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Effect of foliar potassium spraying on productivity and quality of grape fruits (*Vitis vinifera*) under different irrigation levels

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ABSTRACT

The escalating scarcity of water resources poses a significant challenge to global agriculture, threatening the yield and quality of high-value crops such as grapes (Vitis vinifera). Using a trellis system, grapes are not only consumed fresh but are also critical raw materials for products like juices, wines, and raisins, where consistent quality, sugar content, and phytochemical composition are paramount. Sustainable strategies to mitigate water stress effects and enhance fruit quality are therefore of immense industrial interest. This study investigated the efficacy of foliar potassium (K) application as a practical agricultural strategy to ameliorate the adverse effects of different irrigation levels on grape productivity and, more importantly, on key quality attributes relevant to the food processing industry. A field experiment was conducted following a factorial arratement based on a Randomized Complete Block Design (RCBD). Grapevines were subjected to two irrigation levels (100%, 75%, and 50% of crop evapotranspiration - Etc.) and three concentrations of foliar potassium (0.0%, 0.5%, 1.0%, 1.5% K2O). Parameters measured included yield, cluster weight, and a comprehensive set of quality traits: total soluble solids (TSS), titratable acidity (TA), pH, berry firmness, and the concentration of anthocyanins and total phenolics. Water deficit significantly reduced yield but enhanced most quality parameters. The 50% Etc. treatment led to a notable increase in TSS, TSS/TA ratio, and anthocyanin content. Foliar potassium application, particularly at 2%, effectively mitigated yield losses under stress and synergistically improved quality. The interaction between 75% Etc. and 2% K spray resulted in an optimal balance, achieving a yield comparable to full irrigation while significantly boosting TSS, phenolic content, and color intensity—attributes highly sought after for premium wine and juice production. The integrated management of deficit irrigation (75% Etc.) and foliar potassium nutrition (2%) presents a viable and sustainable strategy for the grape industry. This approach not only conserves water but also directs the plant's metabolism towards producing grapes with superior techno-functional quality, enhancing their suitability for high-value processed food products and contributing to the sustainability of agricultural practices.

1-Introduction

Grape (Vitis vinifera L.) is one of the world's most economically significant fruit crops, with its value extending far beyond fresh consumption. The fruit serves as a fundamental raw material for a multi-billion-dollar industrial sector, encompassing wine, juice, jam, and dried fruit production [1]. The quality of these derived products is intrinsically linked to the biochemical and physical attributes of the fresh grapes, including sugar concentration (as °Brix), organic acid profile, phenolic content, and color intensity [2]. Consequently, agricultural practices that optimize this quality parameters are of direct interest to the food industry. A major contemporary threat to sustainable grape production is water scarcity. Deficit irrigation strategies have been widely adopted as a water-saving technique [3]. While known to reduce yield, controlled water stress can positively influence fruit quality by concentrating sugars and stimulating the biosynthesis of secondary metabolites, such as anthocyanins and polyphenols, which are crucial for color, flavor, and health-promoting properties in final products [4]. However, severe water stress can be detrimental to both plant vitality and economic return, necessitating complementary strategies to balance productivity with quality enhancement [5].

Potassium, a vital macronutrient, plays a pivotal role in mitigating abiotic stress and improving fruit quality. Its functions include osmoregulation, stomatal control, and the activation of key enzymes involved in sugar and phenolic compound metabolism. In grapes, adequate K nutrition is associated with improved berry size, sugar accumulation, and color development [6]. Foliar application of potassium offers a rapid and efficient method to supply this nutrient directly to the fruit and leaves, especially under soil moisture limitations where root uptake is compromised. While the individual effects of irrigation regimes and potassium nutrition have been studied separately, their interactive impact on the quality parameters most relevant to industrial processing remains less explored [7]. Most prior research focuses on agronomic yield or basic quality metrics, often neglecting the specific techno-functional traits (e.g., firmness, phenolic profile) that determine the suitability of grapes for different processing streams. Therefore, this study was designed with a clear food industry-oriented perspective [8]. We hypothesize that foliar application of potassium can synergistically interact with regulated deficit irrigation to not only alleviate yield reduction but also to actively tailor the biochemical composition of grape berries for enhanced industrial value. The specific objectives were to quantify the main and interactive effects of different irrigation levels and foliar potassium sprays on grape yield, and on a comprehensive profile of quality attributes, including total soluble solids, acidity, pH, firmness, and the concentration of anthocyanins and total phenolics. The findings aim to provide a scientifically-grounded, practical protocol for producing premium-quality raw materials for the food industry under water-limited conditions.

