSS values while control and low mineral treatments were significantly lower (c–d). Importantly, the yield improvement did not come at the expense of quality attributes. The total acidity (TA) showed the reverse trend. All fertilized treatments resulted in significant reduction of TA compared to control. The lowest TA values (a) were recorded in T6, followed closely by T4 and T3 (ab), while the control showed the highest acidity (d). This confirms that increased productivity was achieved simultaneously with improved fruit chemical balance. The vitamin C (VC) content responded positively to fertilization intensity and nutrient balance. VC values were highest in T6 in both seasons (a), followed by T4 and T3 (b). Reduced mineral or non-bio treatments resulted in significantly lower VC levels (c–d).

Table 4. Effect of mineral and bio-fertilizer treatments on TSS, TA and VC in two seasons (S1, S2)

Treatment	TSS (S1)	TSS (S2)	TA (S1)	TA (S2)	VC (S1)	VC (S2)
T0	10.99[e] ± 0.029	11.07[e] ± 0.034	1.23e ± 0.01	1.21e ± 0.009	48.0[e] ± 1.215	49.3[e] ± 1.01
T1	12.03[c] ± 0.042	12.14[c] ± 0.054	0.98[c] ± 0.003	0.96[c] ± 0.003	63.0[c] ± 2.094	65.0[c] ± 2.232
T2	11.77[d] ± 0.023	11.87[d] ± 0.038	1.05[c] ± 0.012	1.03[c] ± 0.009	56.3[d] ± 1.497	58.6[d] ± 1.987
T3	12.29[b] ± 0.042	12.40[b] ± 0.047	0.95[b] ± 0.003	0.93[b] ± 0.003	69.7[b] ± 1.803	71.8[b] ± 1.711
T4	12.49[b] ± 0.09	12.60[b] ± 0.078	0.92a ± 0.003	0.91[b] ± 0.003	72.4[b] ± 1.532	74.6[b] ± 1.332

T5	$12.12^{c} \pm 0.044$	$12.22^{c} \pm 0.03$	$0.96^{bc} \pm 0.006$	$0.95^{bc} \pm 0.003$	$66.2^{c} \pm 1.715$	$68.4^{c} \pm 1.476$
T6	$12.63^{a} \pm 0.058$	$12.74^{a} \pm 0.033$	$0.91^{a} \pm 0.003$	$0.90^{a} \pm 0.003$	$76.0^{a} \pm 2.071$	$77.7^{a} \pm 1.723$
T7	$11.61^{d} \pm 0.015$	$11.70^{d} \pm 0.017$	$1.14^{d} \pm 0.006$	$1.13^{d} \pm 0.003$	$53.4^{d} \pm 1.515$	$55.7^{d} \pm 1.703$
T8	$11.25^{e} \pm 0.023$	$11.35^{e} \pm 0.027$	$1.17^{d} \pm 0.006$	$1.16^{d} \pm 0.003$	$49.4^{e} \pm 1.054$	$51.5^{e} \pm 1.049$
T9	$11.46^{e} \pm 0.026$	$11.56^{e} \pm 0.021$	$1.16^{d} \pm 0.003$	$1.15^{d} \pm 0.003$	$51.3^{e} \pm 0.958$	$53.5^{e} \pm 1.15$
T10	$11.84^{c} \pm 0.034$	$11.94^{c} \pm 0.038$	$1.00^{c} \pm 0.003$	$0.99^{c} \pm 0.003$	$58.0^{c} \pm 0.857$	$60.3^{c} \pm 0.806$
T11	$11.71^{d} \pm 0.025$	$11.80^{d} \pm 0.041$	$1.10^{d} \pm 0.01$	$1.09^{d} \pm 0.01$	$55.0^{d} \pm 0.843$	$56.6^{d} \pm 0.152$
T12	$11.91^{c} \pm 0.023$	$12.00^{c} \pm 0.03$	$0.98^{c} \pm 0.003$	$0.98^{c} \pm 0.003$	$60.0^{c} \pm 0.916$	$62.6^{c} \pm 0.993$
LSD	1.962	1.966	4.18	4.307	3.962	4.155

Values are **means ± S.E. Within each column and season, means followed by the same superscript letter are not significantly different at P ≤ 0.05 according to LSD.**

TSS: T6[a] > T4[b] > T3[c] > T5[d] > T1[e] > others, **TA**: Inverse trend (lowest acidity): T6[a] < T4[b] < T3[c] (TA decrease is desirable; letters assigned accordingly), VC (Vitamin C): T6[a] > T4[b] > T3[c] > T5[d] > T1[e]> others (f-j)

Fruit juice (FJ), juice volume (JV) and juice weight (JW) were significantly increased with fertilization (Table 5). T6 again formed the highest significance group (a) followed by T4 and T3 (b). The improvements are indicative of improved sink strength and assimilate partitioning under balanced mineral nutrition coupled with bio-fertilization.

