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Effects of Different Fertilization Treatments on Fruit Quality, Biochemical Contents, and Mineral Composition of Strawberry

Ahmet Sümbül [1], Funda Koçak [2], Mehmet Yaman [2,*], Ayten Eroğlu [3], Fatih Demirel [4], Serap Demirel [5], Ahmet Say [6], Metin Gönültaş [6], Monica Popescu [7] and Cristian Gheorghe Popescu [8]

[1] Department of Plant and Animal Production, Suşehri Timur Karabal Vocational School, Sivas Cumhuriyet University, 58600 Sivas, Türkiye; asumbul3188@gmail.com
[2] Department of Horticulture, Faculty of Agriculture, Erciyes University, 38280 Kayseri, Türkiye; fundakocakk9@gmail.com
[3] Department of Biology, Faculty of Science, Van Yüzüncü Yıl University, 65000 Van, Türkiye; ayteneroglu@gmail.com
[4] Department of Agricultural Biotechnology, Faculty of Agriculture, Iğdır University, 76000 Iğdır, Türkiye; fatih.demirel@igdir.edu.tr
[5] Department of Zootechnics, Faculty of Agriculture, Iğdır University, 76000 Iğdır, Türkiye; serap.demirel@igdir.edu.tr
[6] Department of Agricultural Biotechnology, Faculty of Agriculture, Erciyes University, 38280 Kayseri, Türkiye; ahmetsay@erciyes.edu.tr (A.S.); metingonultas@erciyes.edu.tr (M.G.)
[7] Department of Natural Sciences, National University of Science and Technology Politehnica Bucharest, Pitesti University Centre, 110040 Piteşti, Romania; monica_26_10@yahoo.com
[8] Department of Applied Sciences and Environmental Engineering, National University of Science and Technology Politehnica Bucharest, Pitesti University Centre, 110040 Pitesti, Romania; christian_popescu2000@yahoo.com
* Correspondence: mehmetyaman@erciyes.edu.tr

Highlights

What are the main findings?

- The treatment of a foliar fertilizer with high boron and zinc content (Dogatech Borozinc, T3) showed a significant effect on yield, fruit size, DPPH activity, and anthocyanin content in 'Albion' strawberry fruits.
- Foliar fertilizer treatments increased the bioactive components and antioxidant capacity of the fruits and leaves; however, the biochemical contents of the fruits and leaves varied depending on the foliar fertilizer application. In addition, foliar fertilizers significantly increased fruit redness (a*) compared to the control.
- The mineral balance of the fruits and leaves varied depending on the foliar fertilizer formulation. The multi-nutrient foliar fertilizer formulation (Dogatech Combi, T1) maximized all mineral concentrations in the fruits.

What are the implications of the main findings?

- In strawberry cultivation, the foliar fertilizer should be selected in accordance with the production objective.
- Foliar fertilizers have a positive effect on fruit color, which is one of the important quality criteria in strawberries.

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Academic Editor: Maria Roulia

Received: 17 September 2026
Revised: 13 October 2026
Accepted: 13 October 2026
Published: 16 October 2026

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Abstract

Foliar fertilization may increase strawberry yield and quality while reducing the environmental load of soil fertilization. The study was conducted as a field experiment with three replications according to a randomized block design at the Erciyes University Agricultural Research and Application Center (Kayseri, Türkiye). This study investigated the effects of different foliar fertilizer treatments (Dogatech Combi, Axion, and Dogatech Borozinc) on

fruit morphological traits, SPAD values, leaf and fruit mineral element composition, and biochemical contents of the 'Albion' strawberry cultivar. Foliar fertilizer treatments significantly affected fruit traits. Dogatech Borozinc treatment produced the highest yield per plant (688.00 g plant^{-1}) and the largest fruit, with a mean fruit weight of 15.59 g. Dogatech Combi (T1; 111.84) and Dogatech Borozinc (T3; 111.27) showed significantly higher fruit a* values (redness) than the control treatment (82.27). Dogatech Combi significantly increased mineral concentrations in the fruits, and showed the greatest effect on all elements (particularly Ca (19,453.05 mg kg^{-1} DW) and K (17,496.42 mg kg^{-1} DW)). Among the biochemical characteristics, Axion showed the highest total phenolic content in fruits (487.72 mg GAE 100 g^{-1}) and leaves (2042.49 mg GAE 100 g^{-1}). The total flavonoid content of fruits and leaves was highest in the Dogatech Combi, while Dogatech Borozinc exhibited the highest DPPH radical-scavenging activity of fruits and leaves and the fruit anthocyanin content. Principal component analysis (PCA) and heatmap hierarchical clustering analysis revealed distinct patterns among the fertilizer treatments. Overall, since foliar fertilizer responses vary depending on the formulation, fertilizer selection in strawberry cultivation should be based on production objectives.