2-Materials and Method

2.1. Experimental Site and Plant Material

The field trial was conducted during the 2024 growing season in a commercial vineyard located in Diyala Governorate, Iraq. The experimental vines were seven-year-old *Vitis vinifera* L. cv. Halawani, trained on a vertical trellis system with a planting density of 2.5 m (within-row) × 3.0 m (between rows), equating to approximately 1,333 vines per hectare. The soil at the site is classified as a well-drained loam. Standard viticultural practices, including dormant pruning, canopy management, weed control, and pest/disease management, were applied uniformly to all experimental vines throughout the season.

2.2. Experimental Design and Treatments

The experiment was established as a two-factorial randomized complete block design (RCBD) with three replications (blocks). Each experimental unit (plot) consisted of three contiguous vines. The two factors investigated were:

1. **Irrigation Level (I):** Two deficit irrigation regimes were applied.
   - **I_1 (Full Irrigation):** 100% of the crop evapotranspiration (Etc.).
   - **I_2 (Deficit Irrigation):** 50% of Etc.

Irrigation scheduling was based on the standard FAO-56 Penman-Monteith method for reference evapotranspiration (Eto) [9]. Daily Eto was calculated using meteorological data (solar radiation, temperature, humidity, and wind speed) from a nearby automated weather station. The crop coefficient (Kc) values were applied according to the phenological stage of the grapevine (initial, development, mid-season, and late season) to determine Etc. (Etc. = Eto × Kc). Drip irrigation was used to deliver the calculated water volume weekly.

2. **Potassium Foliar Application (K):** Four concentrations of potassium sulfate (K_2SO_4, 0-0-50) were applied.
   - **K_0 (Control):** 0.0% K_2SO_4 (distilled water spray only).
   - **K_1:** 0.5% K_2SO_4 (w/v).
   - **K_2:** 1.0% K_2SO_4 (w/v).
   - **K_3:** 1.5% K_2SO_4 (w/v).

This resulted in eight treatment combinations (2 Irrigation levels × 4 K concentrations) replicated three times.

2.3. Application of Treatments

Irrigation: The differential irrigation regimes were initiated at berry set (EL Stage 27; Eichhorn and Lorenz system) and maintained until harvest.

Foliar Sprays: Potassium sulfate solutions were prepared in distilled water with 0.1% (v/v) non-ionic surfactant (Tween® 20) to ensure adequate leaf coverage and adhesion. Foliar applications were made using a calibrated backpack sprayer until runoff, targeting both sides of the leaves. Applications were timed to three key phenological stages:

1. **Spray 1:** Immediately after fruit set (EL Stage 29).
2. **Spray 2:** At the onset of veraison (EL Stage 35).

3. **Spray 3:** Twenty days after the second spray (approximately three weeks pre-harvest).

Control plots (K_0) were sprayed with distilled water and surfactant at the same times.

2.4. Data Collection

Measurements were taken at three phenological stages: Stage 1 (post-fruit set), Stage 2 (veraison), and Stage 3 (three weeks pre-harvest).

2.4.1. Physiological Parameters

- **Leaf Water Potential (Ψ_l):** Measured at solar noon (± 2 hours) on clear days using a pressure chamber (Model 1000, PMS Instrument Company, USA). One fully expanded, sun-exposed leaf per replicate vine was selected, excised, and measured immediately following the protocol of Scholander et al. (1965) [12].
- **Leaf Gas Exchange:** Net photosynthetic rate (P_n), stomatal conductance (g_s), and transpiration rate (E) were measured between 09:00 and 11:00 h using a portable infrared gas analyzer (LI-6400XT, LI-COR Biosciences, USA). Measurements were taken on the most recent, fully expanded, sun-exposed leaves under ambient CO_2 concentration, photosynthetic photon flux density (PPFD) set to 1500 µmol $m^{-2}\ s^{-1}$, and block temperature set to 30°C.
- **Leaf Chlorophyll Index:** Estimated using a portable chlorophyll meter (SPAD-502Plus, Konica Minolta, Japan). The average of three readings from three different leaves per experimental vine was recorded.

