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Comparative Evaluation of Berry Mineral Element Profiles in Two Hybrid Table Grape Cultivars and Their Parents (*Vitis vinifera* L.)

Sevil Canturk

Department of Horticulture, Faculty of Agriculture, Çukurova University, Adana 01330, Türkiye; scanturk@cu.edu.tr; Tel.: +90-5057039672

Abstract

The mineral composition of grape berries is shaped by a complex interplay of cultivars, soil and climatic conditions, water status, and rootstock–scion interactions. Comparing registered hybrid cultivars with their parents grown at the same site provides a practical phenotypic reference for cultivar evaluation. While mineral accumulation in many grape cultivars is extensively documented, comparative evaluations of berry mineral profiles between registered hybrid cultivars and their parents under the same viticultural conditions remain scarce. In this study, the mineral element profiles of two commercial hybrid table grape cultivars (*Vitis vinifera* L.), 'Ata Sarısı' (Cavus × Cardinal) and 'Tekirdag Seedless' (Alphonse Lavallée × Sultana), were comparatively evaluated in both whole (including naturally seedless cultivars) and seed-removed berry tissues alongside their parents over two growing seasons using ICP-MS. Cultivar was the primary factor determining mineral profiles, whereas neither the year effect nor the cultivar × year interaction was significant, except for a marginal interaction for Mn in whole berries. Alphonse Lavallée was characterized by high K, Cavus by high Ca and Mg, and Cardinal by high Na, Fe, Zn, and Mn. Phenotypically, the mineral profile of Tekirdag Seedless closely resembled that of Sultana for most elements, whereas Ata Sarısı more closely resembled Cavus. Seed-removed fractions of the seeded cultivars had lower concentrations of all elements except K, which did not differ, and Na, which was higher in the seed-removed fractions of Cavus, Cardinal, and Ata Sarısı. PCA explained 66.3% of the total variation in the first two components (PC1: 41.1%; PC2: 25.2%); Cardinal was associated with Na, Ca, Fe, Zn, and Mn along PC1, and Cavus and Ata Sarısı with Mg and Cu along PC2. Rather than establishing generalized genetic inheritance models, the findings provide a baseline phenotypic characterization of the evaluated cultivars at a single site over two seasons; the data show distinct cultivar-specific mineral profiles under identical viticultural conditions and cultural management but do not permit conclusions on the inheritance of mineral traits.

Keywords: grape berry; mineral composition; elemental profiling; hybrid cvs; ICP-MS; *Vitis vinifera* L.

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1. Introduction

The traditional quality concept of table grapes encompasses physical and organoleptic parameters, including cluster architecture, berry size, shape, skin color, sugar levels, and, to some extent, the aromatic profile. However, this conventional approach overlooks the nutritional significance of grapes, particularly their mineral content, which has become

increasingly relevant in contemporary food science and consumer preferences. Mineral composition is a critical but underexplored dimension of fruit quality that merits greater scientific attention, as it plays fundamental roles in human physiological functions, enzymatic reactions, and metabolic processes [1]. Minerals are vital for grapevine development, fruit set, and fruit quality. Grapes contain macro- and micro-nutrients, including potassium, calcium, magnesium, iron, and zinc, which are essential for human health, although their dietary contribution depends on intake and bioavailability. Potassium (K^+), in particular, is the primary cation in ripe grape berries and has a significant impact on fruit quality [2]. These minerals contribute not only to the nutritional value of grapes but also to post-harvest quality, including shelf-life stability, pathogen resistance, berry texture, and sensory attributes, thereby affecting both consumer acceptance and market value [3]. With increasing consumer demand for healthy, natural foods in recent years, the mineral content of table grapes has also gained importance as a quality parameter, warranting systematic investigation [4].

Many factors affect mineral composition and concentration in berries, including cultivar, soil and climate conditions, vine water status, and the rootstock/scion combination [2,5]. The uptake, translocation, compartmentalization, and utilization of mineral elements in grapevines involve sophisticated molecular mechanisms, including specialized transporters, ion channels, and regulatory pathways that ultimately determine the berry mineral profile [6]. Moreover, mineral composition changes dynamically throughout berry development, from berry set to maturity, revealing phenological stage-specific accumulation patterns that reflect the changing physiological requirements of ripening berries [7,8]. In hybrid cultivars, the combination of two parental genomes may result in mineral profiles that differ from those of either parent; however, attributing such differences to specific genetic effects requires segregating progeny populations and appropriate genetic designs. Several studies have examined the accumulation, distribution, and transport of mineral elements in different grape cultivars to date [4,7–12]. However, comparative characterizations of mineral composition and concentration between commercial hybrid grape cultivars and their parents have received comparatively less attention than research on phenolic and aromatic compounds to date. This gap is particularly noteworthy because mineral accumulation in grape berries is governed by complex interactions among genetic, physiological, climatic, and cultural management factors [3].

Ata Sarısı and Tekirdag Seedless, two registered Turkish table grape cultivars with documented parents, were therefore selected for a comparative phenotypic characterization. Although their parent cultivars are internationally recognized, to date, to the best of the author's knowledge, no comparative evaluations in terms of berry mineral element profiles have been conducted between 'Ata Sarısı' and 'Tekirdag Seedless' and their documented parents under the same ecological and vineyard conditions. In commercial table grape growing, breeding programs predominantly operate within *V. vinifera* L. Consequently, assessing mineral variability among *V. vinifera* hybrids and their parents under the same viticultural conditions is immediately relevant in practice. Cultivar-level mineral data obtained under common growing conditions can support the evaluation of cultivars and potential parents and provide reference values for local table grape cultivars. However, the evaluated genotypes share complex pedigree relationships; Cardinal is itself a hybrid derived partly from Alphonse Lavallée, reflecting the interconnected breeding history of table grape cultivars in this study. This study therefore provides a comparative profile of berry macro- and micro-elements in Ata Sarısı and Tekirdag Seedless alongside their parental cultivars grown in the same experimental vineyard, establishing baseline compositional data for these cultivars under the same ecological and viticultural conditions.

2. Results and Discussion

2.1. Mineral Element Composition of the Grape Cultivars

The mineral composition analysis of the studied grape cultivars provided insights into their mineral profiles and enabled a comparative assessment of their performance under the same conditions against their parents. Our findings indicated distinct mineral accumulation patterns in each studied cultivar. Tables 1 and 2 present the mineral composition of the cultivars over the two years, as well as the average for the two years, respectively. Mineral concentrations showed no statistically significant differences between the two years of the study. Cultivar significantly affected all elements in both whole and seedless berries, whereas year had no significant effect for any element ($p > 0.05$), and the cultivar × year interaction was significant only for Mn ($p \leq 0.05$) in whole berries (Table 1). Numerous studies suggest that mineral accumulation in grape tissues is sensitive to climatic fluctuations and environmental factors [2,9,13]. While seasonal temperature fluctuations are reported to influence berry mineral concentrations among the cultivars [2,9], average temperatures in this study were relatively stable, although the two years exhibited slightly different temperature profiles, particularly in maximum and minimum temperatures. Throughout the growing season, 2023 had higher rainfall and lower sunshine duration than 2022. In 2022, however, rainfall was higher during the critical phenological periods of flowering and just after berry set (June and July). However, year had no statistically significant effect on the evaluated minerals (Table 1), indicating that these seasonal climatic variations did not substantially affect mineral concentration under our conditions. Regarding rainfall and water balance, Esteban et al. [7] reported that all parameters examined (including minerals) in non-irrigated vines were equal to or higher than those in irrigated vines. They determined that mineral accumulation processes could offset dilution effects from higher yields; therefore, water balance did not adversely affect grape berry composition. Although the year effect was not statistically significant, the minor variations were observed for most minerals (Table 1). These non-significant year-to-year variations are consistent with the findings of Rogiers et al. [14] who reported that seasonal water status and transpiration rate could alter cation flux. Mineral concentrations were expressed on a fresh-weight basis in this study to align with the fresh consumption of table grapes. However, because moisture content, berry mass, and dry-weight concentrations were not determined, this study cannot distinguish concentration effects associated with tissue composition or water content from differences in total mineral accumulation. Cultivar-dependent natural variations in berry size and the relative proportions of skin, pulp, and seed tissues may cause dilution effects; consequently, a lower fresh-weight concentration in a given cultivar does not necessarily indicate reduced total mineral accumulation per berry. Soil factors should also be considered when interpreting these varietal patterns. Although all cultivars were grown within the same experimental plot under identical cultural practices, soil analysis indicated spatial variation across sampling points, particularly in organic matter, phosphorus, and micronutrients (Table S1). Because these data characterize the experimental area generally rather than vine-specific root zones, localized variability may have contributed to the observed berry mineral profiles. Overall, the main effect of year was not statistically significant for the evaluated minerals. While the lack of significant seasonal effects does not demonstrate strict stability, particularly given the sample size of three biological replicates per year, data are primarily discussed based on the two-year means to describe overall profiles under the identical vineyard conditions (Table 2).