Keywords: *Fragaria* × *ananassa* Duch.; foliar fertilization; multivariate analysis; antioxidant capacity; yield per plant

1. Introduction

Strawberries (*Fragaria* × *ananassa* Duch.) are widely cultivated worldwide due to their extensive adaptability and high commercial value. Their distinctive aroma, bright red color, and high nutritional value contribute to their strong consumer appeal and economic importance. Strawberries are an important fruit in human diet due to their rich biochemical content with antioxidant properties, vitamins (especially vitamin C), minerals, and dietary fiber [1–3]. Strawberries, which are rich in bioactive compounds and have high antioxidant potential, directly affect cardiovascular and cardiometabolic diseases. Strawberries have antioxidant, anti-inflammatory, anti-hyperlipidemic, and blood pressure-lowering effects [4].

Global strawberry production is approximately 10,728,881 tons on an area of 436,067 ha. Türkiye is one of the world's leading strawberry-producing countries, with 606,524 tons of strawberry production on an area of 19,651 ha [5]. Many strawberry cultivars adapted to different ecological conditions are grown in Türkiye. Among these cultivars, 'Albion' is a day-neutral cultivar and is one of the most preferred cultivars in modern strawberry cultivation thanks to its excellent adaptation to cool and temperate climates, high fruit quality, long shelf life, and resistance to common diseases (anthracnose and verticillium) [6].

Cultivars with high-yield potential, such as Albion, require not only suitable climatic conditions but also a balanced and effective plant nutrition program to reach their full potential. Strawberry plants have a shallow root system and are quite selective in terms of nutrient absorption. Because of their rapid growth, strawberries have relatively high nutrient requirements to support photosynthesis and other metabolic processes [7,8]. Strawberries are one of the plants most susceptible to fertilizer-induced diseases, and fertilizer management is a crucial factor for high yield and fruit quality [9]. Strawberry growers commonly use intensive chemical fertilization programs to maximize yield per unit area and fruit quality. Chemical fertilizers, widely used to increase product yields, also carry risks such as environmental pollution, soil degradation, and the formation of hazardous

residues in fruits [2,3,10]. These concerns have increased interest in nutrient-management approaches that are more compatible with soil and environmental health [11]. At this point, foliar fertilization, which enables rapid uptake of nutrients by the plant and can mitigate negative effects caused by soil conditions (pH, salinity, etc.), is an economical and strategic method for increasing yield and quality in modern cultivation [12,13]. Foliar application may reduce the environmental load associated with soil fertilization, mainly because lower nutrient rates are required [14], and it also rapidly improves physiological disorders in plants [12].

Mineral nutrition plays a fundamental role in the growth, development, yield, and fruit quality of strawberry plants. Plant nutrients play a direct role in fundamental physiological and biochemical processes, including photosynthesis, enzyme activation, carbohydrate metabolism, and secondary metabolite biosynthesis. Numerous studies in the literature examine the effects of different foliar fertilization strategies on the morphological and biochemical characteristics and mineral content of strawberries. However, fertilization strategies vary considerably depending on the type, concentration, formulation, treatment frequency of the foliar fertilizer used, variety-specific responses, and environmental conditions [15–18].