Principal component analysis (PCA):

Principal component analysis (Table 6 and Fig. 1) showed that PC_1 explained 98.24% of the total variance and PC_2 explained only 1.14% of the total variance, suggesting that the discrimination of treatments is mainly governed by PC_1.

Table 5. Effect of mineral and bio-fertilizer treatments on Fruit juice (FJ), juice volume (JV) and juice weight (JW) in two seasons (S1, S2)

Treatment	FJ (S1)	FJ (S2)	JV (S1)	JV (S2)	JW (S1)	JW (S2)
T0	39.337 ± 0.48	39.7 ± 0.551	62.153 ± 1.339	64.343 ± 1.381	68.587 ± 1.233	71.19 ± 1.084
T1	43.19 ± 1.052	43.403 ± 0.726	96.563 ± 2.752	100.377 ± 3.163	102.13 ± 0.947	105.7 ± 0.784
T2	42.153 ± 0.342	41.91 ± 0.585	82.543 ± 0.699	83.89 ± 0.813	89.523 ± 1.464	92.21 ± 2.022
T3	44.947 ± 1.344	45.157 ± 1.042	106.16 ± 1.655	110.6 ± 1.286	112.903 ± 2.402	117.053 ± 1.729
T4	45.22 ± 0.616	45.717 ± 0.622	109.46 ± 0.627	114.497 ± 1.338	119.513 ± 0.727	122.803 ± 0.742
T5	44.533 ± 0.121	45.123 ± 0.59	102.717 ± 1.88	105.013 ± 1.52	108.22 ± 1.601	112.667 ± 2.006
T6	45.457 ± 0.461	46.467 ± 0.364	114.19 ± 0.678	123.037 ± 1.9	122.587 ± 1.525	129.043 ± 1.947
T7	41.467 ± 0.247	41.347 ± 0.466	75.5 ± 1.277	77.243 ± 1.047	80.437 ± 0.61	83.357 ± 0.497
T8	40.45 ± 1.144	40.76 ± 1.172	68.737 ± 0.884	71.21 ± 0.614	73.063 ± 1.805	76.62 ± 2.083
T9	41 ± 0.569	40.983 ± 0.545	72.147 ± 1.273	74.13 ± 1.262	76.633 ± 0.731	79.897 ± 1.516
T10	42.38 ± 0.205	42.86 ± 0.066	85.507 ± 0.736	88.81 ± 1.144	93.23 ± 0.456	97.007 ± 0.752
T11	41.973 ± 0.22	41.627 ± 0.105	77.897 ± 1.081	80.493 ± 0.352	84.77 ± 0.679	87.55 ± 0.301
T12	42.98 ± 0.472	43.26 ± 0.653	88.7 ± 1.406	93.583 ± 1.441	96.417 ± 1.238	101.517 ± 1.881
LSD	1.962	1.966	4.18	4.307	3.962	4.155

Table 6. Eigen vector, eigenvalue, and variances for 12 interacted treatments based on ten yield and juice traits of orange fruits

	PC_1	PC_2	PC_3	PC_4
K	**0.3114**	**-0.6058**	0.0520	**-0.4385**

NF	**0.3185**	0.0730	-0.2563	-0.1194
FS	**0.3188**	-0.0835	-0.0605	0.1428
Y	**0.3171**	0.2388	-0.2975	**-0.3235**
FJ	**0.3165**	0.2211	0.1363	**0.646**
JV	**0.3179**	0.2003	-0.0886	0.0846
JW	**0.3186**	0.1387	-0.1108	-0.0192
TSS	**0.3150**	0.0134	**0.8699**	-0.1181
TA	-0.3121	**0.5726**	0.2074	**-0.4029**
VC	**0.3164**	**0.3569**	-0.0315	-0.2595
Eigenvalue	9.8245	0.1141	0.0316	0.0191
% of Variance	98.2447	1.1410	**0.3161**	0.1913
Cumulative (%)	98.2447	99.3857	99.7018	99.8931