Table 1. Mineral element concentration of whole and seedless berries of six table grape cultivars in the 2022 and 2023 growing seasons (mg kg^{-1} FW).

Cultivar	Year	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Iron (Fe)	Copper (Cu)	Zinc (Zn)	Manganese (Mn)
Whole berries (B)									
AL	2022	1355.00 ± 127.90 ^{a1}	59.12 ± 5.20 ^{d}	84.00 ± 5.03 ^{b}	13.32 ± 0.66 ^{e}	1.18 ± 0.06 ^{c}	0.48 ± 0.04	0.42 ± 0.06 ^{b}	1.75 ± 0.09 ^{b}
AL	2023	1381.00 ± 57.74 ^{a}	58.70 ± 1.92 ^{d}	87.00 ± 1.15 ^{b}	13.26 ± 0.63 ^{e}	1.16 ± 0.06 ^{c}	0.50 ± 0.03	0.39 ± 0.09 ^{b}	1.72 ± 0.08 ^{b}
CV	2022	933.34 ± 66.67 ^{b}	90.17 ± 2.89 ^{a}	140.02 ± 10.00 ^{a}	18.48 ± 1.25 ^{de}	1.77 ± 0.15 ^{b}	0.55 ± 0.03	0.69 ± 0.10 ^{ab}	0.98 ± 0.06 ^{c}
CV	2023	867.23 ± 33.42 ^{b}	93.51 ± 1.81 ^{a}	143.33 ± 12.02 ^{a}	20.70 ± 0.91 ^{cd}	1.84 ± 0.06 ^{b}	0.57 ± 0.03	0.77 ± 0.02 ^{a}	1.08 ± 0.06 ^{c}
CA	2022	1133.71 ± 88.06 ^{ab}	79.85 ± 2.40 ^{ab}	73.00 ± 3.51 ^{b}	30.17 ± 1.74 ^{ab}	3.25 ± 0.15 ^{a}	0.45 ± 0.03	0.86 ± 0.03 ^{a}	2.78 ± 0.10 ^{a}
CA	2023	1166.72 ± 88.23 ^{ab}	75.67 ± 1.86 ^{bc}	80.00 ± 2.89 ^{b}	31.53 ± 1.27 ^{a}	3.22 ± 0.06 ^{a}	0.42 ± 0.04	0.84 ± 0.05 ^{a}	2.47 ± 0.07 ^{a}
AS	2022	1067.25 ± 33.38 ^{ab}	64.87 ± 2.47 ^{cd}	151.00 ± 19.22 ^{a}	24.33 ± 1.76 ^{bcd}	1.75 ± 0.06 ^{b}	0.57 ± 0.05	0.68 ± 0.09 ^{ab}	1.23 ± 0.09 ^{c}
AS	2023	1133.92 ± 33.47 ^{ab}	71.87 ± 3.02 ^{bcd}	147.33 ± 4.48 ^{a}	25.08 ± 1.16 ^{bc}	1.70 ± 0.10 ^{b}	0.58 ± 0.05	0.62 ± 0.06 ^{ab}	1.33 ± 0.06 ^{c}
Cultivar (C)		***	***	***	***	***	**	***	***
Year (Y)		NS	NS	NS	NS	NS	NS	NS	NS
Cultivar (C) × Year (Y)		NS	NS	NS	NS	NS	NS	NS	*
Seedless berries (SB)									
AL	2022	1277.00 ± 96.24	26.88 ± 1.73 ^{c}	52.00 ± 4.16 ^{bc}	11.63 ± 0.32 ^{f}	0.83 ± 0.10 ^{e}	0.32 ± 0.03 ^{d}	0.29 ± 0.03 ^{c}	0.88 ± 0.06 ^{bc}
AL	2023	1265.33 ± 57.98	28.65 ± 2.40 ^{c}	55.00 ± 5.77 ^{bc}	11.55 ± 1.28 ^{f}	0.84 ± 0.07 ^{e}	0.32 ± 0.03 ^{d}	0.29 ± 0.04 ^{c}	0.96 ± 0.03 ^{bc}
SU	2022	1213.00 ± 37.00	52.63 ± 1.16 ^{b}	101.00 ± 23.12 ^{ab}	22.08 ± 1.16 ^{e}	2.31 ± 0.11 ^{bc}	0.68 ± 0.05 ^{a}	0.39 ± 0.01 ^{bc}	1.22 ± 0.08 ^{b}
SU	2023	1177.02 ± 96.24	47.87 ± 1.94 ^{b}	100.01 ± 9.24 ^{ab}	22.08 ± 1.16 ^{e}	2.19 ± 0.06 ^{c}	0.62 ± 0.05 ^{ab}	0.37 ± 0.02 ^{bc}	1.14 ± 0.05 ^{bc}
TS	2022	907.00 ± 58.16	52.67 ± 1.74 ^{b}	106.00 ± 3.06 ^{a}	24.53 ± 1.27 ^{de}	1.45 ± 0.10 ^{d}	0.48 ± 0.02 ^{bcd}	0.51 ± 0.06 ^{abc}	1.09 ± 0.05 ^{bc}
TS	2023	928.01 ± 36.30	53.18 ± 1.74 ^{b}	110.00 ± 15.28 ^{a}	28.35 ± 1.21 ^{cd}	1.54 ± 0.12 ^{d}	0.51 ± 0.03 ^{abc}	0.49 ± 0.04 ^{abc}	1.03 ± 0.07 ^{bc}
CV	2022	894.00 ± 110.31	50.62 ± 2.06 ^{b}	106.02 ± 3.06 ^{a}	22.33 ± 0.67 ^{e}	1.64 ± 0.10 ^{d}	0.44 ± 0.03 ^{cd}	0.56 ± 0.09 ^{abc}	0.82 ± 0.02 ^{c}
CV	2023	882.02 ± 89.02	52.80 ± 3.00 ^{b}	112.00 ± 4.16 ^{a}	23.24 ± 0.62 ^{de}	1.58 ± 0.06 ^{d}	0.42 ± 0.03 ^{cd}	0.58 ± 0.08 ^{ab}	0.87 ± 0.04 ^{bc}
CA	2022	1089.00 ± 93.56	68.41 ± 2.35 ^{a}	35.00 ± 5.77 ^{c}	38.46 ± 1.24 ^{a}	2.86 ± 0.06 ^{a}	0.39 ± 0.01 ^{cd}	0.77 ± 0.06 ^{a}	1.70 ± 0.15 ^{a}
CA	2023	1056.01 ± 80.43	70.04 ± 3.46 ^{a}	33.33 ± 1.76 ^{c}	37.03 ± 1.73 ^{ab}	2.74 ± 0.10 ^{ab}	0.37 ± 0.06 ^{cd}	0.72 ± 0.01 ^{a}	1.82 ± 0.08 ^{a}
AS	2022	1043.00 ± 55.22	46.74 ± 1.73 ^{b}	114.00 ± 13.01 ^{a}	32.26 ± 0.63 ^{bc}	1.39 ± 0.12 ^{d}	0.45 ± 0.03 ^{bcd}	0.58 ± 0.09 ^{ab}	1.05 ± 0.06 ^{bc}
AS	2023	1068.00 ± 89.20	42.00 ± 2.65 ^{b}	108.00 ± 6.11 ^{a}	31.99± 1.15 ^{bc}	1.33 ± 0.17 ^{de}	0.47 ± 0.05 ^{bcd}	0.51 ± 0.06 ^{abc}	0.97 ± 0.11 ^{bc}
Cultivar (C)		***	***	***	***	***	***	***	***
Year (Y)		NS	NS	NS	NS	NS	NS	NS	NS
Cultivar (C) × Year (Y)		NS	NS	NS	NS	NS	NS	NS	NS

[1] Values are means of three biological replicates ± standard error ($n = 3$). Within each berry fraction and column, means followed by different lowercase letters differ significantly among cultivar × year combinations (Tukey's HSD test, $p < 0.05$). Where no letters are shown, Tukey's test detected no pairwise differences. Significance of the two-way ANOVA effects with year as a fixed factor: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS: not significant. AL: Alphonse Lavallée, SU: Sultana, TS: Tekirdag Seedless, CA: Cardinal, CV: Cavus, AS: Ata Sarısı, FW: fresh weight. Sultana and Tekirdag Seedless are seedless cultivars and therefore have no whole-berry values.

Table 2. Two-year mean mineral element concentrations of whole (B) and seedless (SB) berries of the six table grape cultivars (mg kg^{-1} FW).

