Physiology and Management of Sustainable Crops
https://www.sciltp.com/journals/pmsc

Article

Searching for an Optimized Potassium Fertilization in Grapevine (*Vitis vinifera* L.) cv. Tempranillo with an Emphasis on Berry Quality and Nutrient Composition

Carolina Salazar-Parra [1,*] and Fermín Morales [2]

[1] Instituto de Investigaciones Agropecuarias, INIA La Platina, Santa Rosa 11610, La Pintana, Santiago 8820808, Chile
[2] Instituto de Agrobiotecnología (IdAB), CSIC-Gobierno de Navarra, Avenida de Pamplona 123, 31192 Mutilva, Spain
* Correspondence: carolina.salazar@inia.cl

How To Cite: Salazar-Parra, C.; Morales, F. Searching for an Optimized Potassium Fertilization in Grapevine (*Vitis vinifera* L.) cv. Tempranillo with an Emphasis on Berry Quality and Nutrient Composition. *Physiology and Management of Sustainable Crops* **2025**, *1*(1), 7. https://doi.org/10.53941/pmsc.2025.100007

Received: 6 June 2025
Revised: 7 October 2025
Accepted: 22 November 2025
Published: 12 December 2025

Abstract: Potassium (K) is an essential macronutrient that plays a central role in grapevine physiology and fruit quality. This study aimed to evaluate the effects of different K concentrations in the nutrient solution on berry composition, color development, and mineral concentration in leaves, petioles, and berries of fruit-bearing cuttings of *Vitis vinifera* L. cv. Tempranillo. Fruit-bearing cuttings were grown under controlled greenhouse conditions and irrigated with modified half-strength Hoagland solutions containing 0%, 25%, 50%, 75%, or 100% K and a control nutrient solution. Berry quality parameters, including total soluble solids, acidity, anthocyanins, and phenolic maturity, were significantly influenced by K availability. Moderate K treatments (50–75%) produced the most favorable outcomes in terms of sugar accumulation, anthocyanin concentration, and nutrient balance. The results suggest that optimized K fertilization is critical for improving grape quality while avoiding potential negative effects associated with deficiency or excess. These findings provide valuable insights for K management in viticulture.

Keywords: potassium nutrition; grapevine physiology; berry quality; *Vitis vinifera*; macronutrients; micronutrients

1. Introduction

Grapevine is an economically important crop in Spain and in the world. *Vitis vinifera* L. cv. Tempranillo is the most internationally recognized Spanish variety, known for its high-quality red wines [1]. The development and growth of grapevine are influenced by multiple environmental factors. Throughout the annual growth cycle, climatic conditions, soil type, and nutrient availability are key determinants of both yield quantity and fruit quality [2].

Fourteen mineral elements are considered essential for higher plant growth: six macronutrients (N, P, K, Ca, Mg, S) and eight micronutrients (Fe, Mn, Zn, Cu, Cl, B, Mo, Ni). In the field, grapevines can be fertilized to enhance fruit quality; however, their nutrient requirements during the fruit load stage are relatively low. Plants have limited, regulated capacity for absorbing essential minerals and may also take up non-essential or potentially toxic elements [3–5]

The nutritional status of grapevines is commonly evaluated through leaf and petiole chemical analysis, which indicates the plant capacity to absorb and allocate mineral nutrients. These tissues serve as sensitive indicators of macro- and micro-nutrient availability and are generally used for nutritional diagnosis in viticulture [6,7]. Comparing mineral concentrations against established reference values enables the detection of deficiencies or imbalances that could limit vegetative growth or impair fruit development [2].

The transport of nutrients such as carbon (C), nitrogen (N), and potassium (K) to fruits occurs primarily through the phloem rather than the xylem [8]. In grape berries, phloem imports increase sharply during ripening and cellular compartment breakdown [9]. These processes are regulated by various transporter-mediated mechanisms that determine the quantity and distribution of nutrients within the plant [2].

The benefits in agriculture of applying mineral elements to the soil have been known for more than 2000 years. By the late 19th century, especially in Europe, large quantities of potassium, superphosphate, and inorganic nitrogen were widely used in agriculture and horticulture to enhance plant growth [3]. While fertilization generally improves vineyard performance, excessive or unbalanced applications can negatively affect grape and wine quality [10]. However, excessive potassium fertilization in vineyards and other irrigated agroecosystems can contribute to soil and groundwater salinization, particularly when K is applied as potash salts such as KCl [11].

Potassium is a highly mobile macronutrient within the plants that serves as an enzyme activator, anion neutralizer, and key player in membrane transport, assimilate translocation, and osmotic regulation [12,13]. In grapevine, K enhances shoot growth, increases resistance to disease and cold, promotes sugar and starch accumulation in berries and woody tissues, and contributes to water status regulation and acidity control in berries through enzymatic activation [4]. Moreover, its function extends to the activation of specific membrane channels, which facilitate the loading and unloading of K^+ in the phloem and support sugar movement to the berries during ripening [14].

Potassium deficiency in grapevines leads to the accumulation of soluble carbohydrates, reduced starch levels, and increased concentrations of soluble N compounds in leaves [14]. Potassium deficiency commonly manifests as interveinal chlorosis, marginal leaf burn, and leaf edge curling, especially in older leaves, often progressing to necrosis and premature defoliation [4]. Physiologically, K-deficient grapevines have reduced stomatal conductance and smaller leaf area, which limit transpiration and photosynthetic efficiency, ultimately affecting grapevine vigor and fruit development [15].

Adequate potassium nutrition has been shown to improve grape quality. Potassium enhances berry color and polyphenol concentration [16], stimulates photosynthesis, and facilitates sugar transport to the fruit, favoring the synthesis of phenolic compounds during ripening. Potassium (K^+) is also the most abundant cation in the grape berry at all stages of its development [17,18]. However, excessive potassium may negatively affect must quality. Although high pH does not reduce the total anthocyanin concentration, it can alter color expression and intensity [19].

Some authors have reported in cv. Tempranillo that excessive potassium accumulation can reduce berry acidity and increase must pH, thereby affecting color stability and wine quality. High K levels have been associated with tartaric acid loss and reduced must color intensity, although without significant changes in total anthocyanin concentration [10,12]. These effects emphasize the importance of optimizing K supply to balance berry composition.

Based on this evidence, the present study aimed to evaluate the influence of different K application rates on grape quality and the nutritional status of leaves, petioles, and berries in *Vitis vinifera* L. cv. Tempranillo.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

Dormant cuttings of *Vitis vinifera* L. cv. Tempranillo were obtained from an experimental vineyard of the Station of Viticulture and Enology of Navarra (Olite, Navarra, Spain). Fruit-bearing cuttings were selected according to Mullins [20] , with modifications by Ollat et al. [21] and Santa María [22]. Readers are referred to Morales et al. [23] for a detailed description of the grapevine fruit-bearing technique. Rooting was conducted in a heat-bed at 27 °C in a cool room maintained at 5 °C. After one month, the cuttings were transferred to 4L plastic pots filled with a 2:1 peat-to-perlite (*v*/*v*) mixture and moved to a greenhouse. Only one flowering stem was allowed to develop per plant. Greenhouse conditions were set at 26/15 °C (day/night), 60–70% relative humidity, and a 15-h photoperiod with natural daylight.

2.2. Experimental Design

Until inflorescence emergence, all plants were irrigated with water. Thereafter, plants were divided into six treatments (four plants per treatment; see Figure 1), each receiving a different K concentration in the nutrient solution. Control plants were irrigated following the nutrient protocol proposed by Ollat et al. [21], in which K was supplied only after fruit set. This protocol has been previously applied in experiments with fruit-bearing cuttings, and empirical observations indicated that fruit set was more successful under this approach. Therefore, it was adopted in the present study. The composition of the control nutrient solution is shown in Table 1.