All measured attributes [potassium (K %), number of fruits (NF), fruit size (FS), yield/tree (Y), fruit juice percentage (FJ), juice volume (JV), juice weight (JW), total soluble solids (TSS%), ascorbic acid (VC)] showed similarly positive loadings on PC_1 (0.3114–0.3188) confirming PC_1 as a composite productivity and nutrient-efficiency axis, while PC_2 was mostly correlated to total-acidity (TA).

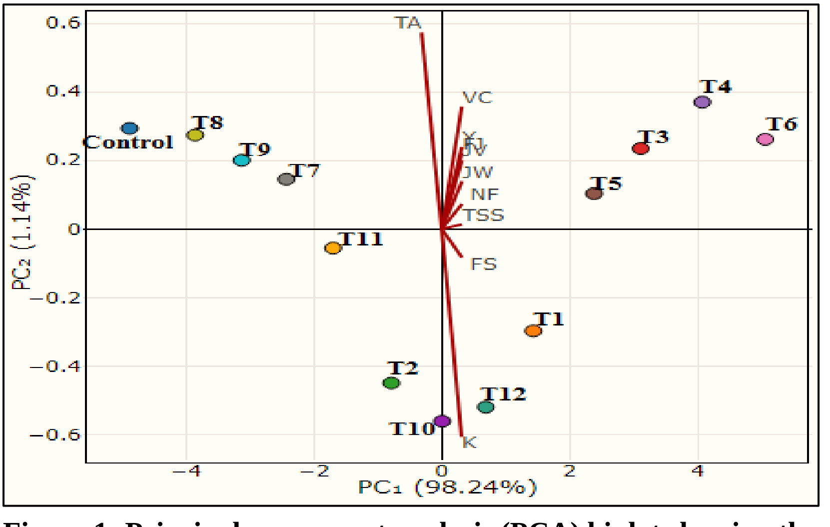


Figure 1: Principal component analysis (PCA) biplot showing the relationships between treatments and measured attributes. PC_1 and PC_2

explained 98.24% and 1.14% of the total variance, respectively. Yield, NF, and fruit size traits load strongly and positively on PC_1 (> 0.30), explaining why T6, T4, and T3 are positioned farthest along the positive PC_1 direction

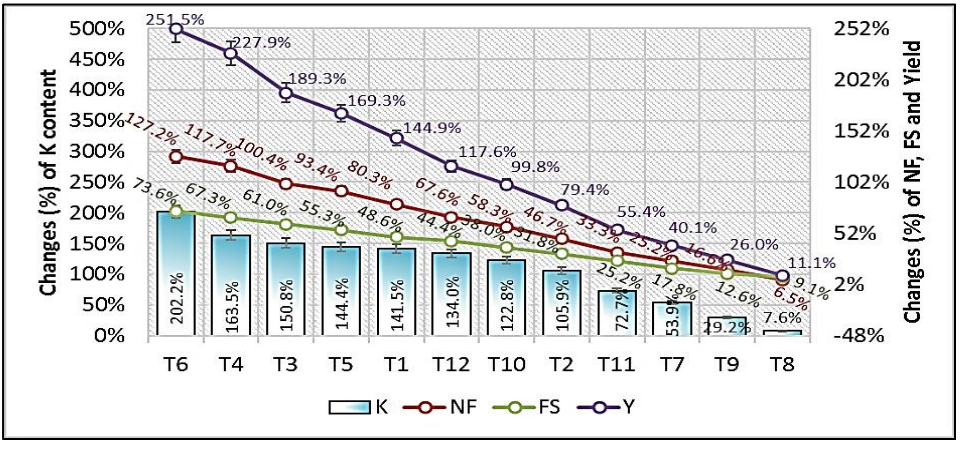
Fruit physical traits (FJ, JV, JW) close vector alignment with yield confirms that increases in productivity reflect enhanced sink strength rather than dilution effects.

TSS and VC vectors cluster with yield and FS, supporting the conclusion that quality improvement accompanies yield enhancement.