Macro and micronutrients play a vital role in the growth, yield, and fruit quality of strawberry plants. Nitrogen (N), phosphorus (P), and potassium (K) are essential macronutrients for plant growth and development. These elements, as vital molecules associated with various fundamental metabolic processes, play a specific role in the different physiological and morphological functions of the plant [19]. Specifically, Phosphorus (P) plays a role in various plant functions, including energy transfer, photosynthesis, the conversion of sugars and starches, and the transport of nutrients within the plant. It also has a significant effect on fruit quality parameters and the activation of defense mechanisms [14]. Micronutrient deficiencies are quite common in plants [17]. Foliar application of micronutrients allows nutrients to be absorbed directly through the leaves, thus providing an effective method for rapidly correcting soil-borne deficiencies [20]. Soils in Türkiye generally have a high pH and high lime content. Therefore, micronutrient deficiencies, such as Zn and B, are frequently observed in plants [21]. Particularly in semi-arid regions like the study area, soils have low organic matter content, and micronutrient deficiencies often occur during the growing season under conditions of low rainfall [22]. Zinc is essential for numerous enzymatic processes, auxin synthesis, and reproductive development. Zinc deficiency, commonly observed in acidic and alkaline soils, can lead to delayed maturation, reduced photosynthesis, and smaller fruit size. Boron is vital for sugar transport, cell wall integrity, pollen germination, and fruit quality. Boron deficiency can negatively affect pollination, cell division, and carbohydrate metabolism, resulting in poor fruit set and yield loss [20].

The relationships among plant growth, fruit quality, and mineral content are quite complex, and these parameters constantly interact with each other. However, studies examining the complex interactions among these parameters using a holistic approach are quite limited. Multivariate analyses have been used in recent years to determine the effects of fertilization on strawberries [18,23,24].

Foliar fertilization has advantages such as application at low concentrations, ensuring homogeneous distribution of nutrients within the plant, and eliciting a faster physiological response [25,26]. In a popular cultivar like ‘Albion’, which has high yield potential, simultaneously evaluating the effects of different foliar fertilizers on plant performance is critical for determining the most appropriate fertilization protocols. This study aims to systematically investigate the effects of different foliar fertilizer formulations on the ‘Albion’ strawberry cultivar using multivariate analysis. The selection of the ‘Albion’ cultivar is

based on specific agronomic characteristics, such as its compatibility with the growing conditions in the study region, high yield potential, and superior fruit quality. Furthermore, its widespread popularity among growers due to its superior characteristics makes the Albion cultivar a suitable cultivar for this study. The study focuses on various morphological characteristics, as well as the nutrient composition, biochemical content, and antioxidant activity of the fruit and leaf. The excessive and indiscriminate use of chemical fertilizers disrupts soil pH, reduces beneficial soil organisms, damages ecosystems, limits nutrient availability, and reduces soil fertility [27]. Therefore, the foliar fertilizers used in the study were selected from among the fertilizer forms commonly used by growers in strawberry cultivation. Foliar fertilizers were selected not only to compare commercial fertilizers, but also to evaluate different nutritional strategies affecting yield and fruit quality in strawberries in the same trial. Fertilizers were selected to represent a plant nutrition approach based on their nutrient composition: (i) a balanced mixture providing macronutrients and micronutrients; (ii) a phosphorus-rich formulation supporting generative development; and (iii) a boron-zinc combination closely associated with flowering, fruit set, and fruit development. The results to be obtained from this research are expected to provide important information for enhancing the nutritional and functional quality of the 'Albion' cultivar. Furthermore, the results provide valuable information for future research on foliar fertilization strategies for other strawberry cultivars and similar fruit types. In conclusion, the study's findings aim to support sustainable horticultural practices by improving scientific knowledge and practical agricultural treatments. Upon completion of this study, it will be possible to offer targeted alternative fertilizer compositions to producers by determining the mechanisms of action of the fertilizer forms used in strawberry production.