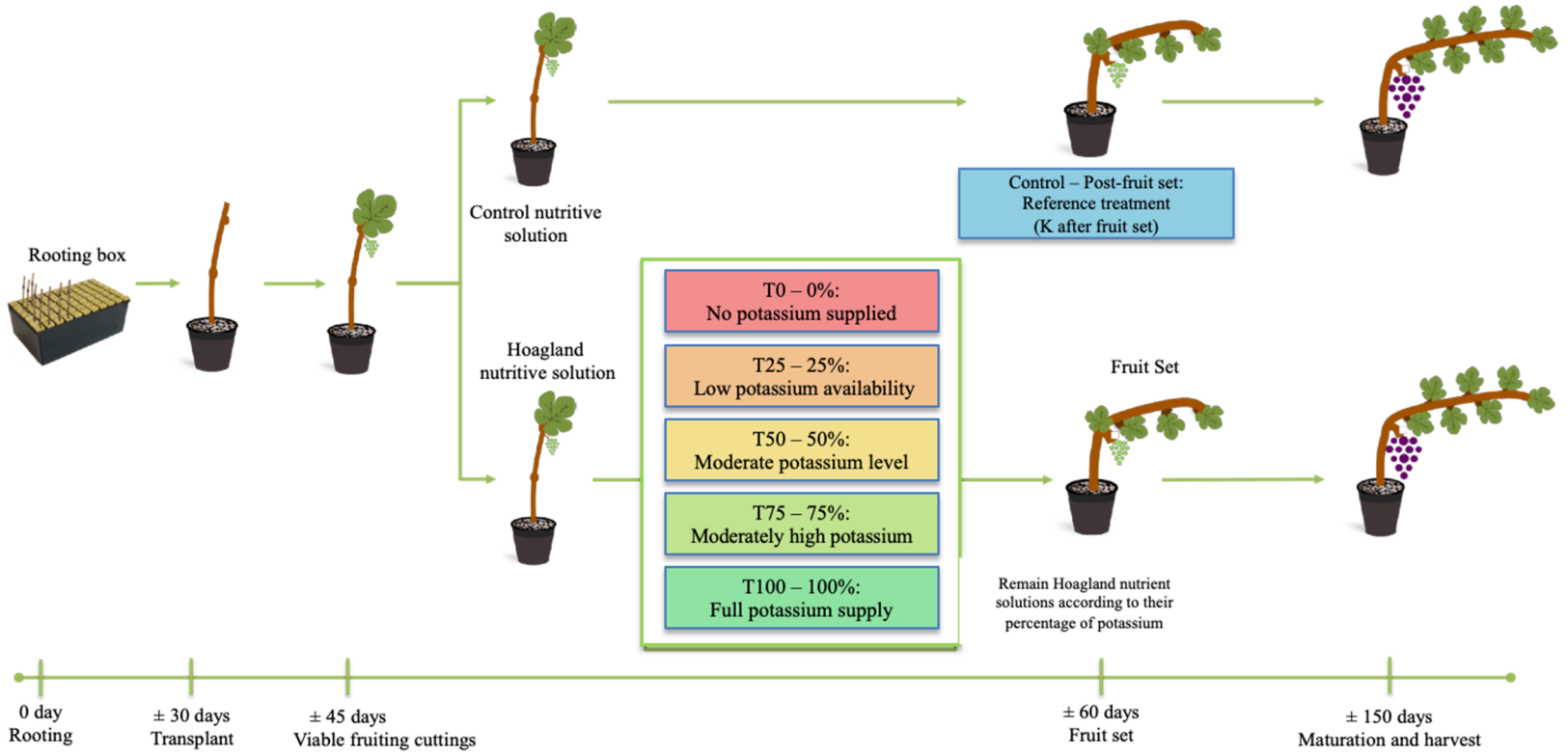

Figure 1. Experimental design. Fruit-bearing cuttings of *Vitis vinifera* cv. Tempranillo were divided into treatment groups. (i) Control (baseline K) plants were irrigated with the nutrient solution described by Ollat et al. [21] without potassium (K) supply until fruit set, after which K was added. (ii) Other groups were irrigated with half-strength Hoagland solution containing five different K concentrations: (include 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). All plants were grown under controlled greenhouse conditions and harvested at ripeness (>20 °Brix), approximately 150 days after planting.

Other treatments were irrigated with modified half-strength Hoagland nutrient solutions containing 0%, 25%, 50%, 75%, or 100% K [24]. Nutrient solutions were pH-adjusted to 6.0 using phosphoric acid and balanced to maintain consistent macronutrient levels (see Table 2). Plants remained under these treatments until ripening, defined as 21–23 °Brix. A detailed experimental design is shown in Figure 1, which includes all phenological phases and their duration. At harvest, bunch weight and berry count were recorded. Samples were immediately frozen and stored at –80 °C for later analysis.

Table 1. Mineral composition of the control nutrient solution (Ollat et al. [21]), used to irrigate control plants after fruit set.

Element	Concentration (mg L^{-1})
N	99.6
P	17.6
K	49.9
Ca	42.1
Mg	12.3
K/Mg	4.05
N/P	5.66

Table 2. Mineral composition of the nutrient solutions used to irrigate K-treated plants from the emergence of the inflorescence. Micronutrients were not modified.

	100% K	75% K	50% K	25% K	0% K
	Half Hoagland (mM)	Half Hoagland (mM)	Half Hoagland (mM)	Half Hoagland (mM)	Half Hoagland (mM)
KNO_3	2.5	2.5	1.75	0.88	0
$MgSO_4$ $7H_2O$	1.0	1.0	1.11	1.23	1.36
KH_2PO_4	1.0	0.10	0	0	0
$Ca(NO_3)_2$ $4H_2O$	2.5	2.77	2.77	3.08	3.39
$(NH_4)_2HPO_4$	0.0	1	1	1	1

2.3. Berry Composition Assessment

For each treatment and harvest, 3–4 subsamples of 25 berries were crushed (skins and seeds removed), centrifuged, and the supernatants were used for analysis. Total soluble solids (°Brix) were measured using a digital ABBE refractometer (Zuzi model no. 315). pH was recorded using a standard pH meter. Total acidity was determined by titrating 10 mL of extract against 0.1 N NaOH and expressed as tartaric acid equivalents. Malic acid was quantified enzymatically (Enzytec L-Malic Acid, Boehringer Mannheim/R-Biopharm). Color index was determined by absorbance at 420, 520, and 620 nm. Tonality index was calculated as A_{420}/A_{520} and color intensity as the sum $A_{420} + A_{520} + A_{620}$.

Additional subsamples (3–4 of 40 berries) were used to assess tannins and phenolic maturity according to Glories and Augustin [25]. Tannins were quantified by methyl cellulose precipitation (AWRI Standard Methods). Maceration was conducted for 4 h using two buffer solutions: pH 3.2 (tartaric acid, simulating winemaking conditions) and pH 1.0 (HCl, for total anthocyanin extraction). After centrifugation, phenolic richness was assessed at 280 nm (A280), and anthocyanins at 520 nm for both pH values. Cellular extractability was calculated by: $(EA\%) = [(A_{pH1} - A_{pH3.2})/A_{pH1}] \times 100$; phenolic maturity $(Mp\%) = [(A_{280} - (A_{pH3.2} \times 40)/1000)/A_{280}] \times 100$. Absorbances were measured with a Hitachi U-2001 spectrophotometer (Hitachi Instruments Inc., Hillsboro, OR, USA).

2.4. Flower Count and Fruit Set Calculation

Fruit set (%) was calculated as the ratio between the number of berries and the total number of flowers per inflorescence, which were manually counted under a magnifying glass and counting prior to anthesis.

2.5. Mineral Analysis

Three samples each of leaves, petioles, and berries per treatment were dried at 85 °C and analyzed following standard AOAC protocols [26] and methods described by Abadía et al. [27,28]. Nitrogen and P were determined via the Kjeldahl method and spectrophotometry, respectively. Potassium was analyzed by flame emission spectroscopy. Calcium, magnesium, iron, manganese, copper, and zinc were measured by atomic absorption

spectrophotometry. Macronutrient results were expressed as % dry weight (DW) and micronutrients as mg kg^{-1} DW. For graphical representation, nutrient concentrations were normalized by dividing each mean value by the maximum observed for that element, allowing a proportional comparison among treatments. Normalized values were then used to construct radar charts.