TA shows its primary association with PC_2 (1.14% variance), explaining why acidity variation does not alter treatment ranking driven by PC_1.

The separation of full-rate (100 units) mineral treatments from reduced-rate MSs combined with bio treatments reflects mineral intensity dominance with bio-fertilizer acting as an efficiency enhancer.

The PCA ordination was strongly supported by the percentage increase over control (Fig.2). Among the genotypes T6 and T4 showed the maximum displacement towards positive PC1 (Fig.1) and maximum gains were observed for almost all the traits including the highest gain in yield (251.52% and 227.93%), potassium accumulation (K, 202.18% and 163.48%) and ascorbic acid (VC, 58.03% and 51.17%). The results confirm a strong synergistic effect between bio-fertilization and the full mineral input.



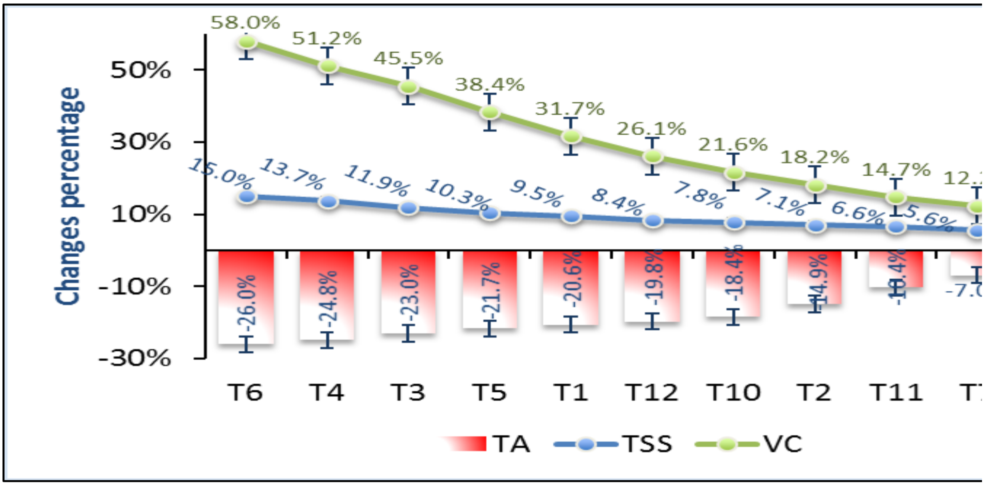


Figure 2: Changes percentage of K% in leaf, physical and chemical traits of orange fruit in descending order compared to the control as affected by fertilizer treatments

Importantly, results also indicate that mineral-only treatments at 100 units (T3, T1 and T2) can outperform some bio-based treatments applied at lower mineral rates (e.g. T10, T11, T12). For example, T3 (100 units; mixed K+F; non-bio) was better than T12 and T10 in yield, K accumulation and structural attributes. This result can be interpreted that the intensity of mineral supply is still a key driver of performance. This is why PCA separation was primarily along PC $_1$, rather than across a strict bio vs. non-bio dichotomy.

As shown in Fig.3, total acidity (TA %) decreased consistently across all treatments (from –4.63% to –26.03%), suggesting that productivity gains were not due to an increase in total acidity (%). The variation in TA had little effect on the ranking of treatments, as it loaded mainly on PC_2, which confirmed the agronomically valid interpretation based on PC_1.

In general, PCA and relative performance indices indicate that bio-fertilization can improve efficiency but cannot completely replace sufficient mineral fertilizer supply, especially at low input levels (50% units).

Integration with PCA interpretation

The univariate results strongly validate the PCA structure. Because PC_1 accounted for nearly all variability (98.24%) and all productivity-related traits (K, NF, FS, Y, FJ, JV, JW, TSS, VC) showed strong positive loadings, PC_1 can be interpreted as a composite performance index. Treatments ranking highest along PC_1 (notably T6, followed by T4 and T3) were exactly those showing statistically superior means across traits. PC_2 (1.14%) was primarily associated with TA and contributed little to treatment discrimination. Consequently, TA variation did not alter treatment ranking, a conclusion fully supported by LSD-based comparisons.