2.4.2. Yield and Fruit Quality Parameters

At commercial harvest maturity (determined by stable total soluble solids and berry color):

- **Yield Components:** Total cluster number and total fruit weight (kg) per vine were recorded.
- **Berry Quality:** A random sample of 100 berries was collected from each plot for analysis.
  - **Total Soluble Solids (TSS):** Determined in freshly extracted juice using a digital refractometer (Atago PAL-1, Japan) and expressed as °Brix.
  - **Titratable Acidity (TA):** Analyzed by titrating 10 mL of juice with 0.1 N NaOH to an endpoint of pH 8.2 and expressed as grams of citric acid equivalent per 100 mL of juice [11].

3-Data analysis

The data were statistically analyzed as in the first part of the study, using two-way ANOVA to test the effects of irrigation, potassium spray, and their interaction. The means were then compared using the LSD test at a 5% probability level.

4-Results

The effect of irrigation and potassium on productivity and quality

The results in Table (1) and figure (1) showed that grape yield under full irrigation (100% Etc.) rated between 9.80 and 11.30 kg/vine, with the highest value in T3 when sprayed with 1.0% K_2SO_4, while yields decreased significantly under water stress (50% Etc.) to 6.50 kg/vine in T5, potassium fertilization gradually increased yields to 8.30 kg/vine in T7. These results are consistent with [15], who reported that water shortages reduce plant growth and yield, while potassium helps improve plant tolerance to water stress. The number of clusters per vine (clusters/vine) gradually increased with increasing potassium concentration under full irrigation, ranging from 11 to 14 clusters in T1–T4. However, under water stress, yields dropped to 11 to 13 clusters. There was a notable improvement when potassium fertilization was used. This finding aligns with Mengel & Kirkby, 2001, who stated that potassium improves nutrient balance and positively affects cluster formation. Full irrigation treatments showed relatively lower TSS values, ranging from 17.2 to 17.8 °Brix, compared to water stress, where values increased to 18.3 to 19.6 °Brix. Meanwhile, TA decreased under full irrigation from 0.66 to 0.62 g citric per 100g, as K_2SO_4 concentration increased. Acidity was slightly higher under water stress, reaching 0.72–0.67 g citric/100g. Our results show that water stress lowers the relative water content of the fruit and raises the sugar concentration. Previous studies have confirmed this finding [16].

Table 1. Effect of irrigation and potassium on grape productivity and quality

Treatment	**Irrigation**	**K2SO4 (%)**	**Yield (kg/vine)**	**Clusters/ vine**	**TSS (°Brix)**	**TA (g citric/100g)**	**RWC (%)**	**Leaf K (mg/kg DW)**
T1	100% ETc	0.0	9.80 ± 0.80	11 ± 1	17.2 ± 0.6	0.66 ± 0.04	87.2 ± 1.7	2150 ± 125
T2	100% ETc	0.5	10.50 ± 0.90	12 ± 1	17.5 ± 0.4	0.64 ± 0.03	88.5 ± 1.5	2320 ± 120
T3	100% ETc	1.0	11.30 ± 1.00	13 ± 1	17.8 ± 0.4	0.62 ± 0.03	89.4 ± 1.5	2600 ± 130
T4	100% ETc	1.5	11.00 ± 0.90	14 ± 1	17.6 ± 0.4	0.63 ± 0.02	88.7 ± 1.6	2550 ± 130
T5	50% ETc	0.0	6.50 ± 0.80	11 ± 1	18.3 ± 0.6	0.72 ± 0.04	75.0 ± 2.1	1950 ± 120
T6	50% ETc	0.5	7.40 ± 0.70	12 ± 1	19.2 ± 0.5	0.68 ± 0.03	77.0 ± 2.2	2100 ± 130
T7	50% ETc	1.0	8.30 ± 0.80	12 ± 1	19.6 ± 0.5	0.67 ± 0.03	78.7 ± 1.9	2350 ± 120
T8	50% ETc	1.5	8.00 ± 0.90	13 ± 1	19.4 ± 0.4	0.68 ± 0.04	78.0 ± 1.8	2275 ± 130