2.6. Statistical Analysis

One-way ANOVA followed by Fisher's LSD post-hoc test was applied to detect differences among treatments ($p < 0.05$). Results are expressed as mean ± standard error. Data exceeding ±2 standard deviations were excluded. All statistical analyses were performed using GraphPad Prism version 9.0 (GraphPad Software, San Diego, CA, USA). Radar charts were constructed using Python 3.10 and the matplotlib library to visualize normalized macronutrient and micronutrient levels across treatments. Significant differences are indicated in the accompanying table as mean ± standard desviation.

3. Results

3.1. Berry Weight and Fruit Set

The weight of 100 berries (Figure 2A) was used as an indicator of berry size. According to LSD test, only the 0% K treatment showed a significantly lower berry weight ($p < 0.05$) with respect to the control, while the other treatments exhibited lower mean values compared to the control, but these differences were not statistically significant. The fruit set index (Figure 2B) did not show statistically significant differences among treatments. However, the 50% K treatment had a slightly lower average compared to the control and 100% K treatments, although this difference was not statistically significant.

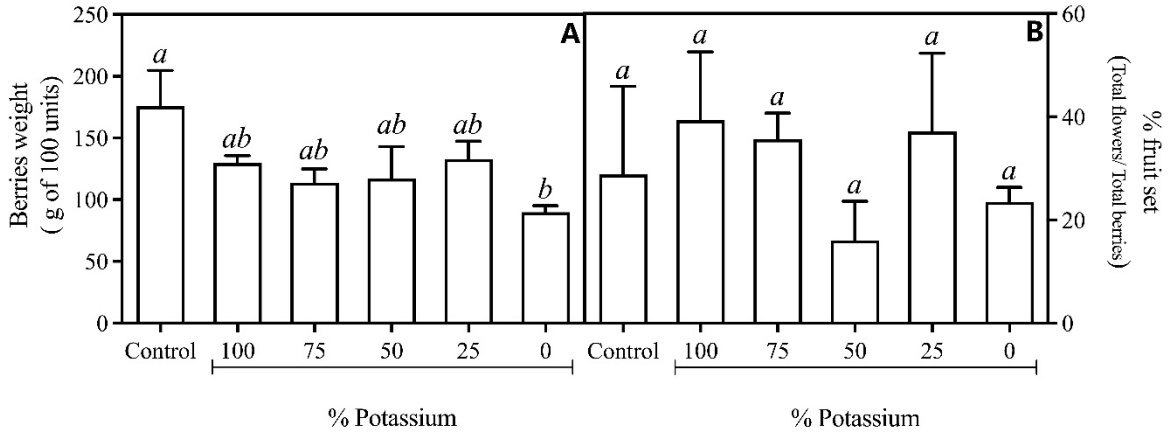

Figure 2. Berry weight (**A**) and fruit set index (**B**) of *V. vinifera* cv. Tempranillo plants subjected to different potassium concentrations (include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). Data represent means ± standard error (n = 4). Different letters indicate significant differences among treatments.

3.2. Berry Composition

Total soluble solids (°Brix) (Figure 3A) were significantly lower in plants treated with 0% K compared to all other treatments (vs. control: $p < 0.001$; 100%: $p < 0.001$; 75%: $p < 0.001$; 50%: $p < 0.01$; 25%: $p < 0.001$). Malic acid levels were reduced in the 50% K treatment relative to the 100% ($p < 0.001$), 75% ($p < 0.01$), and 0% ($p < 0.01$) K treatments. However, no significant difference was found between the 50% K and control treatments.

Control plants showed no significant differences in pH (Figure 3C) or total acidity (Figure 3D) compared to those under other K treatments, except for the 0% K group. Plants exposed to 0% K had significantly lower pH and higher acidity than the control ($p < 0.01$ and $p < 0.001$, respectively), 100% ($p < 0.001$ and $p < 0.05$), 75% ($p < 0.001$ and $p < 0.001$), 50% ($p < 0.01$ and $p < 0.001$), and 25% ($p < 0.01$ for both).

3.3. Color Parameters and Anthocyanins

Color intensity (Figure 4A) showed no significant differences among treatments. Similarly, the tonality index (Figure 4B) did not differ between the control and other treatments, except for the 0% K group, which showed significantly different values compared to the control ($p < 0.001$), 100% ($p < 0.01$), 75% ($p < 0.001$), 50% ($p < 0.01$), and 25% ($p < 0.01$).

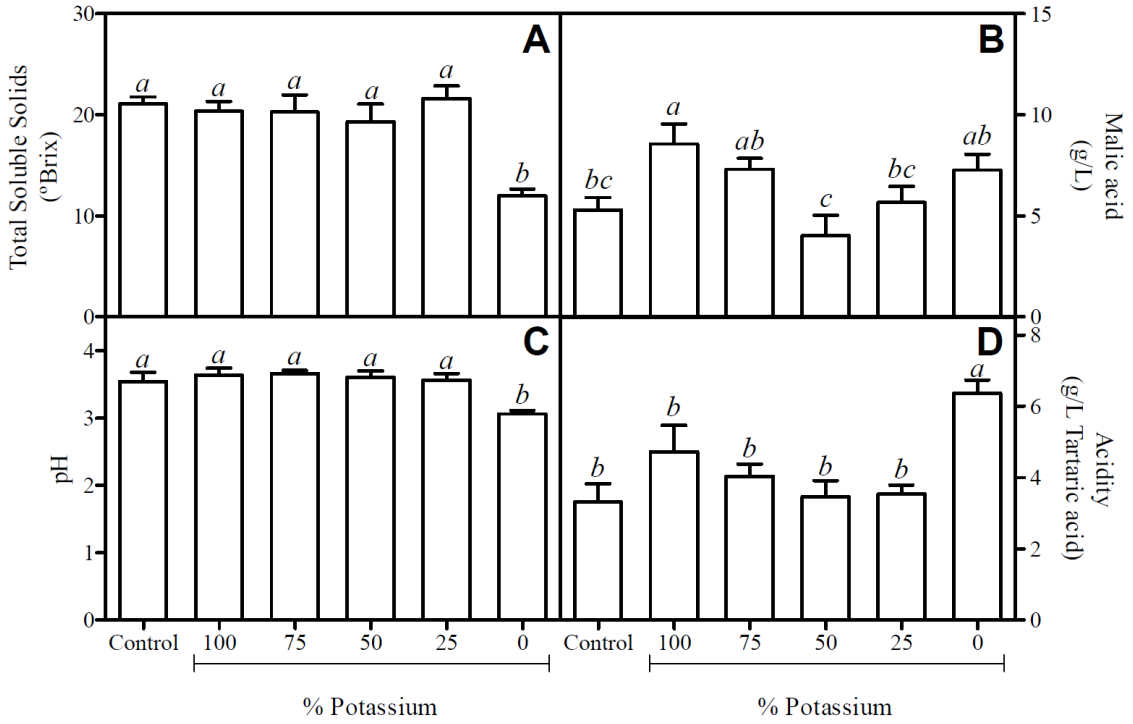

Figure 3. Total soluble solids (TSS) (**A**), malic acid (**B**), pH (**C**), and titratable acidity (**D**) in berries of *V. vinifera* cv. Tempranillo subjected to different potassium concentrations (include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). Data represent means ± standard error (n = 4). Different letters indicate significant differences among treatments.