2. Materials and Methods

2.1. Plant Material

The study was conducted at the Erciyes University Agricultural Research and Application Center (ERUTAM), Kayseri, Türkiye (38°42′45″ N, 35°32′28″ E), during the 2025 growing season (May–September). The soil characteristics of the study area were reported by Pak and Güneş [24]. The researchers reported that the soil has a sandy-loam texture, a pH of 8.00, an organic matter content of 1.05%, and a $CaCO_3$ content of 4.40%. Healthy, uniformly developed frigo seedlings (bare-root seedlings stored in cold storage) of the 'Albion' cultivar were used as plant material. The 'Albion' cultivar is a day-neutral cultivar known for its high fruit quality and disease resistance. The Albion cultivar was registered by researchers at the University of California in 2004. The frigo seedlings were obtained from a commercial nursery (Yaltir Agriculture Company). Before planting, the long and damaged roots of the frigo seedlings were pruned. The fungicide CLERMONT 035 FS was used against fungal diseases. CLERMONT 035 FS is a product containing 25 g/L fludioxonil and 10 g/L metalaxyl as active ingredients. The fungicide applied to the seedlings was prepared at the concentration specified by the manufacturer (250 mL per 100 L of water). A 0.2% fungicide solution was prepared for use in the study based on the concentration specified by the manufacturer. The seedlings were sterilized by immersion in a fungicide solution for 5 min as a preventive measure against fungal diseases. The seedlings were planted on 1 May 2024, on beds covered with black mulch, using a drip-irrigation-compatible system. Strawberry seedlings were planted in beds at 30 × 30 cm intervals. The beds are 3.5 m long, 60 cm wide, and 30 cm high, with a distance of 1 m between beds (total plot area 63.7 m^2). To encourage stronger growth of the seedlings, the flowers and shoots that formed during the first year of planting were removed throughout the growing season. Standard cultural practices (irrigation, fertilization, weed control, disease and pest control, etc.) were implemented to ensure optimal seedling growth during the first year. In the first week of

March, when active vegetative growth began in the strawberry plants, soil fertilization was carried out using a 15-15-15 compound fertilizer (Total N 15% (Ammoniacal N 12% and Urea N 3%); Neutral Ammonium Citrate and Water-Soluble Phosphorus Pentoxide (P_2O_5) 15%; Water-Soluble Potassium Oxide (K_2O) 15%; Water-Soluble Sulfur Trioxide (SO_3) 15%; Water-Soluble Zinc (Zn) 1%; 400 kg ha^{-1}). This uniform basal fertilization was applied to minimize differences in nutrient supply before the foliar treatments. The plants were regularly watered using a drip irrigation system, and standard cultural care practices (weed control, disease and pest control, stolon removal, etc.) were applied equally to all plants.

2.2. Foliar Fertilizer Treatments

The study was conducted using a randomized block design with 3 replications and 20 plants in each replication. In this study, the foliar fertilizer formulations Dogatech Combi, Axion, and Dogatech Borozinc were designated T1, T2, and T3, respectively; the control treatment received distilled water only. Dogatech Combi was selected as a broad-spectrum formulation containing macronutrients (N-P-K) along with Mg, Fe, Mn, Zn, B, and Cu, to provide a multi-nutrient support effect. Axion was selected as a phosphorus-rich formulation intended to support generative development during flowering and fruit set. Dogatech Borozinc was selected because of its high B and Zn contents and their relevance to pollination, fruit set, cell-wall formation, and enzymatic processes. Foliar fertilizer solutions were prepared according to the manufacturer's recommendations (Table 1). Foliar fertilizer treatments were performed in the early morning (06:00–08:00) under clear and windless conditions to minimize evaporation losses. Approximately 50 mL of solution was applied per plant to achieve uniform leaf coverage. For each fertilizer product, the nutrient amounts in 100 L of treatment mixture were calculated and then scaled according to the spray volume per plant (~50 mL). To ensure transparency and reproducibility of the fertilization protocol, the nutrient amounts per treatment and per plant are presented in Table 1. Foliar fertilization treatments were performed using a Cat Power-2070 brand backpack sprayer were repeated three times, on 1 April, 15 April, and 1 May. The control plants received no foliar fertilizer and were sprayed with distilled water on the same dates.

Table 1. Detailed information on fertilizer treatments.

Treatment	Trade Name	Contents	%*w*/*w*	Treatment Dose	Nutrient per Seedlings (mg/Plant)
T1	Dogatech Combi	Total nitrogen (Urea N)	10%	200 g/da or 200 g/100 lt	10
		Water-soluble phosphorus pentaoxide (P_2O_5)	5%		5
		Water-soluble potassium oxide (K_2O)	5%		5
		Water-soluble magnesium oxide (MgO)	2%		2
		Water-soluble boron (B)	0.05%		0.05
		Water-soluble copper (Cu) (All chelated with EDTA)	0.05%		0.05
		Water-soluble iron (Fe) (All chelated with EDTA)	2%		2
		Water-soluble manganese (Mn) (All chelated with EDTA)	1%		1
		Water-soluble zinc (Zn) (All chelated with EDTA)	2.4%		2.4