Cultivar	Berry Fraction	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Iron (Fe)	Copper (Cu)	Zinc (Zn)	Manganese (Mn)
AL	B	1368.00 ± 63.03 ^{a1}	58.91 ± 2.48 ^{d}	85.50 ± 2.40 ^{bc}	13.29 ± 0.41 ^{f}	1.17 ± 0.04 ^{g}	0.49 ± 0.02 ^{bcde}	0.41 ± 0.05 ^{def}	1.74 ± 0.05 ^{b}
AL	SB	1271.17 ± 50.32 ^{ab}	27.77 ± 1.38 ^{g}	53.50 ± 3.25 ^{de}	11.59 ± 0.59 ^{f}	0.83 ± 0.06 ^{h}	0.32 ± 0.02 ^{f}	0.29 ± 0.02 ^{f}	0.92 ± 0.04 ^{e}
SU	SB	1195.00 ± 46.81 ^{ab}	50.25 ± 1.47 ^{ef}	100.50 ± 11.13 ^{bc}	22.08 ± 0.73 ^{de}	2.25 ± 0.06 ^{c}	0.65 ± 0.03 ^{a}	0.38 ± 0.01 ^{ef}	1.18 ± 0.05 ^{cd}
TS	SB	917.50 ± 31.02 ^{c}	52.92 ± 1.11 ^{de}	108.00 ± 7.02 ^{b}	26.44 ± 1.16 ^{c}	1.50 ± 0.07 ^{ef}	0.50 ± 0.02 ^{bcd}	0.50 ± 0.03 ^{cde}	1.06 ± 0.04 ^{cde}
CV	B	900.29 ± 36.48 ^{c}	91.84 ± 1.70 ^{a}	141.67 ± 7.03 ^{a}	19.59 ± 0.85 ^{e}	1.80 ± 0.07 ^{d}	0.56 ± 0.02 ^{abc}	0.73 ± 0.05 ^{ab}	1.03 ± 0.04 ^{cde}
CV	SB	888.00 ± 63.45 ^{c}	51.71 ± 1.70 ^{def}	109.00 ± 2.67 ^{b}	22.78 ± 0.46 ^{cde}	1.61 ± 0.05 ^{def}	0.43 ± 0.02 ^{def}	0.57 ± 0.05 ^{bcd}	0.84 ± 0.02 ^{e}
CA	B	1150.22 ± 56.23 ^{ab}	77.76 ± 1.65 ^{b}	76.50 ± 2.57 ^{cd}	30.85 ± 1.01 ^{b}	3.24 ± 0.07 ^{a}	0.44 ± 0.02 ^{de}	0.85 ± 0.03 ^{a}	2.62 ± 0.09 ^{a}
CA	SB	1072.50 ± 55.67 ^{bc}	69.23 ± 1.91 ^{c}	34.17 ± 2.7 ^{e}	37.75 ± 1.01 ^{a}	2.80 ± 0.06 ^{b}	0.38 ± 0.03 ^{ef}	0.75 ± 0.03 ^{ab}	1.76 ± 0.08 ^{b}
AS	B	1100.59 ± 25.87 ^{bc}	68.37 ± 2.34 ^{c}	149.17 ± 8.86 ^{a}	24.71 ± 0.96 ^{cd}	1.73 ± 0.05 ^{de}	0.57 ± 0.03 ^{ab}	0.65 ± 0.05 ^{bc}	1.28 ± 0.05 ^{c}
AS	SB	1055.50 ± 47.25 ^{bc}	44.37 ± 1.77 ^{f}	111.00 ± 6.57 ^{b}	32.13 ± 0.59 ^{b}	1.36 ± 0.09 ^{fg}	0.46 ± 0.02 ^{cde}	0.55 ± 0.05 ^{cde}	1.01 ± 0.06 ^{de}
One-way ANOVA		***	***	***	***	***	***	***	***
Seeded cultivars only (AL, CV, CA, AS; two-way ANOVA)									
Cultivar (C)		***	***	***	***	***	***	***	***
Berry fraction (BF)		NS	***	***	***	***	***	***	***
Cultivar (C) × Berry fraction (BF)		NS	***	NS	***	NS	NS	NS	***

[1] Values are means ± standard error of six observations ($n = 6$; three biological replicates in each of two consecutive years). Within each column, means followed by different letters differ significantly among the ten cultivar × berry fraction combinations (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$). The effect of seed presence was tested with a two-way ANOVA (cultivar × berry fraction) on the four seeded cultivars. The letters refer only to the one-way ANOVA among the ten cultivar × berry fraction combinations; the two-way ANOVA restricted to the seeded cultivars (lower part of the table) is reported with significance symbols only. *** $p < 0.001$, NS: not significant. AL: Alphonse Lavallée, SU: Sultana, TS: Tekirdag Seedless, CA: Cardinal, CV: Cavus, AS: Ata Sarısı, B: whole berry; SB: seedless berry (naturally seedless cultivars) or seed-removed berry fraction (seeded cultivars); FW: fresh weight.

When evaluating macro mineral concentrations, Alphonse Lavallée stood out for its potassium (K) content, while Cavus showed high concentrations of calcium (Ca) and magnesium (Mg). Cardinal showed elevated sodium (Na) levels, a mineral considered beneficial for plants. K, the most abundant element in grape berries, differed significantly among the cultivars (Table 2): whole berries of Alphonse Lavallée had the highest K concentration (1368 mg kg^{-1}), significantly higher than those of Cavus (900 mg kg^{-1}) and Tekirdag Seedless (918 mg kg^{-1}), whereas the other cultivars had intermediate values (1056–1271 mg kg^{-1}) with overlapping significance groups. This pattern aligns with findings by Rogiers et al. [14] who documented similar cultivar-specific K accumulation patterns. In the early stages of grape berry development, minerals are supplied through both phloem and xylem; however, in some grape cultivars, xylem flow is interrupted or reduced at the onset of ripening. This may be related to a low transpiration rate [15] due to surface conductance and stomatal occlusion by a wax layer [16]. Therefore, K moves into the berries mainly through the phloem. Moreover, variations in the leaf-to-fruit ratio among cultivars also significantly affect K influx from leaves to berries [17]. Numerically, the K concentration of Ata Sarısı (1101 mg kg^{-1}) fell between those of its parents, Cavus and Cardinal, without differing significantly from either parent (Table 2), and was closer to Cardinal's.

In contrast, Tekirdag Seedless exhibited lower K concentrations than both parents, falling outside the parental range. This finding contrasts with the results of Amiri and Fallahi [18] and Pisciotta et al. [19], who generally observed intermediate mineral concentrations in hybrid cultivars. Because grapevines are highly heterozygous, a single selected progeny genotype need not show values intermediate between those of its parents; with only two hybrids, however, such deviations cannot be interpreted as evidence of a particular inheritance pattern. Although Alphonse Lavallée had the highest K content, Tekirdag Seedless had low content. Similarly, although Cavus had one of the lowest K concentrations, Ata Sarısı did not. Thus, in the two parent–progeny combinations examined here, the K concentration of the hybrid did not simply mirror that of either parent; whether this applies more generally would require larger progeny populations.

Cavus had the highest Ca concentration (91.8 mg kg^{-1} in whole berries), whereas whole berries of Ata Sarısı (68.4 mg kg^{-1}) had significantly lower Ca than those of both of its parents (Table 2). Alphonse Lavallée had the lowest Ca concentration in both whole berries and the seed-removed fraction. The remarkably low Ca values of this cultivar differ from typical accumulation patterns reported in the literature. Unlike K and N, Ca is immobile in the phloem. Therefore, roots take it up and redistribute it to shoots via the xylem in both the symplast and apoplast, but the phloem cannot mobilize it from older tissues and redistribute it. Nutrient uptake largely depends on the transpiration rate [20,21]. Low transpiration rates in young leaves, enclosed tissues, and clusters may lead to cessation of xylem flow and low Ca concentrations after véraison in some cultivars [22]. In Sultana, higher values were observed than in the seedless fraction of Alphonse Lavallée, and the Ca content of their hybrid, Tekirdag Seedless, was close to that of Sultana.

Regarding Ca content, the differences between whole and seed-removed berries varied among cultivars in the seeded cultivars (AL, CV, CA, and AS), reflecting a significant cultivar × berry fraction interaction rather than a uniform response. These tissue-specific mineral accumulation patterns were indicated by Cabanne and Donèche [9]. Previous studies identified the seeds as the main sink for Ca, Mn, and Zn, and the flesh as the main sink for Cu, K, Mg, and Na [5]; however, in this study, these fraction-based variations are not based on direct mineral measurement of the seeds, but on tissue-specific distribution and differences in mass proportions of tissues. On the other hand, high Ca concentration

is also important for fruit quality, as it promotes firmer berry texture and pulp tissues by cross-linking pectic substances with Ca ions [9,13].