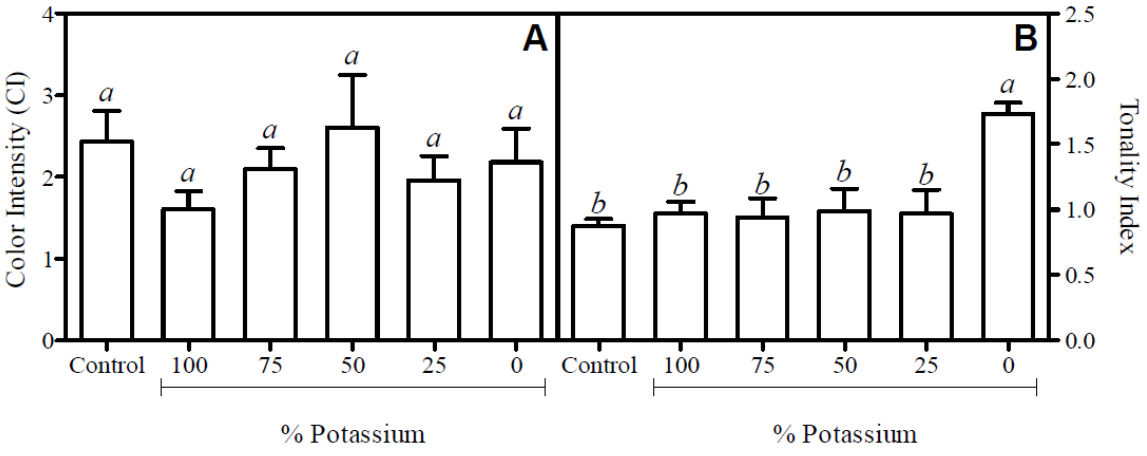

Figure 4. Color intensity (**A**) and tonality index (**B**) of berries from *V. vinifera* cv. Tempranillo subjected to different potassium concentrations (include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). Data represent means ± standard error (n = 4). Different letters indicate significant differences among treatments.

In grapes subjected to 0% K, total anthocyanin concentrations remained extremely low, suggesting that these plants may not have reached veraison, lower than those treated with 25% ($p < 0.01$), 50% ($p < 0.01$), and 75% ($p < 0.05$) K (Figure 5A). Potential anthocyanins (extracted at pH 3.2) (Figure 5B) were also significantly lower in

the 0% K treatment compared to the control ($p < 0.05$) and the 100% ($p < 0.01$), 75% ($p < 0.01$), 50% ($p < 0.001$), and 25% ($p < 0.01$) K treatments.

Extractable anthocyanins (EA%) (Figure 5C) did not differ significantly among treatments. However, phenolic maturity (Mp%) (Figure 5D) was significantly higher in the 0% K group compared to the control and all other K treatments ($p < 0.01$). Polyphenolic richness (Figure 5E) was significantly higher in the 0% K treatment compared to the control ($p < 0.05$). Tannin concentration (Figure 5F) was lower in the 50% and 75% K treatments compared to the 25% K treatment ($p < 0.05$).

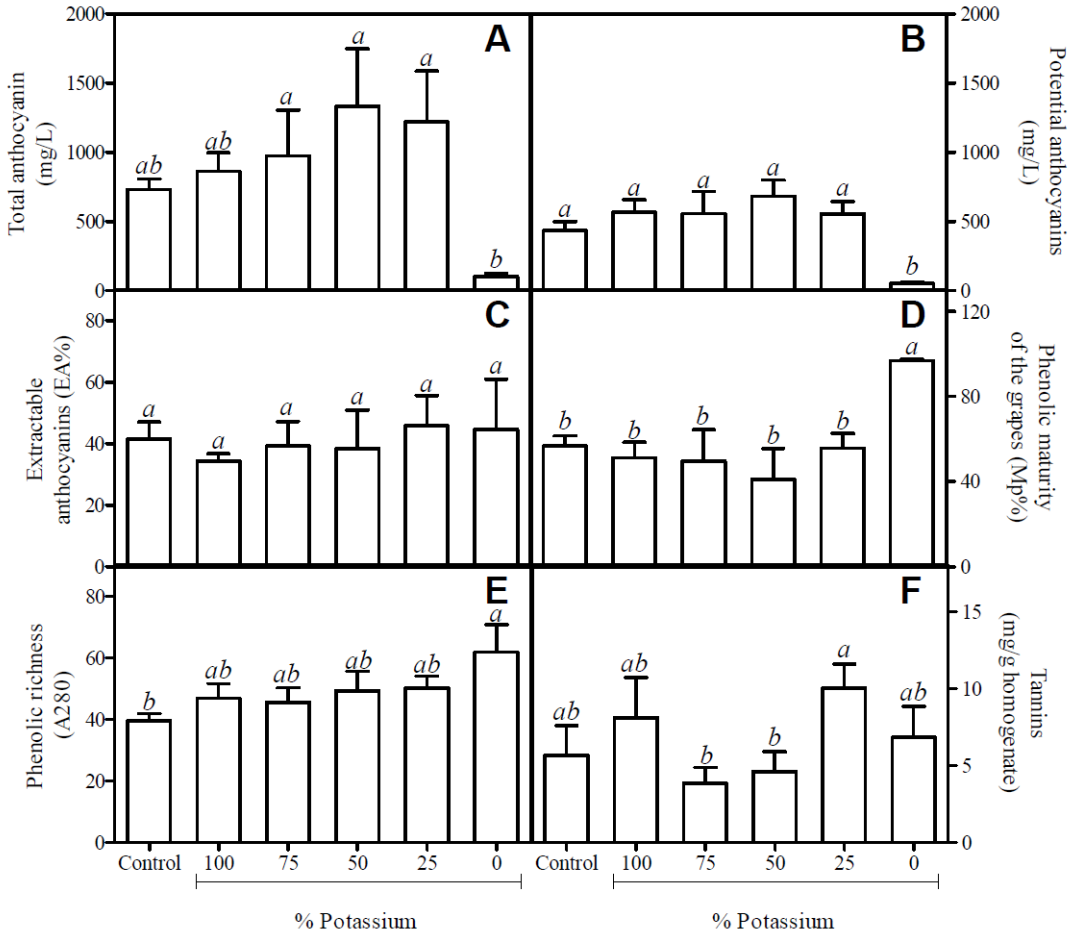

Figure 5. Total anthocyanins (**A**), potential anthocyanins (**B**), extractable anthocyanins (**C**), phenolic maturity (**D**), phenolic richness (**E**), and tannins (**F**) in berries of *V. vinifera* cv. Tempranillo subjected to different potassium concentrations (include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). Data represent means ± standard error (n = 4). Different letters indicate significant differences among treatments ($p < 0.05$) based on LSD test.

3.4. Nutrients

Figure 6 provides a comparative visualization of normalized macronutrient and micronutrient concentrations across leaves, petioles, and berries in grapevines under different K treatments. The radar plots reveal nutrient-specific responses to K supply. For macronutrients, the 100% K treatment led to higher concentrations of K and N in leaves and petioles, while control and 0% K treatments were associated with increased Mg and Ca, particularly in petioles. In berries, nutrient concentrations showed more balanced patterns, with relatively stable K and Ca values across treatments and higher Mg and N levels under 0% K. Regarding micronutrients, leaves from the 100% K group had higher Fe and Mn, whereas Cu and Zn were the highest in berries from the 0% K treatment. These patterns confirm the nutrient-specific and tissue-dependent nature of K-induced nutritional imbalances and align with the statistical trends observed in the accompanying Table 3.