Similarly, full irrigation treatments recorded the highest averages for relative water content in leaves (RWC) at 87.2 to 89.4%. The levels dropped significantly under water stress to 75.0% in treatment T5. However, the averages gradually improved, reaching 78.7% in T7 when potassium was applied. This shows how potassium helps improve leaf water retention during drought conditions. These findings align with results from Brandt at 2025 [17].

As for the potassium concentration in the leaves (Leaf K), it increased significantly with increasing the applied concentration in the spray, ranging between 2150–2600 mg/kg DW under full irrigation, while it decreased under water stress to 1950 mg/kg DW in T5, and with increasing the K_2SO_4 concentration, it improved to reach 2350 mg/kg DW in T7, confirming the effectiveness of foliar spray in improving plant potassium nutrition even under water-deficient conditions. This is consistent with what was found by [18,19].

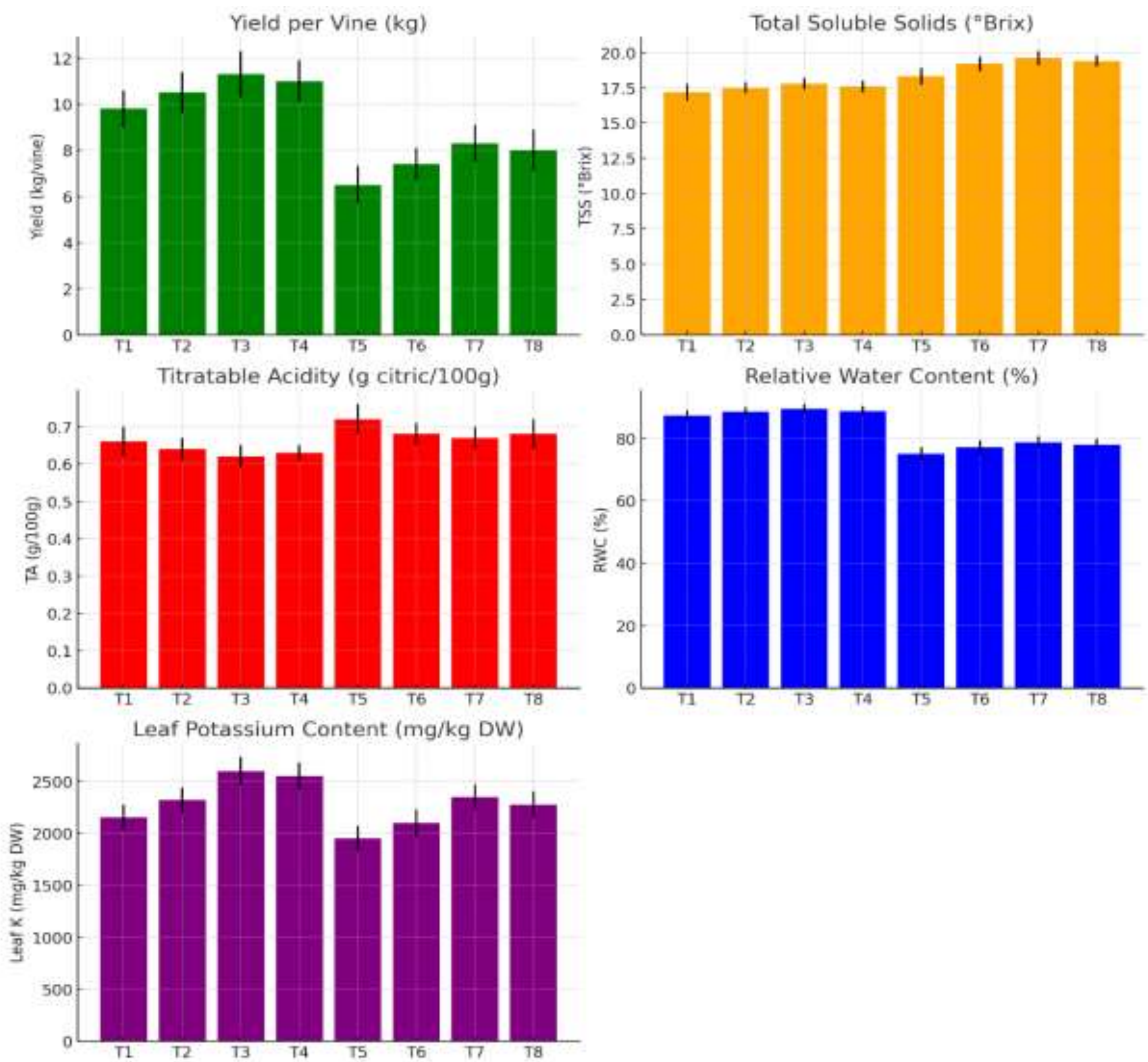

Figure 1. Effect of irrigation levels and foliar potassium application on yield, fruit quality, and physiological traits of grapevine

The effect of irrigation and potassium on the physiological indicators

The results in Table (2) and figure (2) showed that the leaf water potential (Leaf) values under full irrigation (100% ETc) rated between -0.73 and -0.69 MPa (T1–T4), while they decreased significantly under water stress (50% ETc) to rate between -1.07 and -0.92 MPa (T5–T7). These results are consistent with what was indicated by [15] that water shortage leads to a clear decrease in leaf due to a decline in water absorption efficiency.