Cavus and Ata Sarısı showed the highest Mg concentrations in both seeded and seedless berries, whereas Alphonse Lavallée and Cardinal showed notably lower Mg concentrations (Table 2). When evaluating these phenotypic similarities, it should be noted that the pedigree background is shared, as Cardinal is a hybrid derived partly from Alphonse Lavallée (Table 3). In both hybrids (Tekirdag Seedless and Ata Sarısı), Mg concentrations were closer to those of Sultana and Cavus, respectively. Because this study evaluates only two selected hybrid cultivars, it cannot attribute this similarity to a specific genetic mechanism; these phenotypic patterns reflect cultivar-specific accumulation under identical vineyard conditions rather than demonstrated genetic inheritance mechanisms. Similarly, Grace et al. [23] investigated 10 mineral elements in 29 grape genotypes and reported that none of the single genotypes contained the maximum levels of all mineral nutrients. Tekirdag Seedless had a higher Na concentration than Alphonse Lavallée and Sultana, and the difference was statistically significant (Table 2). Ata Sarısı had Na content between Cavus and Cardinal. Alphonse Lavallée had the lowest Na concentration, and Cardinal had the highest value.

Table 3. Grape cultivars used in the study and some of their characteristics.

Code	Cultivar	Parents	Skin Color	Seed
TS	Tekirdag Seedless	Alphonse Lavallée × Sultana	Blue-black	Seedless
AS	Ata Sarısı	Cavus × Cardinal	Yellow	Seeded
AL	Alphonse Lavallée	Karistvala Kolkhuri × Muscat Hamburg	Blue-black	Seeded
SU	Sultana		Yellow	Seedless
CA	Cardinal	Flame Tokay × Alphonse Lavallée	Dark red-violet	Seeded
CV	Cavus		Green-yellow	Seeded

Whole berries of Cardinal had the highest Fe (3.24 mg kg^{-1}) and Mn (2.62 mg kg^{-1}) concentrations, significantly higher than all other cultivar × berry fraction combinations, and the highest Zn concentration (0.85 mg kg^{-1}), although for Zn the difference from whole berries of Cavus and from the seed-removed fraction of Cardinal was not significant. Cardinal did not stand out for Cu, which was highest in Sultana (0.65 mg kg^{-1}) (Table 2). Grace et al. [23] also reported that Cardinal berries and seeds are rich in Ca and Fe.

Tekirdag Seedless showed intermediate Fe, Cu, and Mn concentrations, and its Zn content was similar to that of Sultana and higher than that of the seedless berries of Alphonse Lavallée. The micro-mineral accumulation pattern of Ata Sarısı was more complex. Its Mn concentration was between Cavus and Cardinal. The Fe concentration of Ata Sarısı (1.73 mg kg^{-1}) did not differ significantly from that of Cavus (1.80 mg kg^{-1}) and was markedly lower than that of Cardinal (3.24 mg kg^{-1}). Its Cu and Zn contents were similar to those of Cavus. These differences in berry mineral concentrations between cultivars support observations by Sofo et al. [24] on cultivar-dependent variations in micronutrient accumulation in grape tissues. Cu, Mn, and Zn are primarily transported via the xylem; therefore, transpiration rates influence their uptake. However, xylem sap composition, pH, and redox potential may also determine metal ion translocation. These elements, particularly Cu, are transported together with amino acids or organic acids, which may form complexes with Zn [25]. While few metal ion transporters in the plant vacuole have been identified [26], macro- and micro-minerals can, in some cases, be transported together via the same antiporter. For example, Mg and Zn can be transported via the same H+ antiporter; Zn can also be taken up into the vacuole through another H+ antiporter shared with Mn. From this point of view, it is possible that the accumulation patterns of certain

minerals in grape berries are interrelated; however, this was not tested in the present study. Future molecular studies may further clarify the underlying transport mechanisms governing these tissue concentrations.

2.2. Influence of Seed Presence on Berry Mineral Concentrations

In the two-way ANOVA on the seeded cultivars (Alphonse Lavallée, Cavus, Cardinal, and Ata Sarısı) (Table 2), berry fraction had a statistically significant main effect for all elements except K ($p < 0.001$). For elements where the cultivar × berry fraction interaction was not significant (Mg, Fe, Cu, and Zn), seed removal consistently reduced concentrations across all four cultivars, with seed-removed fractions lower than whole berries, while K concentrations remained unaffected. In contrast, cultivar × berry fraction interactions were significant for Ca, Na, and Mn ($p < 0.001$), showing that the response to seed removal varied by cultivar rather than being uniform. Specifically, the reduction in Ca upon seed removal varied, being largest in Alphonse Lavallée (−52.8%, from 58.9 to 27.8 mg kg^{-1}) and Cavus (−43.7%, from 91.8 to 51.7 mg kg^{-1}), smaller in Ata Sarısı (−35.1%, from 68.4 to 44.4 mg kg^{-1}), and the smallest in Cardinal (−11.1%, from 77.8 to 69.2 mg kg^{-1}). For Mn, seed removal reduced levels by −47.1% in Alphonse Lavallée (1.74 to 0.92 mg kg^{-1}), −32.8% in Cardinal (2.62 to 1.76 mg kg^{-1}), −21.1% in Ata Sarısı (1.28 to 1.01 mg kg^{-1}), and −18.4% in Cavus (1.03 to 0.84 mg kg^{-1}). In contrast, Na increased in the seed-removed fraction of Ata Sarısı, Cardinal, and Cavus, while remaining constant in Alphonse Lavallée. These findings are consistent with the studies of Özcan et al. [27], Tangolar et al. [10] and Kunter et al. [12], which reported high micro-mineral accumulation in the seeds, as well as in the skin and pulp tissues. However, our results partially contradict some studies that report more pronounced differences between seeded and seedless varieties [8].

Concurrently, naturally seedless cultivars (Sultana and Tekirdag Seedless) showed relatively high concentrations of macro- and micro-elements, demonstrating that high mineral density can occur without seeds. These profiles may reflect unique, cultivar-specific accumulation patterns concentrated in the skin and mesocarp tissues. When interpreting the differences in mineral concentrations between whole berries and the seed-removed fraction (SB), it should be noted that this comparison does not directly reflect measured seed mineral content, but rather relative tissue distribution and differences in tissue mass proportions. The literature widely recognizes seeds as major sinks for mineral nutrients (such as phosphorus, calcium, and microelements); thus, interpretation of statements identifying seeds as the principal storage tissues in this study is based on general grapevine physiology. Therefore, these fraction-based comparisons provide preliminary insights into cultivar-specific partitioning within berry tissues while acknowledging the structural and mass-related variations. Furthermore, variations in berry size among cultivars influence the skin/flesh ratio, suggesting that the mineral accumulation and distribution into berry tissues may differ. In seedless berries, the absence of seed also affects the skin/flesh ratio; indeed, Boselli et al. [28] reported that the presence of seeds in berries and the number of seeds per berry can influence berry size and mineral composition. These observations highlight that berry flesh and skin tissues are substantial mineral stores in their own right, aligning with Likar et al. [29] regarding the significant contribution of tissues except seeds to overall berry mineral composition.

2.3. Multivariate Analysis

PCA and heatmap analyses were applied to the mineral composition dataset as descriptive and exploratory tools to summarize variance structure and visualize phenotypic relationships among cultivars; they are not presented as confirmatory tests, and their outputs are interpreted accordingly. The PCA matrix comprised all 60 individual observations,

encompassing the ten cultivar × berry fraction combinations across two growing seasons with three independent biological replicates ($10 \times 2 \times 3 = 60$). In contrast, the heatmap visualized standardized mean values ($n = 20$) across cultivar × year × berry fraction combinations. PCA captured 66.3% of the total variance in the first two components (PC1: 41.1%; PC2: 25.2%; Figure 1); PC3 (14.6%) also had an eigenvalue > 1 and was mainly associated with K and Cu (loadings 0.63 and 0.50; Figure 1B). PC1 was defined by positive loadings of Fe (0.50), Zn (0.49), Ca (0.42), Na (0.40), and Mn (0.39), whereas K loaded only weakly on this axis (−0.12). PC2 was dominated by Mg (0.63) and Cu (0.48) on the positive side and by K (−0.42) and Mn (−0.34) on the negative side. Cardinal samples were located on the positive side of PC1, in the direction of Na, Ca, Fe, Zn, and Mn. Whole berries of Cavus and Ata Sarısı were located on the positive side of PC2, reflecting their higher Mg and Cu concentrations, whereas Alphonse Lavallée was located on the negative side of both axes, in the direction of K. In the biplot (Figure 1C), points for 2022 and 2023 within each cultivar clustered closely together, indicating minimal seasonal contribution to the overall ordination. However, a distinct separation between whole and seed-removed fractions was evident, particularly for Cavus, Ata Sarısı, and Alphonse Lavallée, demonstrating that seed removal contributed to the multivariate structure. Sultana, Tekirdag Seedless and the seed-removed fractions of Cavus and Ata Sarısı overlapped in the upper-left quadrant, indicating broadly similar profiles. These multivariate groupings illustrate phenotypic similarities under the evaluated vineyard conditions.