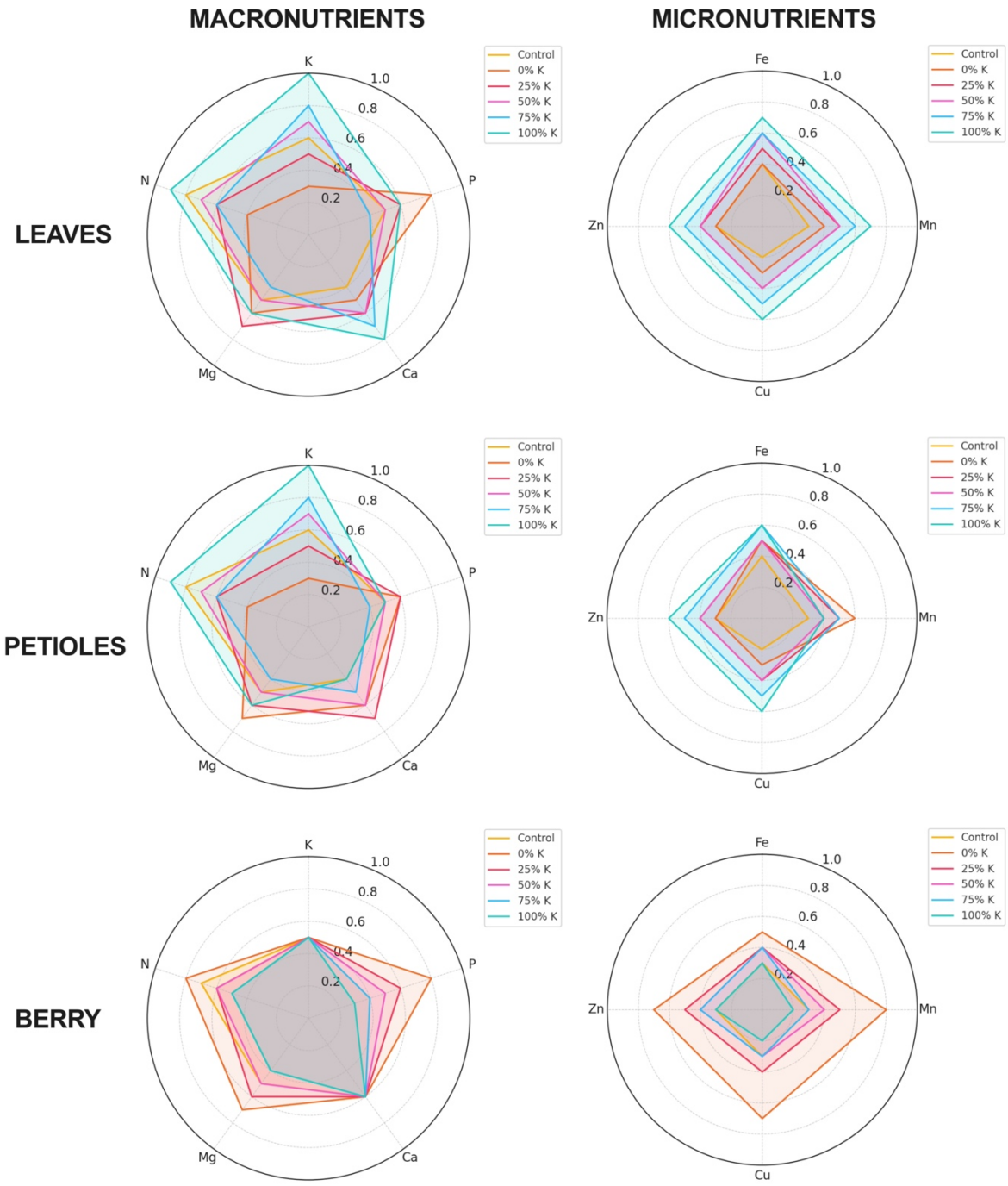

Figure 6. Radar charts showing normalized concentrations of macro- and micronutrients in grapevine (*V. vinifera* cv. Tempranillo) leaves, petioles, and berries under different potassium (K) treatments. Each axis represents a specific nutrient (macronutrients: N, P, K, Ca, Mg; micronutrients: Fe, Mn, Cu, Zn), and the values have been normalized to allow visual comparison across tissues. Treatments include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution.

Table 3. Concentration of macro- (% dry weight, DW) and micronutrients (mg kg^{-1} DW) in grapevine (*V. vinifera* cv. Tempranillo) petioles, leaves, and berries under different potassium (K) treatments (include Control (baseline K), 0% K (K-deficient), and 25%, 50%, 75%, and 100% K levels in nutrient solution). Values are expressed as mean ± standard deviation (n = 4). Different letters within each column and organ indicate significant differences among treatments.

	Treatment	Ca	K	Mg	P	N	Cu	Fe	Mn	Zn
Petiole	Control	2.92 ± 1.50 a	0.75 ± 0.16 c	1.78 ± 0.47 bc	0.21 ± 0.06 c	0.37 ± 0.08 d	9.45 ± 3.48 ab	59.96 ± 24.89 ab	44.28 ± 20.70 b	26.29 ± 3.91 c
	100%	1.55 ± 0.47 b	3.71 ± 1.31 a	1.07 ± 0.26 d	0.22 ± 0.06 c	0.71 ± 0.27 b	15.03 ± 10.68 a	44.07 ± 19.80 c	24.03 ± 10.26 b	51.43 ± 4.63 bc
	75%	1.90 ± 0.48 ab	3.46 ± 0.65 a	0.96 ± 0.19 d	0.26 ± 0.09 bc	0.89 ± 0.30 a	8.22 ± 2.26 b	70.00 ± 43.22 c	27.64 ± 9.62 b	36.08 ± 13.77 bc
	50%	1.70 ± 0.69 b	2.01 ± 0.51 b	1.27 ± 0.34 cd	0.36 ± 0.09 ab	0.44 ± 0.13 cd	4.38 ± 1.08 b	49.83 ± 10.65 ab	22.52 ± 7.72 b	31.53 ± 10.98 bc
	25%	1.47 ± 0.31 b	1.07 ± 0.84 c	1.89 ± 0.88 b	0.30 ± 0.06 b	0.63 ± 0.08 bc	5.62 ± 3.56. b	73.37 ± 36.87 a	31.67 ± 15.98 b	39.01 ± 9.53 ab
	0%	1.88 ± 0.50 b	0.38 ± 0.10 c	2.83 ± 0.50 a	0.47 ± 0.17 a	0.83 ± 0.07 ab	3.77 ± 1.51 b	86.59 ± 29.95 a	63.45 ± 25.13 a	28.28 ± 12.14 a
Leaf	Control	1.22 ± 0.28 c	0.89 ± 0.07 bc	0.63 ± 0.12 ab	0.29 ± 0.03 c	2.33 ± 0.74 c	8.13 ± 2.83 b	84.19 ± 28.23 b	53.55 ± 20.36 bc	21.33 ± 8.31 c
	100%	2.16 ± 0.60 ab	1.89 ± 0.26 a	0.79 ± 0.09 a	0.46 ± 0.05 ab	3.58 ± 0.52 ab	17.15 ± 4.59 a	133.92 ± 31.61 a	88.42 ± 34.29 a	37.13 ± 4.73 a
	75%	2.39 ± 1.13 a	1.64 ± 0.36 a	0.56 ± 0.12 b	0.42 ± 0.06 bc	3.56 ± 0.46 ab	8.31 ± 3.33 b	130.96 ± 48.18 a	78.69 ± 40.89 ab	31.05 ± 8.70 ab
	50%	1.06 ± 0.34 c	1.21 ± 0.39 b	0.57 ± 0.14 b	0.37 ± 0.14 bcd	2.89 ± 0.70 bc	7.03 ± 3.04 b	85.00 ± 14.47 b	36.31 ± 9.99 c	24.70 ± 3.36 bc
	25%	1.40 ± 0.63 bc	1.02 ± 0.44 b	0.80 ± 0.18 a	0.46 ± 0.07 ab	3.12 ± 0.51 ab	6.04 ± 1.87 b	103.67 ± 11.56 b	56.38 ± 29.32 abc	28.83 ± 6.04 bc
	0	1.80 ± 0.79 abc	0.55 ± 0.10 c	0.84 ± 0.25 ab	0.54 ± 0.09 a	3.71 ± 0.53 a	6.59 ± 2.39 b	88.88 ± 22.71 b	65.50 ± 16.39 abc	27.09 ± 3.92 bc
Berry	Control	0.27 ± 0.31 a	1.07 ± 0.17 a	0.09 ± 0.01 b	0.14 ± 0.03 c	0.71 ± 0.20 b	4.79 ± 1.03 b	25.25 ± 6.89 ab	7.36 ± 1.27 b	4.50 ± 0.52 c
	100%	0.10 ± 0.05 a	1.38 ± 0.30 a	0.12 ± 0.03 ab	0.16 ± 0.03 c	0.79 ± 0.10 b	7.87 ± 2.64 b	8.58 ± 5.61 c	7.86 ± 2.37 b	6.18 ± 1.30 bc
	75%	0.33 ± 0.26 a	1.36 ± 0.25 a	0.12 ± 0.03 ab	0.19 ± 0.03 bc	0.85 ± 0.13 b	6.56 ± 2.71 b	10.14 ± 3.03 c	9.57 ± 3.47 b	6.68 ± 2.36 bc
	50%	0.19 ± 0.12 a	1.33 ± 0.24 a	0.11 ± 0.03 ab	0.18 ± 0.04 ab	0.72 ± 0.12 b	6.14 ± 3.41 b	18.40 ± 8.41 bc	8.09 ± 2.40 b	6.49 ± 1.70 bc
	25%	0.32 ± 0.25 a	1.36 ± 0.75 a	0.12 ± 0.06 ab	0.18 ± 0.03 b	0.80 ± 0.15 b	7.16 ± 2.49 b	31.77 ± 21.33 a	9.90 ± 6.07 b	8.49 ± 5.01 ab
	0%	0.44 ± 0.52 a	1.16 ± 0.17 a	0.15 ± 0.03 a	0.26 ± 0.13 a	1.36 ± 0.12 a	14.36 ± 8.86 a	38.67 ± 16.89 a	17.42 ± 3.a	11.56 ± 2.31 a