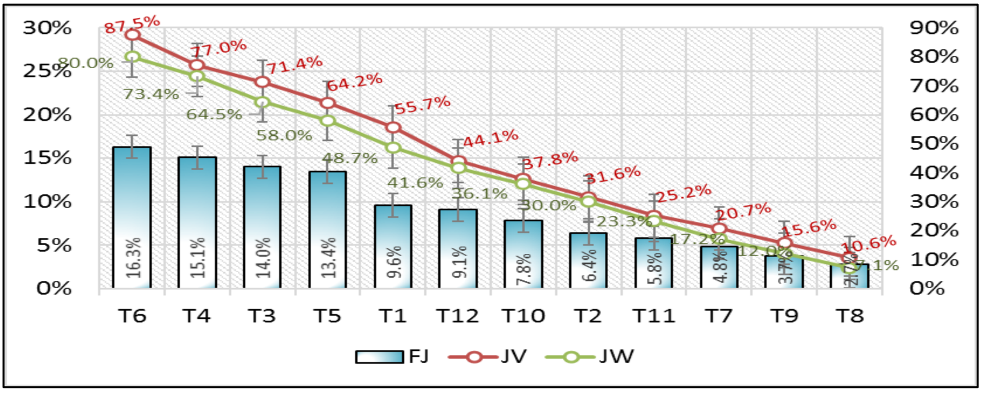


Figure 3: Changes percentage of Orange fruit juice (%), juice volume (JV) and weight (JW) in descending order compared to the control as affected by fertilizer treatments

Mineral versus bio contributions

A key outcome is that mineral supply level remained the dominant factor, while bio-fertilization acted as a strong enhancer rather than a substitute. This is evident from the fact that full-rate mineral treatments without bio-inputs (e.g., T3 and T1) significantly outperformed bio-fertilized treatments at reduced mineral rates (T10–T12) for most traits. Nevertheless, bio-fertilization consistently improved efficiency within each mineral level, as shown by the superiority of T6 over all other treatments and of T4 over T1.

Agronomical advice

In agronomic applied terms, the T6 treatment (100 units, 50% K + 50% F with bio-input) is the most effective, giving the best results in terms of yield, potassium accumulation as well as both fruit and juice performance, and decreasing total acidity. If mineral composition (mixed F and K) or cost is a concern, T4 and T5 are good alternatives. In absence of bio-fertilizers, 100-unit mineral treatments (T3, T1, T2) are still valid choices and can do better than low-rate mineral with bio-fertilized systems. Bio-fertilization at reduced mineral rates (50 units) should, however, be considered as a resource-saving alternative rather than as a strategy to maximize yields. Therefore, regimes of full mineral supply integrated with bio-inputs are strongly recommended for high-productivity systems, whereas mineral-only regimes should be reserved for input-limited conditions.

Hierarchical cluster analysis:

The hierarchical cluster analysis of the twelve treatments based on the standardized mean values of yield related traits as well as both fruit and juice quality traits on average of both seasons grouped the treatments into three major functional clusters based on overall agronomic desirability (Figure 4). The clustering pattern was in line with the PCA score and loading plots, which confirmed the robustness of trait-based discrimination of treatments.