The Z-score heatmap (Figure 2) showed the same patterns: Cardinal had above-average Na, Ca, Fe, Zn and Mn in both years; whole berries of Cavus and Ata Sarısı had above-average Mg, Cu and Ca; Alphonse Lavallée had the highest K and below-average values for most other elements, particularly in seedless berries; Sultana had the highest Cu; and Tekirdag Seedless was close to the overall mean for most elements except for its low K. These patterns were similar in 2022 and 2023. From a compositional perspective, these findings describe distinct mineral profiles among the evaluated cultivars under identical vineyard conditions. Although certain cultivars had higher levels of specific elements, such as micro-minerals in Cardinal or K in Alphonse Lavallée, these differences represent comparative elemental concentrations rather than demonstrated nutritional advantages.

The Pearson correlation matrix (Figure 3) was evaluated as an exploratory analysis complementing the PCA ($n = 60$). The strongest positive correlations were found between Ca and Zn ($r = 0.72$), Fe and Mn ($r = 0.70$), Fe and Zn ($r = 0.69$), Na and Fe ($r = 0.67$), Na and Zn ($r = 0.59$), Ca and Fe ($r = 0.58$), and Mg and Cu ($r = 0.56$) ($p < 0.001$). The Na–Ca–Fe–Zn–Mn group corresponds to elements with positive loadings on PC1 and largely reflects the high concentrations in Cardinal, whereas the Mg–Cu association corresponds to PC2 and reflects Cavus and Ata Sarısı. K was weakly negatively correlated with Mg ($r = -0.34$), Na ($r = -0.32$), Zn ($r = -0.27$), and Ca ($r = -0.26$), weakly positively correlated with Mn ($r = 0.32$), and not correlated with Fe or Cu; therefore, the data do not indicate a consistent antagonism between K and micronutrients. Because the correlations were computed across cultivars, years, and berry fractions, they mainly reflect statistical covariation among cultivar profiles and should be interpreted as descriptive patterns, not physiological interactions within the vine.

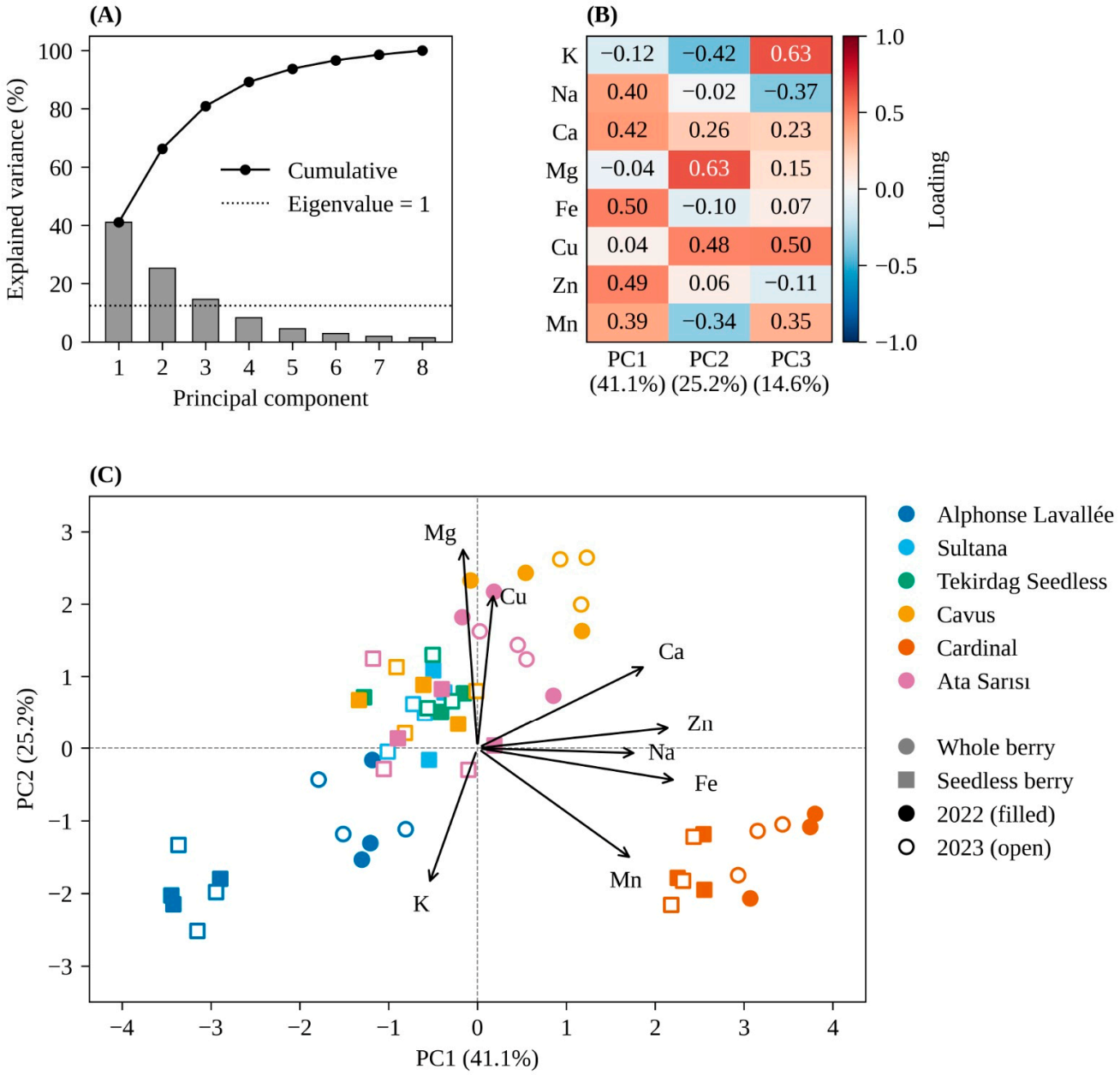

Figure 1. Principal component analysis (PCA) of mineral concentrations in grape berries from six cultivars over two growing seasons (2022–2023). (**A**) Scree plot showing the percentage of variance explained by each principal component (PC) and the cumulative variance (black line). (**B**) Loadings of the three components with eigenvalues > 1. (**C**) Biplot of PC1 and PC2; colors represent cultivars, circles and squares indicate whole and seedless berries, and filled and open markers denote 2022 and 2023, respectively. SB indicates both naturally seedless berries and the seed-removed berry fraction of seeded cultivars. PCA was performed on the correlation matrix of autoscaled data (mean-centred and scaled to unit variance; $n = 60$); in (**C**), sample scores are plotted and loading vectors are rescaled to fit the score axes.

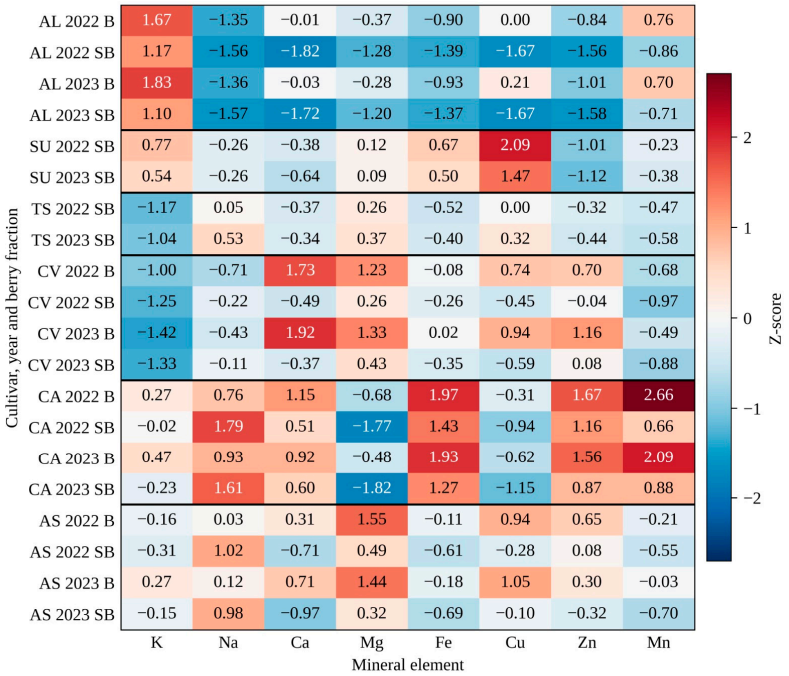

Figure 2. Heatmap of Z-score standardized mineral concentrations in grape berries grouped by cultivar, year, and berry type. Row labels indicate cultivar abbreviation, harvest year, and berry type (B = whole berry; SB = seedless berry). SB indicates both naturally seedless berries and the seed-removed berry fraction of seeded cultivars. Bold horizontal lines separate cultivar groups. For each element (column), Z-scores were calculated from the 20 cultivar × year × berry fraction means using the mean and standard deviation of these 20 values; the color gradient represents deviation from this column mean (blue: below mean; red: above mean). AL = Alphonse Lavallée, SU = Sultana, TS = Tekirdag Seedless, CA = Cardinal, CV = Cavus, AS = Ata Sarısı. Values are Z-scores of the means ($n = 3$).