3.5. Macronutrients

Table 3 details means and differences between macro- and micronutrients in leaves, petioles and berries. In general, grapevine leaves from control plants had lower concentrations of macronutrients (K, P, Ca, Mg, and N) compared to those from plants grown under the 100% K treatment. Meanwhile, plants irrigated with the Hoagland nutrient solution containing 50% K showed macronutrient levels statistically similar to the control. In petioles, K and N concentrations were lower in the control than in the 100% K treatment. Conversely, Ca and Mg levels were higher in the control group than in the 100% K-treated plants. No significant difference was observed in P concentration between the control and 100% K. In berries, K and Ca concentrations showed no significant differences among treatments. However, plants under 0% K exhibited significantly ($p < 0.05$) higher levels of P, Mg, and N compared to control plants.

In addition to K, differences in Ca, Mg, P, Mn, and Zn may influence berry osmotic balance, ripening physiology, and metabolic activity. These shifts can affect color, acidity, and phenolic development. Moreover, excessive or unbalanced fertilization can lead to soil and groundwater salinization [11].

A reduction in K supply led to a marked decrease in K levels in leaves and petioles. Leaves from the 100% and 75% K treatments had significantly higher K concentrations than the control ($p < 0.001$ and $p < 0.01$, respectively). In petioles, plants treated with 100%, 75%, and 50% K had significantly higher K than the control ($p < 0.001$, $p < 0.001$, and $p < 0.01$, respectively). However, K levels in berries were unaffected by K concentration in the nutrient solution.

P concentration in leaves increased significantly in plants under the 0% K treatment compared to control, 75%, and 50% K treatments ($p < 0.001$, $p < 0.05$, and $p < 0.01$, respectively). In petioles, the 0% K group also showed higher P compared to control, 100%, 75%, and 25% K treatments ($p < 0.001$, $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively). In berries, the 0% K treatment had significantly more P than the control ($p < 0.01$) and 100% K ($p < 0.05$).

Ca concentration in leaves was significantly higher in the 100% and 75% K treatments than in the control ($p < 0.05$). In petioles, Ca levels in the control were lower than in all other treatments except for the 75% K group.

Mg concentration in leaves was higher in the 100% and 25% K treatments compared to the 75% and 50% K treatments ($p < 0.05$). In petioles, plants under 0% K had the highest Mg concentrations. Similarly, berries from the 0% K group had significantly more Mg than the control ($p < 0.05$).

In both leaves and petioles, control plants had higher N concentrations than other treatments, except for the 50% K treatment.

3.6. Micronutrients

Micronutrient concentrations varied across tissues and K treatments, as shown in Figure 6 and Table 3. In general, leaves of control plants had lower levels of Fe, Mn, Cu, and Zn than those irrigated with the 100% K solution. However, values in control plants were often comparable to those under 0% K. In petioles, Fe and Mn concentrations were significantly higher in the 0% K group, while Cu and Zn did not differ significantly among treatments. In berries, plants under 0% K had the highest Mn and Cu levels, significantly exceeding those observed in all other treatments. As shown in Table 3, control berries showed the lowest concentrations of Mn, Cu, and Zn. Specifically, leaf Fe concentration was significantly lower in control plants than in the 100% and 75% K groups, while Fe in berries was higher in control ($p < 0.05$) than in these same treatments. Manganese levels in leaves were also reduced in control plants compared to the 100% K group.

In petioles and berries, Mn was significantly higher under 0% K than in all other treatments ($p < 0.05$). Cupper concentrations in leaves and petioles peaked under 100% K and were significantly higher than those under 0%, 25%, 50%, and 75% K, including the control (p values ranging from < 0.001 to < 0.05). In contrast, berry Cu levels were highest in the 0% K group. Zinc concentration in leaves and petioles was significantly lower in control plants compared to the 100% K treatment, but no statistical difference was observed between control and 0% K ($p < 0.01$). In berries, Zn was significantly higher in 0% K plants than in the control ($p < 0.001$) and all other treatments ($p < 0.01$).

4. Discussion

Soil fertilization is a common viticultural practice that directly influences vineyard yield as well as must and wine quality. However, unbalanced fertilizer applications may negatively affect fruit quality [10]. Potassium accumulation is essential for grapevine growth and development [17], but excessive levels in berries at harvest may compromise wine quality, particularly in red cultivars [29].

4.1. Potassium Fertilization Influences Technological and Phenolic Berry Quality

Plants grown without K supply exhibited smaller berries, lower total soluble solids, reduced pH, and increased titratable acidity. Berry size is influenced by K availability, as this nutrient affects both skin turgor and vegetative growth [3]. Its absence may thus limit berry expansion and weight.

Results indicated that berry size was not influenced by fruit set. Although fruit set index did not differ significantly among treatments, plants receiving 100%, 75%, and 25% K showed slightly higher values, indicating a possible improvement. This would align with field observations where K fertilization increased cluster number and weight, leading to higher yield [30].

Total soluble solids, expressed in °Brix, are a key indicator of sugar accumulation during ripening. In grapes, K is the most abundant cation and plays a central role in osmotic regulation, charge balance, and sugar transport [31]. It is well established that high K concentrations increase juice pH by reducing tartaric acid levels, potentially altering the sensory and color stability characteristics of the wine [10,12,14].

Malic acid concentration was highest in plants treated with the half-strength Hoagland solution with the highest K (100% K). Since tartaric acid is a stronger acid than malic acid, a lower tartrate:malate ratio at the same total acidity may result in a higher must pH [32]. Recent studies have expanded the understanding of tartaric acid stability in wine, highlighting that factors such as K concentration and storage conditions significantly influence the precipitation of potassium bitartrate, thereby affecting wine acidity and pH [33].

Phenolic compounds increased only in plants without K supply, likely due to incomplete ripening. Flavonoids, a major class of phenolics, do not diminish with maturity, potentially explaining the elevated polyphenol index. Delgado et al. [10] observed that in N-deficient conditions, polyphenols accumulated strongly, an effect diminished with increased K fertilization.

Total and potential anthocyanin levels decreased under 0% K, likely because these plants did not reach full maturity. However, the measured color intensity did not fully correspond to this trend. This apparent discrepancy may reflect the contribution of other compounds that can be influencing optical density, which were not specifically determined in this study.

Under optimal nutrition, anthocyanins contribute substantially to the polyphenolic concentration of red grape skins during ripening [34]. Potassium starvation (as observed in the 0% K treatment) has also been reported to impair N utilization and induce chlorosis in leaves. In other crops, K deficiency increases susceptibility to disease and alters key metabolic processes [14]. These physiological effects may further contribute to delayed ripening and reduced anthocyanin synthesis under K deficiency.

4.2. Potassium Fertilization Affects Macro- and Micronutrient Concentrations in Leaves, Petioles and Berries

As expected, increasing K concentrations in the nutrient solution led to higher K levels in leaves and petioles, confirming uptake and utilization. Several studies have reported increased K levels in grapevine tissues following K application [10,35–37]. Despite no significant differences in berry K concentration, fruit quality differences, particularly in soluble solids, were evident and likely related to K deficiency.