As for chlorophyll content (SPAD), the full irrigation treatments recorded higher values (39-43 units), with the highest being in T3 (43 units) when sprayed with 1.0% K_2SO_4, the values dropped to 35 units under water stress in T5. However, spraying with potassium increased them to 39 units in T7. This result is consistent with what was stated by Imtiaz *et al* (2023) [20] that potassium contributes to enhancing chlorophyll synthesis and maintaining the stability of cell membranes, which reduces chlorophyll degradation under water stress.

Table 2. Physiological indicators of grapes under the influence of potassium foliar spray and water stress

Treatment	Irrigation	K_2SO_4 (%)	leaf (MPa)	SPAD (Unit)	Transpiration rate (mmol $H_2O/m^2·s$)	Stomatal Conductance (mmol/$m^2·s$)
T1	100% ETc	0.0	-0.73 ± 0.04	39 ± 3	4.9 ± 0.2	152 ± 12
T2	100% ETc	0.5	-0.71 ± 0.05	41 ± 3	5.1 ± 0.2	155 ± 10
T3	100% ETc	1.0	-0.69 ± 0.02	43 ± 2	5.6 ± 0.2	161 ± 11
T4	100% ETc	1.5	-0.69 ± 0.05	41 ± 3	5.2 ± 0.4	159 ± 10
T5	50% ETc	0.0	-1.07 ± 0.06	35 ± 3	3.5 ± 0.3	112 ± 12
T6	50% ETc	0.5	-0.98 ± 0.06	37 ± 3	3.5 ± 0.3	120 ± 10
T7	50% ETc	1.0	-0.92 ± 0.05	39 ± 2	3.8 ± 0.2	128 ± 11
T8	50% ETc	1.5	-0.95 ± 0.06	38 ± 3	3.8 ± 0.2	130 ± 10

Regarding the transpiration rate, it reached 4.9–5.6 mmol $H_2O/m^2•s$ in the full irrigation treatments, with the highest value in T3 (5.6 mmol $H_2O/m^2•s$), while it decreased to 3.5 mmol $H_2O/m^2•s$ in the T5 treatment (50% ETc without spray). Potassium spraying helped gradually increase transpiration under stress to reach 3.8 mmol $H_2O/m^2•s$ at T7 and T8. These results are consistent with what was reported by Cakmak 2005 [15] who showed that potassium enhances the regulation of stomatal opening and closing, thus maintaining transpiration rates even under drought conditions.