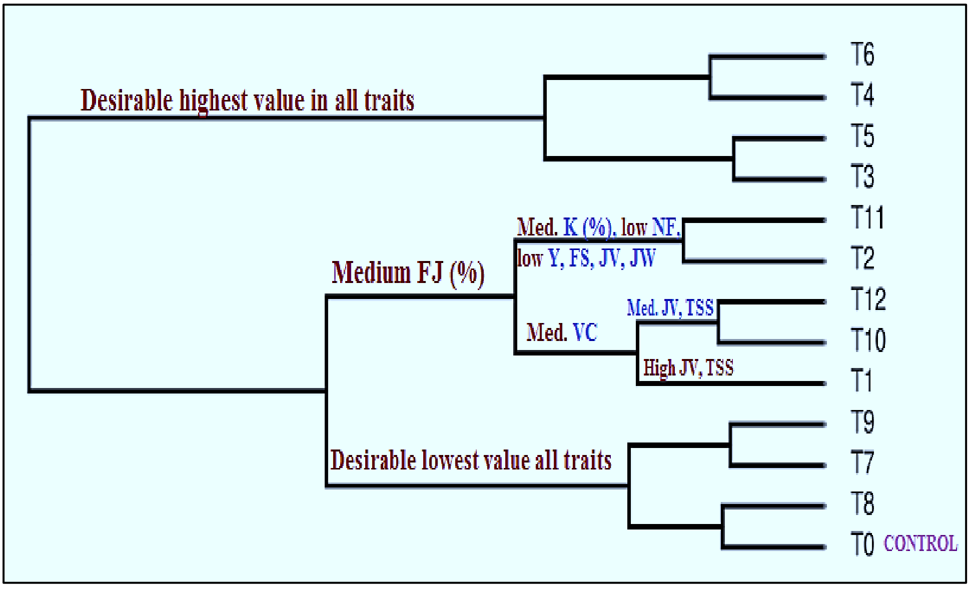


Figure 4: Hierarchical cluster analysis of treatments based on multi-trait performance

Cluster Interpretation Consistent with PCA

Cluster I: Treatments having high performance and agronomic superiority (Upper cluster: T6, T4, T5, T3).

This cluster is the most desirable cluster with high values for almost all measured traits including yield (Y), fruit size (FS), juice volume (JV), juice weight (JW), potassium (K) and vitamin C (VC) with reduced total acidity (TA). In this cluster, T6 and T4 formed a tight sub-cluster indicating strong multivariate similarity and overall dominance. This is consistent with the PCA results where these treatments were found in the positive quadrant of PC1, strongly associated with yield related traits (Y, FS, JV, JW) and quality attributes (TSS and VC), with loadings > 0.30, indicating strong positive contributions. Despite being somewhat worse than T6 and T4, treatments T5 and T3 were still included in the high-desirability cluster, demonstrating that mineral-based diet, either by itself or in conjunction with bio-inputs, can result in elite phenotypic performance. Interestingly, the inclusion of T3 (non-bio) in this cluster supports the PCA result that mineral nutrition dominated trait expression and that biological inputs were not always superior.

Cluster II: Intermediate performance with trait-specific advantages (T11, T2, T12, T10, T1) Middle cluster.

With treatments displaying acceptable but not maximal values for the majority of characteristics, this cluster reflects intermediate agronomic performance. Rather than general supremacy, this group is distinguished by characteristic specialization. In line with their PCA proximity to juice-related vectors, T12 and T10 were strongly linked to medium to high JV and TSS. Despite not reaching top yield or fruit size, T1 separated slightly because of high JV and TSS. In line with their negative or weak PC1 scores, T11 and T2 had medium potassium levels (K) but decreased nitrogen efficiency (NF) and lowered yield features. For this cluster, the annotation of medium FJ (%) and medium VC fully agrees with PCA loadings; VC did not dominate treatment separation and displayed moderate contributions (0.20–0.30).

Cluster III: The least attractive and low-performing therapies (T9, T7, T8, and T0 control in the lower cluster)

The least desired agronomic profiles are represented by this cluster, which unites treatments with consistently low values across yield, fruit size, juice characteristics, and quality criteria. The efficiency of the administered therapies in comparison to baseline circumstances is validated by the inclusion of the control (T0) at the far end of this cluster. Although treatments T7 and T9 slightly outperformed the control, they were still strongly linked to poor PC1 scores and modest associations with productive qualities. T8's close proximity to the origin and negative trait vectors in PCA further demonstrated its limited reactivity across all traits, as it grouped close to the control.

PCA-based synthesis:

The PCA results are completely supported by the dendrogram structure: High-performing (T6, T4) and low-performing (T0, T8) treatments were distinguished by PC_1 (productivity–quality axis). The internal structure of the intermediate cluster (T10, T12, T1) was explained by PC_2 (juice and quality differentiation). In both studies, treatments with moderate yield but high JV and TSS clustered together, indicating persistent multivariate behavior. The biological interpretation of trait interactions is supported, and the validity of treatment ranking is strengthened by this convergence between PCA and cluster analysis.

Agronomic Consequences

From a practical standpoint:

Elite treatments T6 and T4 are advised for simultaneously optimizing fruit quality and yield.

T5 and T3 are affordable substitutes and T3 show that great productivity can be attained without biological inputs.

When juice quality (TSS, JV) is more important than overall yield, intermediate treatments (T10, T12) might be appropriate.