Mineral elements, both macro and micro, not only impact nutrition but also affect berry osmotic balance. Berries from 0% K plants showed signs of dehydration (data not shown). K deprivation affected not only K concentration but also altered the relative balance of other macro- and micronutrients. Since sugars and K are major osmolytes during ripening, reduced K may disrupt osmotic regulation [12]. Although other minerals like Na, Ca, Mg, Cu, Mn, and phosphate also contribute, their roles are limited by lower concentrations, mobility, or potential toxicity.

Phosphorus, essential for macromolecule synthesis and energy transfer, increased in 0% K plants but remained below toxic thresholds (>1% DW; [38]). Interactions among K, Ca, and Mg have been well documented. Morris and Cawthon [39] reported K-induced reductions in Ca and Mg, whereas in this study, increased K correlated with higher Ca and unchanged Mg. Conversely, K deficiency elevated Mg levels, consistent with compensatory uptake patterns. As Keller [40] explains, K^+, Ca^{2+}, and Mg^{2+} compete for absorption in grapevine roots due to their similar charges, and high K supply may suppress Ca and Mg uptake through antagonistic effects, particularly under conditions of limited cation availability.

Calcium distribution varied across tissues: it increased in leaves, decreased in petioles, and remained unchanged in berries of 0% K plants. Some authors have suggested K–Ca antagonism may reduce berry K concentration and thus acidity [36,41,42]. However, in this study, Ca variations had no impact on acidity except under 0% K.

Magnesium is crucial for plant growth, playing several important roles including serving as a central component of chlorophyll and as an activator of many enzymes [43]. Magnesium levels were higher in petioles

and berries of plants under 0% K. Xie et al. [44] reported that high K supply can suppress Mg uptake and translocation in plants due to antagonistic interactions between these macronutrients. In the present study, we observed the opposite effect, low K led to increased Mg, consistent with compensatory uptake patterns. Optimal Mg concentration for plant growth ranges from 0.15 to 0.35% of dry weight [38]. In this study, Mg concentrations exceeded this range, yet no symptoms of chlorosis or impaired photosynthesis were observed.

Although K concentrations varied across treatments, N levels remained balanced. However, N concentration increased in leaves, petioles, and berries under 0% K. Nitrogen is crucial for grapevine metabolism and fermentation, influencing wine quality [45]. Excess N can promote vegetative growth at the expense of carbohydrate storage and increase berry N compounds such as amino acids and ammonium.

These shifts in Mg, P, N and other minerals under reduced K supply may influence berry osmotic balance, acidity regulation and metabolic activity, helping to explain differences observed in technological and phenolic parameters.

Iron, essential for enzymes and photosynthesis, was higher in leaves of 100% and 75% K plants, but lower in berries. Since Fe deficiency affects photosynthetic efficiency and fruit set [46], the current Fe distribution suggests no deficiency symptoms.

Micronutrient distribution varied with K availability. Contrary to Morris et al. [47], who reported reduced Mn levels with K addition, our results showed increased Mn in petioles and berries under 0% K, while in leaves, Mn concentration was highest with 75% and 100% K. Similarly, Cu concentrations increased in leaves and petioles with 100% K, but the highest berry Cu levels were observed under 0% K. Although Cu deficiency is uncommon, it may impair cell wall lignification [38]. Zinc also followed a comparable pattern: levels rose in leaves and petioles with 100% K, yet berries from 0% K plants showed the highest Zn accumulation. No zinc deficiency symptoms, such as necrotic spots or shortened internodes, were detected [48]. These findings align with the observations of Tränkner et al. [49], who reported that K deficiency can disrupt the uptake and distribution of micronutrients like Mn, Cu, and Zn in plant tissues.

5. Conclusions

This study demonstrated that K availability significantly influences grapevine physiology, berry quality, and nutrients in *Vitis vinifera* cv. Tempranillo. Among the treatments tested, moderate K levels (50% and 75% K) consistently resulted in optimal effects, including optimal sugar accumulation, improved anthocyanin concentration, and favorable phenolic maturity. In contrast, complete K omission (0% K) led to reduced berry size and sugar concentration, but induced an increase in Mg, Mn, and N concentrations. Full K supply (100% K) increased tissue K concentration but did not enhance fruit quality compared to moderate treatments and was associated with increased pH and reduced acidity.

These results highlight that K availability significantly influenced veraison timing, berry sugar levels, and nutrient composition in different grapevine organs. The relationship between K supply and tissue K concentration was consistent, particularly in leaves and petioles.

Author Contributions

C.S.-P.: experimental design, execution of the experiment, data acquisition, data analysis, writing—original draft preparation; F.M.: supervision, experimental design, data interpretation, writing—reviewing and editing. Both authors made substantial contributions to this work. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding. The experiment was conducted at the Universidad de Navarra (Pamplona, Spain) as part of complementary doctoral research activities, without specific project-based financial support. No funds were received to cover publication costs.

Institutional Review Board Statement

Not applicable. This study did not involve humans or animals requiring ethical approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available on reasonable request from the corresponding author.

Acknowledgments

The authors thank the University of Navarra (Pamplona, Spain) for providing access to its facilities during the development of this study.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) for language editing and support in the design of visual materials. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version of the manuscript.

References

1. Intrigliolo, D.S.; Castel, J.R. Response of *Vitis vinifera* cv. 'Tempranillo' to partial rootzone drying in the field: Water relations, growth, yield and fruit and wine quality. *Agric. Water Manag.* **2009**, *96*, 282–292.
2. Peuke, A.D. Nutrient composition of leaves and fruit juice of grapevine as affected by soil and nitrogen fertilization. *J. Plant Nutr. Soil Sci.* **2009**, *172*, 557–564.
3. Marschner, H. *Mineral Nutrition of Higher Plants*, 2nd ed.; Academic Press: Cambridge, MA, USA, 1995.
4. Bavaresco, L.; Gatti, M.; Fregoni, M. Nutritional deficiencies. In *Methodologies and Results in Grapevine Research*; Delrot, S., Medrano, H., Or, E.; et al., Eds.; Springer: Berlin, Germany, 2010; pp. 165–191.
5. White, P.J.; Brown, P.H. Plant nutrition for sustainable development and global health. *Ann. Bot.* **2010**, *105*, 1073–1080. https://doi.org/10.1093/aob/mcq085.
6. Brunetto, G.; da Silva, J.A.B.; Ceretta, C.A.; et al. Grapevine mineral nutrition: Physiological basis and diagnosis. *Acta Physiol. Plant.* **2003**, *25*, 489–500. https://doi.org/10.1023/A:1024832113098.
7. Schreiner, R.P. Nutrient uptake and distribution in young Pinot noir grapevines over two seasons. *Am. J. Enol. Vitic.* **2016**, *67*, 436–448. https://doi.org/10.5344/ajev.2016.15099.
8. Pate, J.S. Transport and partitioning of nitrogenous solutes. *Annu. Rev. Plant Physiol.* **1980**, *31*, 313–340.
9. Lang, A.; Düring, H. Partitioning control by water potential gradient—Evidence for compartmentation breakdown in grape berries. *J. Exp. Bot.* **1991**, *42*, 1117–1122.
10. Delgado, R.; Martín, P.; Del Álamo, M.; et al. Changes in the phenolic composition of grape berries during ripening in relation to vineyard nitrogen and potassium fertilization rates. *J. Sci. Food Agric.* **2004**, *84*, 623–630.
11. Buvaneshwari, S.; Riotte, J.; Sekhar, M.; et al. Potash fertilizer promotes incipient salinization in groundwater-irrigated semi-arid agriculture. *Sci. Rep.* **2020**, *10*, 3691. https://doi.org/10.1038/s41598-020-60365-z.
12. Mpelasoka, B.S.; Schachtman, D.R.; Treeby, M.T.; et al. A review of potassium nutrition in grapevines with special emphasis on berry accumulation. *Aust. J. Grape Wine Res.* **2003**, *9*, 154–168.
13. Zhenming, N.; Xuefeng, X.; Yi, W.; et al. Effects of leaf-applied potassium, gibberellin and source-sink ratio on potassium absorption and distribution in grape fruits. Sci. Hortic. 2008, 115, 164–167.
14. Villette, J.; Cuéllar, T.; Verdeil, J.L.; et al. Grapevine potassium nutrition and fruit quality in the context of climate change. Front. Plant Sci. 2020, 11, 123. https://doi.org/10.3389/fpls.2020.00123/full.
15. Sperling, O.; Perry, A.; Ben-Gal, A.; et al. Potassium deficiency reduces grapevine transpiration through decreased leaf area and stomatal conductance. *Plant Physiol. Biochem.* **2024**, *208*, 108534. https://doi.org/10.1016/j.plaphy.2024.108534.
16. Mohammed, S.; Singh, D.; Ahlawat, V.P. Growth, yield and quality of grapes as affected by pruning and basal application of potassium. Haryana J. Hortic. Sci. 1993, 22, 179–182
17. Rogiers, S.Y.; Coetzee, Z.A.; Walker, R.R.; et al. Potassium in the grape (*Vitis vinifera* L.) berry: Transport and function. *Front. Plant Sci.* **2017**, *8*, 1629. https://doi.org/10.3389/fpls.2017.01629.
18. Pirie, A.; Mullins, M.G. Interrelationships of sugars, anthocyanins, total phenols and dry weight in skin of grape berries during ripening. *Am. J. Enol. Vitic.* **1977**, *28*, 204–209.
19. Morris, J.R.; Sims, C.A.; Cawthon, D.L. Effects of excessive potassium levels on pH, acidity and color of fresh and stored grape juice. *Am. J. Enol. Vitic.* **1983**, *34*, 35–39.
20. Mullins, M.G. Test-plant for investigations of the physiology of fruiting in *Vitis vinifera* L. *Nature* **1966**, *209*, 419–420.