Stomatal conductance recorded the highest values under full irrigation (152–161 mmol/m²•s), while it decreased significantly to 112 mmol/m²•s in T5. With increasing potassium concentrations under water stress, the values gradually increased to reach 130 mmol/m²•s in T8. Previous studies such as [21] have confirmed that potassium plays a major role in stomatal efficiency and improving stomatal conductance under water stress.

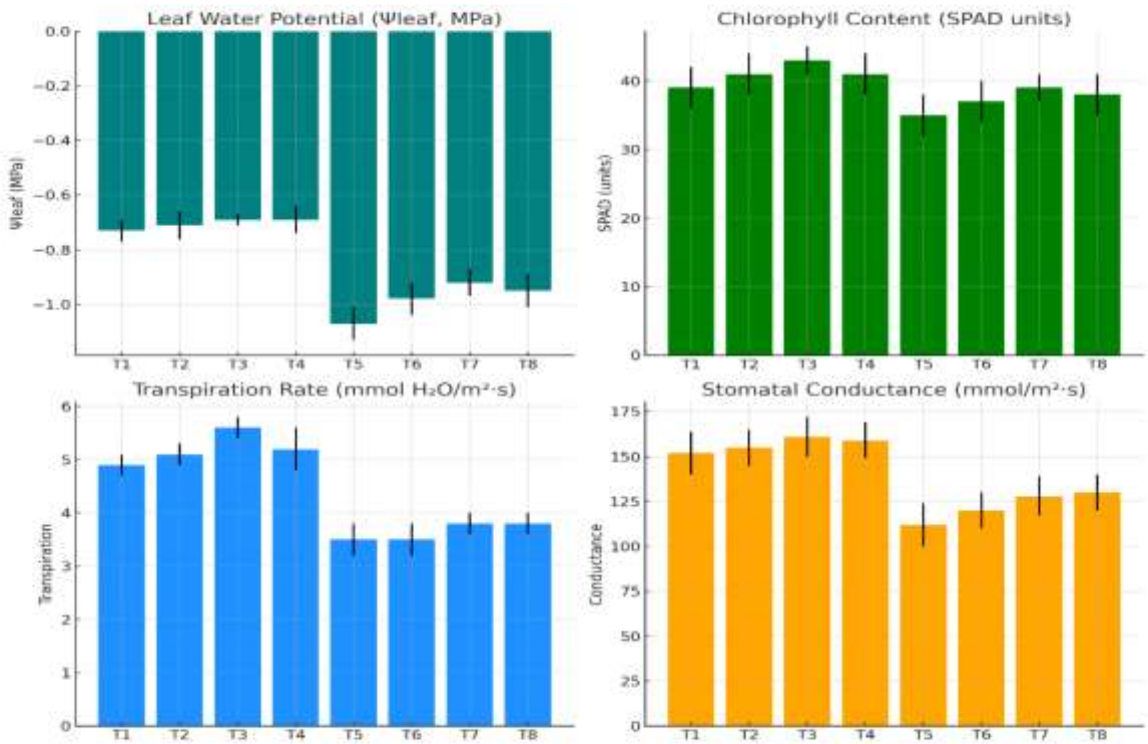

Figure 2. Physiological indicators of grapes under the influence of potassium spraying and water stress

5-Conclusion

The results showed that full irrigation improved grape yield and quality. It led to higher yields, more cluster count, and increased relative water content. In contrast, water stress caused a significant drop in these indicators. However, applying potassium through the leaves, especially at a concentration of 1.0% K_2SO_4, helped reduce the negative effects of water shortages. It improved chlorophyll content, increased transpiration rates and stomatal conductance, and increased potassium concentrations in leaves, which positively impacted water use efficiency and drought tolerance. Foliar application of potassium can be an effective way to improve grape yield and quality when irrigation is limited. In conclusion, the foliar application of potassium is not merely a corrective measure for nutrient deficiency but a strategic tool for "quality priming" under water-scarce conditions. We recommend the adoption of the 75% ETc + 2% K protocol as a best management practice for vineyards supplying the high-value food processing sector. Future research should focus on the economic feasibility analysis of this practice and its impact on the sensory attributes and shelf-life of the specific processed products (e.g., wine, juice) derived from grapes cultivated under this sustainable regime.

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