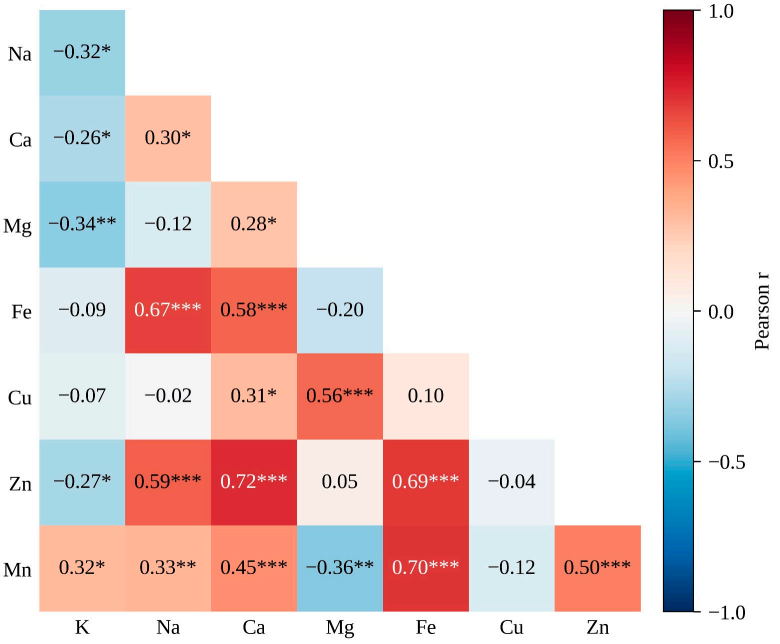

Figure 3. Pearson correlation matrix of mineral element concentrations (K, Na, Ca, Mg, Fe, Cu, Zn, and Mn) in grape berries across six cultivars and two growing seasons (2022–2023). Values represent Pearson correlation coefficients (r); color intensity indicates the strength and direction of the correlation (blue: negative, red: positive). $n = 60$; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Significance levels are not adjusted for multiple comparisons; the matrix is presented as an exploratory analysis.

3. Materials and Methods

3.1. Research Area and Plant Materials

The experiment was conducted in the vineyards of the Research Station for Viticulture in Kalecik, Ankara (40°06′ N 33°25′ E, 670 m a.s.l.) during the 2022 and 2023 growing seasons. Two hybrid table grape cultivars (*Vitis vinifera* L.) and their parent cultivars (*Vitis vinifera* L.) were used in the study. All cultivars were grown in the same experimental vineyard. 'Tekirdag Seedless' and 'Ata Sarısı' were released from the national breeding programs in Türkiye. Ata Sarısı was registered by Yalova Atatürk Horticulture Central Research Institute in 1989. Tekirdag Seedless was registered by Tekirdag Viticulture Research Institute in 1990 as a seedless cultivar. Both are used for fresh consumption because of their large berries and attractive clusters. Some of the characteristics of the cultivars are presented in Table 3 and Figure 4. The trial plot was planted in 2000 with a row spacing of 1.5 m × 3 m. Grapevines were grafted onto 1103P rootstock and trained to a bilateral cordon. The experimental vineyard soil was clay loam. Although the studied grape cultivars were grown in adjacent rows, within the same experimental plot, Table S1 presents the analysis of soil samples collected from four representative points across the experimental plot (K15, K16, K19, and K24), to establish general baseline edaphic characteristics of the site [30]. The research region has a continental climate. Table S2 presents the main climatic conditions for the 2022 and 2023 growing seasons. Meteorological data were obtained from the Turkish State Meteorological Service station in the research area.

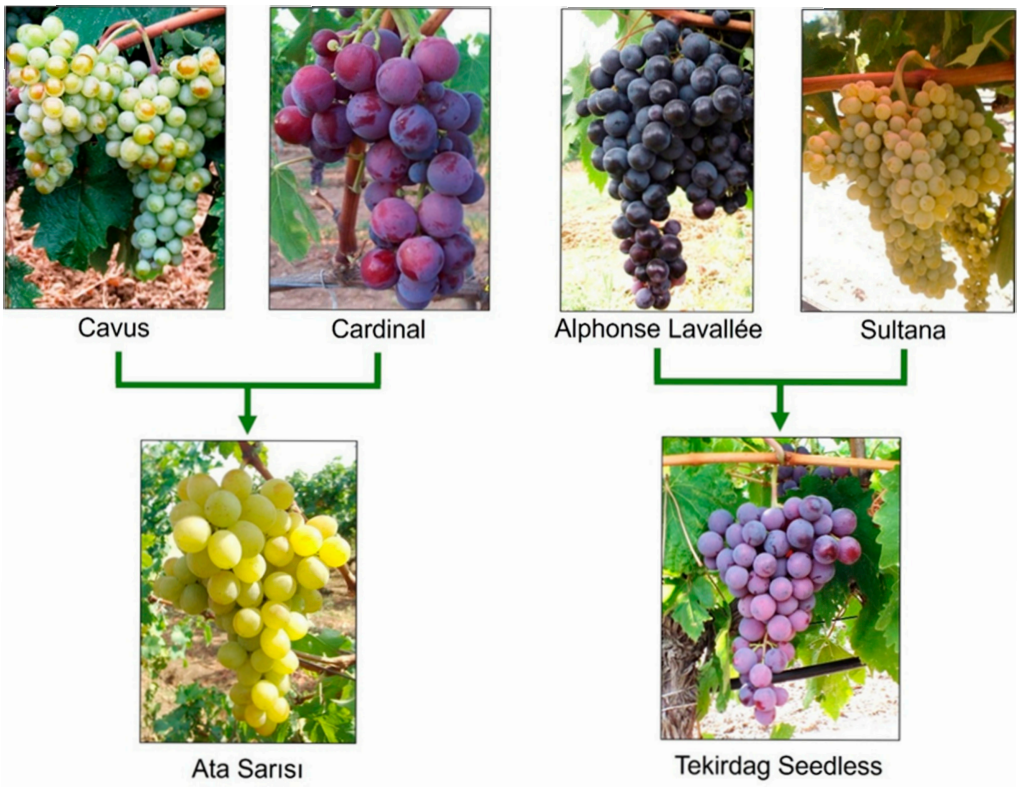

Figure 4. Parental cultivars and their respective hybrids used in the study. Upper panel (left to right): Cavus (CV), Cardinal (CA), Alphonse Lavallée (AL), and Sultana (SU). Lower panel: Ata Sarısı (AS) (hybrid of Cavus × Cardinal) and Tekirdag Seedless (TS) (hybrid of Alphonse Lavallée × Sultana).

3.2. Experimental Design and Berry Sampling

The experiment followed a completely randomized design with three independent biological replicates ($n = 3$). Each replicate consisted of four vines with uniform growth vigor. The vines were spur-pruned to 2–3 buds in the dormant period. Drip irrigation

was applied 3 times per growing season, from budburst to pre-véraison, supplying 15 L of water per vine over 10 h per irrigation event. Vines were managed and grown using standard cultural practices. Sulfur and copper spraying were used against powdery mildew and downy mildew. Each grape cultivar was manually harvested at commercial maturity, approximately 15–18 °Bx [31]. Because ripening times slightly varied among the studied grape cultivars, harvests were completed sequentially across an approximately 10-day period each year, ensuring the same maturity level across both years. To obtain a representative biological sample for each replicate, three healthy clusters were harvested from each of the four vines (a total of 12 clusters per replicate). After transferring the clusters to the laboratory, random berry samples were collected from the top, middle and bottom of each harvested cluster to form a total sample of 150 healthy berries, which constituted the final analytical replicate. Berries were thoroughly rinsed with distilled water and gently dried. For seeded cultivars, this composite sample was divided into two equivalent analytical sets: one set was processed and analyzed as whole (seeded) berries (B), and the second set was used for the analysis of the seedless berry fraction (SB). Thus, for each seeded cultivar, the whole-berry and seed-removed samples of a given replicate were obtained from the same composite berry sample, so that the two fractions are directly comparable. The prepared samples were placed in sealed polyethylene zip-lock bags, immediately frozen, and stored in a deep freezer at −20 °C for a maximum of 15 days. Mineral analyses were initiated after harvesting all grape cultivars in both years to ensure consistent analytical conditions. Sampling, digestion, and ICP-MS measurements were performed independently for each of the three biological replicates across two consecutive growing seasons. Two years of data were evaluated as separate production cycles, and the average across the two years was also evaluated.