Because of their persistently subpar multivariate performance, T7, T8, and the control are not advised for commercial manufacturing.

Final Thoughts

The importance of balanced nutrient management strategies in production systems is highlighted by the hierarchical clustering, which is consistent with PCA and clearly shows that overall agronomic superiority in oranges is driven by integrated enhancement of yield and quality traits rather than reliance on bio-inputs alone.

Discussion

Physiological integration of mineral potassium nutrition and biofertilization.

The results obtained here show that the physiological ceiling of orange tree performance is set by the availability of mineral potassium, and that bio-fertilization improves the efficiency of potassium acquisition and use within that ceiling. The best performance of the treatment T6 (100 units, 50% mineral K +

50% feldspar with bio-fertilizer) in both seasons indicates optimized balance between potassium supply, root uptake capacity and internal nutrient translocation. Potassium is an important regulator of phloem loading, enzyme activation, osmotic adjustment, and stomatal conductance, which in turn control carbon assimilation and assimilate partitioning in citrus. So, the remarkable increases in leaf K concentration, number of fruits, mass of fruits, and total yield under sufficient mineral K supply are ascribed to the improved photosynthetic efficiency and the enhanced translocation of carbohydrates from source leaves to developing fruit sinks. In citrus, similar physiological responses to potassium mineral fertilization have been widely reported, where the greater availability of K promotes the accumulation of leaf K, reproductive development and fruit quality attributes such as juice volume, total soluble solids and vitamin C, while simultaneously reducing fruit acidity by modulating the metabolism of organic acids (**Quaggio et al., 2006; Alva et al., 2006; Ashraf et al., 2010; Desai et al., 2014; Aly et al., 2015; Hafez et al., 2017; El-Tanany & Abdallah, 2019**).

The concurrent increase in fruit number, fruit size and yield indicated that the potassium-induced yield increase was due to increased sink establishment (flower retention and fruit set) and sink strength (more assimilate allocation per fruit). The reduction in total acidity observed, especially under T6 and complete mineral K treatments, further demonstrates that potassium nutrition favored a metabolic shift toward sugar accumulation, and controlled degradation or dilution of organic acids during fruit development, resulting in better sensory and processing quality without affecting yield. These physiological processes were vastly intensified by bio-fertilization but could not substitute the need to supply the plant with adequate mineral potassium. Treatments with bio-inputs and reduced levels of mineral K (T10–T12) always showed lower performance than full mineral treatments, indicating that microbial activity contributes mainly to potassium solubilization, root absorption and rhizosphere nutrient availability, rather than being an independent source of nutrients. This interpretation is consistent with previous reports that bio-potassium fertilizers increase leaf K concentration, fruit yield and quality traits, but still rely on an adequate basal mineral K supply for maximal physiological function (**El-Salhy et al., 2017; Abdallah, 2021; Wen et al., 2021**). The stability of treatment responses across the seasons further supports the view that integrated mineral–bio potassium nutrition builds a resilient physiological framework, able to sustain efficient nutrient uptake, assimilate partitioning and fruit quality formation under varying environmental conditions.

Physiological and agronomic consequences

Mechanistically, the combination of full mineral potassium fertilization with bio-inputs (T6) is the most efficient in optimizing the intensity of nutrients supply and nutrient-use efficiency leading to maximum photosynthetic output, sink development and fruit biochemical quality. Thus, reduced mineral potassium strategies should be considered as efficiency or sustainability options, not as yield-maximizing options in systems with high citrus production, even if they are supported by bio-fertilizers.

Conclusion

The study highlights that the performance of orange trees is primarily constrained by mineral potassium availability, with bio-fertilization enhancing potassium acquisition and utilization. Treatment T6, combining 50% mineral potassium with 50% feldspar and bio-fertilizer, yielded optimal results, indicating a balance between potassium supply and nutrient uptake. Improvements in leaf potassium concentration, fruit number, size, and yield are linked to enhanced photosynthesis and nutrient translocation. The combination of mineral and bio-potassium fertilizers is identified as the most effective approach for maximizing photosynthetic efficiency and fruit quality, with the need for adequate mineral potassium remaining crucial even when using bio-fertilizers. Overall, while bio-fertilization benefits potassium solubilization and nutrient availability, it cannot replace the necessity for sufficient mineral potassium in citrus production systems..

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