21. Ollat, N.; Génny, L. Les boutures fructifères de vigne: Validation d'un modèle d'étude du développement de la physiologie de la vigne. I. Caractéristiques de l'appareil végétatif. *J. Int. Des Sci. De La Vigne Et Du Vin* **1998**, *32*, 1–9.
22. Santa María, E. Incidencia de Botrytis Cinerea en Relación con Diferentes Aspectos Fisiológicos de la vid. Ph.D. Thesis, Universidad de Navarra, Navarra, Spain, 2004.
23. Morales, F.; Antolín, M.C.; Aranjuelo, I.; et al. From vineyards to controlled environments in grapevine research: Investigating responses to climate change scenarios using fruit-bearing cuttings. *Theor. Exp. Plant Physiol.* **2016**, *28*, 171–191.
24. Hoagland, D.R.; Arnon, D.I. The water-culture method for growing plants without soil. *Calif. Agric. Exp. Stn. Circ.* **1950**, *347*, 1–32.
25. Glories, Y.; Augustin, M. Maturité phénolique du raisin, conséquences technologiques: Applications aux millésimes 1991 et 1992. In *Journée technique du CIVB*; Actes du Colloque : Bordeaux, France, 1993; p. 56.
26. AOAC. *Official Methods of Analysis of the Association of Official Analytical Chemists*, 15th ed.; Helrich, K., Ed.; AOAC: Washington, DC, USA, 1990.
27. Abadía, J.; Nishio, J.N.; Terry, N. Mineral composition of peach leaves affected by iron chlorosis. *J. Plant Nutr.* **1985**, *8*, 697–707.
28. Abadía, A.; Sanz, M.; Montañés, L. Photosynthetic pigments and mineral composition of iron-deficient pear leaves. *J. Plant Nutr.* **1989**, *12*, 827–838.
29. Davies, C.; Shin, R.; Liu, W.; et al. Transporters expressed during grape berry (*Vitis vinifera* L.) development are associated with an increase in berry size and berry potassium accumulation. *J. Exp. Bot.* **2006**, *57*, 3209–3216.
30. Amiri, M.E.; Fallahi, E. Influence of mineral nutrients on growth, yield, berry quality, and petiole mineral nutrient concentrations of table grape. *J. Plant Nutr.* **2007**, *30*, 463–470.
31. Lang, A. Turgor-regulated translocation. *Plant Cell Environ.* **1983**, *6*, 683–689.
32. Boulton, R. The general relationship between potassium, sodium and pH in grape juice and wine. *Am. J. Enol. Vitic.* **1980**, *31*, 182–186.
33. Cui, W.; Wang, X.; Han, S.; et al. Research progress of tartaric acid stabilization on wine characteristics. *Food Chem. X.* **2024**, *23*, 101728. https://doi.org/10.1016/j.fochx.2024.101728.
34. Somers, T.C. Pigment development during ripening of the grape. *Vitis* **1976**, *14*, 269–277.
35. Wolf, T.K.; Haeseler, C.W.; Bergman, E.L. Growth and foliar elemental composition of Seyval Blanc grapevines as affected by four nutrient solution concentrations of nitrogen, potassium and magnesium. *Am. J. Enol. Vitic.* **1983**, *34*, 271–277.
36. Garcia, M.; Daverede, C.; Gallego, P.; et al. Effect of various potassium–calcium ratios on cation nutrition of grape grown hydroponically. *J. Plant Nutr.* **1999**, *22*, 417–425.
37. Poni, S.; Quartieri, M.; Tagliavini, M. Potassium nutrition of Cabernet Sauvignon grapevines (*Vitis vinifera* L.) as affected by shoot trimming. *Plant Soil* **2003**, *253*, 341–351.
38. Marschner, H. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: Cambridge, MA, USA, 2012.
39. Morris, J.R.; Cawthon, D.L. Effect of irrigation, fruit load, and potassium fertilization on yield, quality, and petiole analysis of Concord (*Vitis labrusca* L.) grapes. *Am. J. Enol. Vitic.* **1982**, *33*, 145–148.
40. Keller, M. *The Science of Grapevines: Anatomy and Physiology*, 2nd ed.; Academic Press: Cambridge, MA, USA, 2015.
41. Gautier, P. Diagnostic foliaire de la vigne. Études par analyses factorielles en composantes principales sur plusieurs années. In Proceedings of the 5th International Colloquium Plant Nutrition Control, Casteltranco Veneto, Italy, 1980; pp. 587–590.
42. Fregoni, M. Exigences d'éléments nutritifs en viticulture. *Bull. l'OIV* 1985, 650–651.
43. Maguire, M.E.; Cowan, J.A. Magnesium chemistry and biochemistry. *BioMetals* **2002**, *15*, 203–210. https://doi.org/10.1023/A:1016058229972.
44. Xie, K.; Cakmak, I.; Wang, S.; et al. Synergistic and antagonistic interactions between potassium and magnesium in higher plants. *Crop J.* **2021**, *9*, 249–256. https://doi.org/10.1016/j.cj.2020.10.005.
45. Bell, S.J.; Henschke, P.A. Implications of nitrogen nutrition for grapes, fermentation and wine. *Aust. J. Grape Wine Res.* **2005**, *11*, 242–295.
46. Bertamini, M.; Nedunchezhian, N. Grapevine growth and physiological responses to iron deficiency. *J. Plant Nutr.* **2005**, *28*, 737–749.
47. Morris, J.R.; Cawthon, D.L.; Fleming, J.W. Effects of high rates of potassium fertilization on raw product quality and changes in pH and acidity during storage of Concord grape juice. *Am. J. Enol. Vitic.* **1980**, *31*, 323–328.
48. Alloway, B. *Zinc in Soils and Crop Nutrition*. International Zinc Association: Brussels, Belgium; International Fertilizer Industry Association: Paris, France, 2008. Pp. 1–139.
49. Tränkner, M.; Tavakol, E.; Jákli, B. Functioning of potassium and magnesium in photosynthesis, photosynthate translocation and photoprotection. *Physiol. Plant.* **2018**, *163*, 414–431. https://doi.org/10.1111/ppl.12747.