3.3. Mineral Analysis

Macro- and micro-mineral concentrations of grape samples, including sodium (Na), a beneficial mineral for plants, were determined using ICP-MS (Inductively Coupled Plasma Mass Spectrometry, 7500a Agilent, Santa Clara, CA, USA) [32]. Mineral analysis was done on whole berries (B) and seedless berries (SB). Berries of naturally seedless cultivars were named "SB" directly (Sultana and Tekirdag Seedless). For seeded cultivars (Ata Sarısı, Alphonse Lavallée, Cardinal and Cavus), two equivalent analytical sample sets were used, as described above: one set was processed and analyzed as whole berries (B), while for the second set, seeds were manually removed prior to homogenization to obtain the seed-removed berry fraction (SB). That is, the abbreviation SB represents both the berries of naturally seedless cultivars and the 'seed-removed berry fraction' obtained from seeded cultivars. The whole- and seedless-berry samples were then homogenized using a blender. Briefly, 5 g of the homogenate was weighed and transferred to a vessel. Then, 5 mL of 65% nitric acid (HNO_3) and 5 mL of distilled water were added. After waiting for 30 min, the vessels were placed in the closed microwave sampling system (CEM MARS 5, CEM Corporation, Matthews, NC, USA). The microwave oven program was set for six samples, as listed in Table 4. After being cooled to room temperature, 0.5 mL of nitric acid was added to each vessel. The samples were then transferred to a volumetric flask and made up to 50 mL with deionized water. The samples were filtered through a 0.45 µm membrane, and ICP-MS analysis was performed under the conditions shown in Table 5. The concentrations of potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), manganese (Mn), iron (Fe), copper (Cu), and zinc (Zn) were determined in the extracts using external standardization by preparing standard curves for each element analyzed. The results were expressed in mg kg^{-1} fresh weight. As a methodological limitation, validation procedures or spike-recovery tests were not performed in this study; therefore, absolute trace element concentrations were

interpreted with this analytical constraint in mind. Furthermore, because moisture content of berries or dry-weight concentrations were not determined, the data were interpreted strictly as fresh-weight concentrations.

Table 4. Operating conditions of the microwave oven.

Stage	Max. Watt	Power (%)	Ramp. Time	Press. Control	Max. Temp.	Stirrer	Hold Time (min)
1	600	100	15.00	600 psi	180 °C	–	10.00
2	600	100	10.00	600 psi	210 °C	–	10.00

Table 5. Instrumental operating conditions for ICP-MS.

Spectrometer	Mass
Radiofrequency power	1500 W
Plasma gas flow rate (argon)	15 L min^{-1}
Auxiliary gas flow rate	0.95 L min^{-1}
Carrier gas flow rate	1.01 L min^{-1}
Sampling depth	7.3 mm
Acquisition mode	Spectrum
Number of replicates	3
Spray chamber temperature	2 °C
Nebulizer	Babington type
Cone	Nickel

3.4. Statistical Analysis

The experiment was conducted using a completely randomized design (CRD). All data are presented as mean ± standard error (Mean ± SE) of three independent biological replicates ($n = 3$), with each replicate representing the pooled composite sample of four vines. Because Sultana and Tekirdag Seedless have no whole-berry fraction, the data were analyzed in three ways: (i) for each berry fraction separately, a two-way ANOVA with cultivar, year, and cultivar × year as fixed factors was performed (Table 1) according to the model $Yijk = \mu + Cultivar_i + Year_j + (Cultivar \times Year)_{ij} + \varepsilon_{ijk}$, where μ is the overall mean, $Cultivar_i$ and $Year_j$ are the fixed main effects, $(Cultivar \times Year)_{ij}$ is their interaction, and ε_{ijk} is the random error associated with the biological replicates (k = 1–3 per cultivar and year). The same designated four-vine plots were sampled in both seasons; replicates were treated as independent within each year, and the possible dependence between years arising from repeated sampling of the same plots was not modelled separately; (ii) data were pooled over the two growing seasons ($n = 6$), and the ten cultivar–berry fraction combinations were compared by one-way ANOVA (Table 2), to summarize the overall cultivar profiles over the two seasons; pooling was used for description because the year effect and the cultivar × year interaction were not significant (Table 1), except for Mn in whole berries, and the standard errors of the pooled means include between-year variation; (iii) the effect of seed presence was tested with a two-way ANOVA (cultivar × berry fraction) restricted to the four seeded cultivars. Means were separated with Tukey's HSD test at $p < 0.05$. Normality of residuals and homogeneity of variances were checked with the Shapiro–Wilk and Levene's tests, respectively; deviations from normality were minor and limited to a few elements, and log-transformation did not alter the significance of the main effects; thus, untransformed data are reported. Pearson correlation coefficients and PCA were computed on the individual observations ($n = 60$, 10 cultivar × berry fraction combinations, across 2 years × 3 biological replicates) after autoscaling; PCA was performed on the correlation matrix, and components with eigenvalues > 1 were retained. The heatmap illustrates the

Z-scores of the cultivar × year × berry fraction means to summarize overall profile patterns. All statistical analyses were performed in Python 3.12 using statsmodels 0.15 and SciPy 1.17, and figures were generated with Matplotlib 3.10.

4. Conclusions

This two-year study characterized distinct, cultivar-specific berry mineral element concentration profiles among the evaluated table grape cultivars grown under the same vineyard conditions. Alphonse Lavallée stood out for K content, Cavus for Ca and Mg, and Cardinal for Na, Fe, Zn, and Mn. These distinctive mineral signatures reflected cultivar differences under identical growing conditions, though determining their actual nutritional significance requires future bioavailability studies.

The comparison between whole berries and the seed-removed fractions of the seeded cultivars showed generally lower mineral concentrations in the seed-removed fractions, with significant differences for all elements except K; Na was an exception, being higher in the seed-removed fractions of three cultivars. Interestingly, naturally seedless cultivars such as Sultana and Tekirdag Seedless exhibited relatively high levels of certain minerals, indicating that skin and flesh tissues alone can accumulate substantial amounts of minerals, although direct analysis of each tissue is needed to verify tissue-specific partitioning. Furthermore, the evaluated hybrid cultivars exhibited distinct mineral profiles that did not necessarily match or fall intermediate to those of their parents under identical growing conditions. These comparisons should be interpreted strictly as phenotypic characterizations under the specific vineyard conditions tested, not as evidence of genetic inheritance or heritability patterns. Because grapevine cultivars are highly heterozygous, each registered cultivar represents a single selected genotype, and the pedigree involves shared ancestry (with Cardinal derived partly from Alphonse Lavallée), observed phenotypic similarities cannot be directly interpreted as general inheritance models. The study was also limited to two hybrid cultivars and their four parents, with three biological replicates per cultivar and year, which restricts the statistical power to detect small differences and the generality of the comparisons. Finally, findings may vary depending on ecological conditions, cultural practices, and/or soil characteristics. Given that all genotypes were evaluated at a single experimental vineyard over two seasons, future multi-environment trials, direct analysis of each berry tissue, and genetic studies are needed to separate genetic and environmental variables and elucidate the mechanisms governing mineral accumulation across berry tissues.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants15223584/s1, Table S1: Physicochemical properties of the soil samples collected from the experimental vineyard plot; Table S2: Climatic conditions of the experimental vineyard (Kalecik, Ankara) in the 2022 and 2023 growing seasons.