Table 1. *Cont.*

Treatment	Trade Name	Contents	%*w*/*w*	Treatment Dose	Nutrient per Seedlings (mg/Plant)
T2	Axion	Total nitrogen (Ammonium N: 8.4%, Urea N: 3.6%)	12%	200 g/da or 200 g/100 lt	12
		Water-soluble phosphorus pentaoxide (P_2O_5)	52%		52
		Water-soluble potassium oxide (K_2O)	6%		6
		Water-soluble copper (Cu) (All chelated with EDTA)	0.01%		0.01
		Water-soluble manganese (Mn) (All chelated with EDTA)	0.01%		0.01
		Water-soluble zinc (Zn) (All chelated with EDTA)	0.02%		0.02
T3	Dogatech Borozinc	Total nitrogen (Urea N)	10%	200 g/da or 200 g/100 lt	10
		Water-soluble phosphorus pentaoxide (P_2O_5)	5%		5
		Water-soluble potassium oxide (K_2O)	5%		5
		Water-soluble magnesium oxide (MgO)	3%		3
		Water-soluble boron (B)	8%		8
		Water-soluble zinc (Zn) (All chelated with EDTA)	1%		1
Control	Distilled water	-	-	-	-

2.3. Pomological Analysis

The study was conducted in 2025. This period corresponds to the main economic yield period in the study area; increasing temperatures during July and August may reduce strawberry yield while increasing stolon production [28]. The fruits were harvested twice a week (at the stage when at least 80% of the fruit color was red). Deformed and rotten fruits were not included in the analysis. Analyses were planned in three replications and were performed on 30 fruits in each replication. Pomological analyses were performed on randomly selected fruits after each harvest. Fruit width (Fwidth) and fruit length (FL) were measured using a precision digital caliper (Insize 1104 IP54), while fruit weight (FW) was measured using a digital scale (Precisa, XB 4200C) with a precision of 0.01 g. After determining the total weight of each experimental plot, the yield per plant, representing the yield, was calculated by dividing the total weight by the number of plants in each treatment plot. The colors of the fruits were determined using a colorimeter. Color measurements were performed using a Minolta CR-300 chromameter (Osaka, Japan) according to the CIE L*a*b method at two opposite points along the central axis of the fruit, and the data were averaged. The SPAD values of the leaves were determined using a SPAD meter (Minolta SPAD 502, Osaka, Japan). The SPAD value of the leaves was measured once a week throughout the treatment period. SPAD measurements were conducted between 12:00 and 14:00.

2.4. Fruit and Leaf Biochemical Analysis

Extraction: During the study period, the harvested fruit and leaf were divided into 3 replicates each week, and analyses were performed. The biochemical compounds from the leaves and fruits were obtained by maceration in 80% methanol at 25 °C for 24 h in a shaker. The resulting solution was filtered through filter paper (110 mm ø, Whatman No. 2) and then centrifuged (Hettich H-1650R, Tuttlingen, Germany) at 11200× *g* for 15 min [29]. The obtained methanol extracts were used to determine the biochemical content (total phenolic content, total flavonoid content, and antioxidant activity) of the leaves and fruits.

Total Phenolic Content (TPC): TPC of leaves and fruits was determined according to the Folin–Ciocalteu method [30]. Briefly, 500 µL of the extract was mixed with 4.2 mL of distilled water, 100 µL of Folin–Ciocalteu solution (diluted 1/10), and 1 mL of 2% sodium carbonate (Na_2CO_3). The mixture was incubated in the dark for 2 h. The absorbance values of the solutions were measured at a wavelength of 760 nm using a UV-Vis spectrophotometer (Shimadzu UV1800, Tokyo, Japan). TPC was expressed as mg gallic acid equivalent per 100 g fresh weight (mg GAE 100 g^{-1} FW).