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Data Availability Statement: The original contributions presented in this study are included in the Supplementary Materials. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ICP-MS	Inductively Coupled Plasma Mass Spectrometry
PCA	Principal Component Analysis
ANOVA	Analysis of Variance
CRD	Completely Randomized Design
SE	Standard Error
FW	Fresh Weight
B	Whole Berry
SB	Seedless Berry
AL	Alphonse Lavallée
SU	Sultana
TS	Tekirdag Seedless
CV	Cavus
CA	Cardinal
AS	Ata Sarısı

References

1. Hatterman-Valenti, H.; Kaya, O.; Yilmaz, T.; Ates, F.; Turan, M. Phenolic, amino acid, mineral, and vitamin contents during berry development in 'Italia' and 'Bronx Seedless' grape cultivars. *Horticulturae* **2024**, *10*, 429. [CrossRef]
2. Martins, V.; Cunha, A.; Gerós, H.; Hanana, M.; Blumwald, E. Mineral compounds in grape berry. In *The Biochemistry of the Grape Berry*; Bentham Science: Sharjah, United Arab Emirates, 2012; pp. 23–43.
3. Kunter, B.; Unal, O.B.; Keskin, S.; Hatterman-Valenti, H.; Kaya, O. Comparison of the sugar and organic acid components of seventeen table grape varieties produced in Ankara (Türkiye): A study over two consecutive seasons. *Front. Plant Sci.* **2024**, *15*, 1321210. [CrossRef]
4. Cantürk, S.; Kunter, B.; Aykut, O.; Keskin, N. Gülüzümü'nün (*Vitis vinifera* L.) mineral madde kompozisyonu ve tanedeki dağılımı. *Bahçe* **2016**, *45*, 683–687.
5. Bertoldi, D.; Larcher, R.; Bertamini, M.; Otto, S.; Concheri, G.; Nicolini, G. Accumulation and distribution pattern of macro- and microelements and trace elements in *Vitis vinifera* L. cv. Chardonnay berries. *J. Agric. Food Chem.* **2011**, *59*, 7224–7236. [CrossRef]
6. Kaya, O.; Incesu, M.; Ates, F.; Keskin, N.; Verdugo-Vásquez, N.; Gutiérrez-Gamboa, G. Study of volatile organic compounds of two table grapes (cv. Italia and Bronx Seedless) along ripening in vines established in the Aegean Region (Turkey). *Plants* **2022**, *11*, 1935. [CrossRef]
7. Esteban, M.A.; Villanueva, M.J.; Lissarrague, J.R. Effect of irrigation on changes in berry composition of Tempranillo during maturation. Sugars, organic acids, and mineral elements. *Am. J. Enol. Vitic.* **1999**, *50*, 418–434. [CrossRef]
8. Rogiers, S.Y.; Greer, D.H.; Hatfield, J.M.; Orchard, B.A.; Keller, M. Mineral sinks within ripening grape berries (*Vitis vinifera* L.). *Vitis* **2006**, *43*, 115–123.
9. Cabanne, C.; Donèche, B. Calcium accumulation and redistribution during the development of grape berry. *Vitis* **2003**, *42*, 19–21.
10. Tangolar, S.G.; Özoğul, Y.; Tangolar, S.; Torun, A. Evaluation of fatty acid profiles and mineral content of grape seed oil of some grape genotypes. *Int. J. Food Sci. Nutr.* **2009**, *60*, 32–39. [CrossRef]
11. Gomes, T.M.; Toaldo, I.M.; da Silva Haas, I.C.; Burin, V.M.; Caliari, V.; Luna, A.S.; de Gois, J.S.; Bordignon-Luiz, M.T. Differential contribution of grape peel, pulp, and seed to bioaccessibility of micronutrients and major polyphenolic compounds of red and white grapes through simulated human digestion. *J. Funct. Foods* **2019**, *52*, 699–708. [CrossRef]
12. Kunter, B.; Keskin, N.; Canturk, S. Effects of cultivar-rootstock combinations on mineral composition of grapes. In *Proceedings of the International Cukurova Agriculture and Veterinary Congress*; İKSAD Publishing House: Ankara, Türkiye, 2021; Volume 9, pp. 628–637.
13. Shimizu, H.; Akamatsu, F.; Kamada, A.; Koyama, K.; Iwashita, K.; Goto-Yamamoto, N. Effects of variety and vintage on the minerals of grape juice from a single vineyard. *J. Food Compos. Anal.* **2022**, *107*, 104377. [CrossRef]
14. Rogiers, S.Y.; Coetzee, Z.A.; Walker, R.R.; Deloire, A.; Tyerman, S.D. Potassium in the grape (*Vitis vinifera* L.) berry: Transport and function. *Front. Plant Sci.* **2017**, *8*, 1629. [CrossRef]
15. Greer, D.H.; Rogiers, S.Y. Water flux of *Vitis vinifera* L. cv. Shiraz bunches throughout development and in relation to late-season weight loss. *Am. J. Enol. Vitic.* **2009**, *60*, 155–163. [CrossRef]
16. Rogiers, S.Y.; Hatfield, J.M.; Jaudzems, V.G.; White, R.G.; Keller, M. Grape berry cv. Shiraz epicuticular wax and transpiration during ripening and preharvest weight loss. *Am. J. Enol. Vitic.* **2004**, *55*, 121–127. [CrossRef]
17. Zhenming, N.; Xuefeng, X.; Yi, W.; Tianzhong, L.; Jin, K.; Zhenhai, H. Effects of leaf-applied potassium, gibberellin and source-sink ratio on potassium absorption and dis-tribution in grape fruits. *Sci. Hortic.* **2008**, *115*, 164–167. [CrossRef]

18. Amiri, M.E.; Fallahi, E. Influence of mineral nutrients on growth, yield, berry quality, and petiole mineral nutrient concen-trations of table grape. *J. Plant Nutr.* **2007**, *30*, 463–470. [CrossRef]
19. Pisciotta, A.; Di Lorenzo, R.; Novara, A.; Laudicina, V.A.; Barone, E.; Santoro, A.; Gristina, L.; Barbagallo, M.G. Cover crop and pruning residue management to reduce nitrogen mineral fertilization in Mediterranean vineyards. *Agronomy* **2021**, *11*, 164. [CrossRef]
20. White, P.J. The pathways of calcium movement to the xylem. *J. Exp. Bot.* **2001**, *52*, 891–899. [CrossRef]
21. White, P.J.; Broadley, M.R. Calcium in plants. *Ann. Bot.* **2003**, *92*, 487–511. [CrossRef]
22. Bondada, B.R.; Matthews, M.A.; Shackel, K.A. Functional xylem in the post-veraison grape berry. *J. Exp. Bot.* **2005**, *56*, 2949–2957. [CrossRef]
23. Grace, U.M.; Verma, M.K.; Singh, S.K.; Sethi, S.; Pandey, R.; Mir, A.I.; Kumar, C. Elemental variation of berry mineral nutrient content in early maturing grapes genotypes grown under sub-tropical climate. *Grape Insight* **2023**, *1*, 81–88. [CrossRef]
24. Sofo, A.; Nuzzo, V.; Tataranni, G.; Manfra, M.; De Nisco, M.; Scopa, A. Berry morphology and composition in irrigated and non-irrigated grapevine (*Vitis vinifera* L.). *J. Plant Physiol.* **2012**, *169*, 1023–1031. [CrossRef]
25. Reichman, S. *The Responses of Plants to Metal Toxicity: A Review Focusing on Copper, Manganese and Zinc*; Australian Minerals & Energy Environment Foundation: Melbourne, VIC, Australia, 2022; Volume 14.
26. Martinoia, E.; Maeshima, M.; Neuhaus, H.E. Vacuolar transporters and their essential role in plant metabolism. *J. Exp. Bot.* **2007**, *58*, 83–102. [CrossRef]
27. Özcan, M.M.; Al Juhaimi, F.; Gülcü, M.; Uslu, N.; Geçgel, Ü. Determination of bioactive compounds and mineral contents of seedless parts and seeds of grapes. *S. Afr. J. Enol. Vitic.* **2017**, *38*, 212–220. [CrossRef]
28. Boselli, M.; Volpe, B.; Di Vaio, C. Effect of seed number per berry on mineral composition of grapevine (*Vitis vinifera* L.) berries. *J. Hortic. Sci.* **1995**, *70*, 509–515. [CrossRef]
29. Likar, M.; Vogel-Mikuš, K.; Potisek, M.; Hančević, K.; Radić, T.; Nečemer, M.; Regvar, M. Importance of soil and vineyard management in the determination of grapevine mineral composition. *Sci. Total Environ.* **2015**, *505*, 724–731. [CrossRef]
30. Akça, M.O.; Türkmen, F.; Taşkın, M.B.; Soba, M.R.; Öztürk, H.S. Ankara Üniversitesi Kalecik Araştırma ve Uygulama Çiftliği topraklarının verimlilik durumlarının incelenmesi. *Toprak Bilim. Ve Bitki Besleme Derg.* **2015**, *3*, 54–63.
31. Keller, M. Developmental physiology. In *The Science of Grapevines*; Keller, M., Ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2020; Volume 6, pp. 199–277. [CrossRef]
32. Nordic Committee on Food Analysis (NMKL). *Metals. Determination by Atomic Absorption Spectrophotometry After Wet Digestion in a Microwave Oven*; Method 161; Nordic Committee on Food Analysis (NMKL): Oslo, Norway, 1998.

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