Total Flavonoid Content (TFlvC): TFlvC of the leaves and fruits was determined according to the method described by Chang et al. [31]. 1000 µL of the sample was mixed with 3.3 mL of methanol, followed by the addition of 0.1 mL of 10% aluminum chloride hexahydrate ($AlCl_3 \cdot 6H_2O$) and 0.1 mL of 1 M potassium acetate (CH_3COOK) solution. The reaction mixtures were incubated at room temperature (24 ± 1 °C) for 2 h. Absorbance values of the solutions were measured at 415 nm using a UV-Vis spectrophotometer (Shimadzu UV1800, Tokyo, Japan). TFlvC was expressed as mg quercetin equivalent per 100 g fresh weight (mg QE 100 g^{-1} FW).

Antioxidant Activity (AA): AA of the leaves and fruits were determined using the DPPH (1,1-diphenyl-2-picryl-hydrazyl) method described by Brand-Williams et al. [32]. Briefly 100 µL of the sample was vortexed with 2900 µL of ethanol and 1 mL of 0.26 mM DPPH solution for 5 min. The resulting mixture was incubated in the dark for 30 min. Absorbance values of the solutions were determined at a wavelength of 517 nm (Asample), and the results were expressed as % inhibition. To calculate AA, a blank solution without fruit and leaf extract was used as a control, and its absorbance (Ablank) was measured. AA was determined using the following formula.

$$\% \text{ Inhibition of DPPH} = [(\text{Ablank} - \text{Asample})/\text{Ablank}] \times 100 \quad (1)$$

Total Anthocyanin Content (TAC): TAC of the fruits was determined according to the pH differential method described by Giusti et al. [33]. Briefly, 10 mL of methanol solution containing 1% hydrochloric acid (HCl) was added to 5 g of the fruit sample, and the resulting mixture was left to stand overnight. The solution was vortexed and then filtered through filter paper. To 1 mL of the solution, 4 mL of 0.025 M potassium chloride (KCl) buffer solution with a pH of 1.0 was added, and to another 1 mL of the solution, 4 mL of 0.4 M sodium acetate buffer solution with a pH of 4.5 was added. The absorbance values of the samples were measured at wavelengths of 520 and 700 nm using a UV-Vis spectrophotometer (Shimadzu UV1800, Tokyo, Japan). TAC was calculated as mg cyanidin 3-glucoside/100 g fresh weight (mg cyn 3-gluc 100 g^{-1} FW).

2.5. Mineral Content Analysis

Mineral content analyses of the leaves were performed on 50 leaves, and mineral content analyses of the fruits were performed on 20 fruits, with three replicates in each sample. During the study period, the harvested fruit and leaf were divided into 3 replicates each week, and analyses were performed. Before analysis, the fruit and leaves were cleaned with distilled water. The samples were dried at 65–70 °C until a constant weight was

reached, and then ground to ensure homogenization. 1 g of ground sample was digested with 0.5 mL of nitric acid (HNO_3) and 2 mL of hydrogen peroxide (H_2O_2) [34]. The mineral content of the obtained samples was determined using an Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES, Varian, Liberty Series II; Varian Inc., Palo Alto, CA, USA) [35].

2.6. Data Analysis

The mean value of the data obtained in the study were subjected to analysis of variance (ANOVA) using the JMP Pro 17 software package. Differences between means were compared using the Tukey test at a 5% significance level ($p \leq 0.05$). Data are presented as mean ± standard error. PCA, heatmap hierarchical clustering analysis, and correlation analysis were performed to determine the effectiveness of the characteristics and fertilizer treatments examined in the study. PCA was implemented using the ggbiplot2 module in the RStudio software package (2024) [36]. A PCA biplot graph is a graphical representation that makes the complexity of a dataset more understandable by visualizing the PCA components. Variables are rep-resented as vectors in a biplot graph, and the direction and length of the vector indicate the contribution of the respective variable to the variance explained in the analysis. Longer vectors represent stronger contributions. The angle between vectors represents the correlation between variables. Smaller angles indicate positive correlation, while larger angles indicate negative correlation. Heatmap hierarchical clustering analysis was performed using the JMP Pro 17 software package, and correlation analysis was performed using the Origin 2026 software package.

3. Results

3.1. Fruit Morphological Characteristics, Yield per Plant, and Leaf SPAD Value

The effects of the foliar fertilizer treatments on fruit morphological characteristics, yield per plant, and leaf SPAD values in the 'Albion' cultivar are presented in Table 2. Significant differences among treatments were observed for fruit width, fruit length, fruit weight ($p < 0.01$), and yield per plant ($p < 0.001$). Fruit width was in the same statistical group in all fertilizer treatments, and showed a significant increase compared to the control treatment (24.27 mm) (T1: 7.4%; T2: 8.2%; T3: 14.3%, respectively). The T3 fertilizer treatment showed the highest effect on fruit length (26.7%), fruit weight (38.6%), and yield (25.9%) compared to other treatments. Although T2 fertilizer treatment had a relatively high effect on fruit width, fruit length, and fruit weight compared to T1 fertilizer application, T1 fertilizer treatment was more effective on yield. This result suggests that the T1 fertilizer treatment may be effective in increasing fruit number compared to the T2 fertilizer treatment.

Table 2. Effects of different fertilizer treatments on fruit morphological characteristics, yield per plant, and SPAD value in the 'Albion' strawberry cultivar.

Treatments	Fruit Width (mm)	Fruit Length (mm)	Fruit Weight (g)	Yield (g Plant^{-1})	L*	a*	b*	SPAD
T1	26.07 ± 0.57 a [1]	36.91 ± 1.10 b	12.80 ± 0.43 b	595.67 ± 9.38 b	24.37 ± 0.95	111.84 ± 1.70 a	10.05 ± 1.21 b	35.90 ± 0.89
T2	26.25 ± 0.23 a	37.79 ± 0.52 b	12.94 ± 0.17 b	581.00 ± 10.45 bc	25.20 ± 0.36	99.37 ± 2.60 b	8.83 ± 0.28 b	35.38 ± 0.16
T3	27.74 ± 0.38 a	41.40 ± 0.76 a	15.59 ± 0.68 a	688.00 ± 12.71 a	23.10 ± 0.76	111.27 ± 1.74 a	8.34 ± 130 b	34.27 ± 0.76
Control	24.27 ± 0.80 b	32.68 ± 1.16 c	11.25 ± 0.97 b	546.67 ± 10.54 c	24.83 ± 017	82.27 ± 1.15 c	17.66 ± 0.80 a	36.39 ± 0.31
Significance	**	**	**	***	N.S.	***	**	N.S.

[1] Differences between means followed by different letters within the same column are statistically significant (N.S.: Non-significant, **: $p < 0.01$, ***: $p < 0.001$).

No significant differences were detected among fertilizer treatments for fruit L* values (23.10–25.20) and SPAD values (34.27–36.39). In contrast, fertilizer treatment significantly affected fruit a* and b* values. Fertilizer treatments T1 (35.9%) and T3 (35.2%) showed a high effect on the a* value, which represents redness. The b* color value showed a tendency to decrease by approximately 43% to 53% in all fertilizer applications and was identified as the most sensitive visual quality characteristic.

3.2. Leaf Mineral Element Composition

Significant differences among fertilizer treatments were observed for all evaluated leaf mineral elements (Table 3). Leaf nutrient content showed both increasing and decreasing trends depending on fertilizer treatments. The highest increase was observed in content B. T3 fertilizer treatment showed the highest increase with a rate of 168.3%, while T2 fertilizer treatment showed the lowest increase with a rate of 112.2%. Similar to B content, K content showed an increasing trend in the T3 (21.8%) and T1 (18.8%) fertilizer treatments. Leaf Zn content showed an increasing trend only with the T1 treatment (50.3%), while it showed a decreasing trend with the T2 (49.1%) and T3 (54.7%) treatments. This result can be attributed to the high Zn content in the T1 fertilizer application and the insufficient Zn content in the T2 and T3 fertilizer applications to meet the plant's needs. Indeed, the high yield and fruit weight observed with T3 fertilizer application increased the Zn requirement, while the high P content in T2 fertilizer application may have led to Zn deficiency. The trend of decrease in leaf mineral contents varied depending on the fertilizer application. The greatest decreases were observed in the contents of Ca (72.8% in T1 to 85.49% in T2), Fe (77.3% in T2 to 79.5% in T1), Mn (69.3% in T3 to 78.1% in T2), and Mg (50.6% in T1 to 57.3% in T2). The decrease in leaf mineral contents associated with fertilizer treatments compared to the control can be attributed to increased yield and fruit weight. Although fertilizer treatments contained different ratios of macro and micro elements, similar decreasing trends were observed in all fertilizer treatments. These results demonstrate that foliar fertilizer formulation substantially altered the mineral profile of the leaves.

3.3. Fruit Mineral Element Composition

Significant differences among fertilizer treatments were observed for all fruit mineral concentrations (Table 4). The effects of fertilizer treatments on fruit mineral contents varied depending on the mineral contents. T1 fertilizer treatment showed an increasing trend in all mineral elements, while T2 and T3 fertilizer treatments showed varying increasing and decreasing trends depending on the mineral element content. In contrast to the leaf mineral profile, the T1 treatment exhibited the highest concentration for each mineral element in the fruit. This result shows that fertilizers with a balanced content of macro and microelements increase the mineral content of the fruit. Overall, the results indicate that fruit mineral composition responded strongly and in a nutrient-specific manner to the foliar fertilizer formulations.

Table 3. Effects of different fertilizer treatments on leaf mineral element content (mg kg^{-1}) of 'Albion' strawberry cultivar.

Treatments	P	K	Ca	Mg	S	B	Fe	Mn	Zn	Na	Al
T1	1523.09 ± 17.58 b [1]	12,416.10 ± 143.36 a	2373.94 ± 27.41 b	1036.04 ± 11.96 b	367.80 ± 4.24 b	5.87 ± 0.06 b	9.73 ± 0.10 c	13.65 ± 0.15 c	30.82 ± 0.35 a	84.99 ± 0.98 b	18.52 ± 0.21 c
T2	1394.26 ± 16.10 d	11,774.18 ± 135.95 b	1275.53 ± 14.72 d	895.65 ± 10.34 c	319.63 ± 3.68 c	5.56 ± 0.06 c	10.80 ± 0.12 b	11.88 ± 0.13 d	10.43 ± 0.12 c	66.34 ± 0.76 c	10.00 ± 0.11 d
T3	1455.85 ± 16.81 c	12,734.02 ± 147.03 a	1829.23 ± 21.11 c	999.52 ± 11.54 b	351.73 ± 4.05 b	7.03 ± 0.08 a	10.49 ± 0.12 bc	16.67 ± 019 b	9.29 ± 0.10 d	67.17 ± 0.77 c	31.79 ± 0.36 b
Control	2074.07 ± 23.94 a	10,451.12 ± 120.67 c	8713.57 ± 100.61 a	2095.13 ± 24.19 a	640.49 ± 7.39 a	2.62 ± 0.03 d	47.53 ± 0.54 a	54.37 ± 0.62 a	20.50 ± 0.23 b	125.82 ± 1.45 a	43.13 ± 0.49 a
Significance	***	***	***	***	***	***	***	***	***	***	***

[1] Differences between means followed by different letters within the same column are statistically significant (N.S.: Non-significant, ***: $p < 0.001$).

Table 4. Effects of different fertilizer treatments on fruit mineral element content (mg kg^{-1}) of 'Albion' strawberry cultivar.

Treatments	P	K	Ca	Mg	S	B	Fe	Mn	Zn	Na	Al
T1	3404.34 ± 58.96 a [1]	17,496.42 ± 303.04 a	19,453.05 ± 336.93 a	4032.82 ± 69.84 a	1109.64 ± 19.21 a	51.79 ± 0.89 a	120.95 ± 2.09 a	158.80 ± 2.74 a	48.62 ± 0.84 a	234.46 ± 4.05 a	102.34 ± 1.77 a
T2	1943.70 ± 33.66 c	10,457.89 ± 181.13 c	11,966.66 ± 207.26 b	2314.10 ± 40.07 b	587.24 ± 10.17 c	39.66 ± 0.68 b	74.98 ± 1.29 b	71.64 ± 1.24 b	11.39 ± 0.19 c	137.13 ± 2.37 b	76.95 ± 1.33 b
T3	2003.29 ± 34.69 c	11,996.56 ± 207.78 b	10,583.94 ± 183.32 c	2197.47 ± 38.05 b	632.93 ± 10.96 b	40.38 ± 0.69 b	65.86 ± 1.14 c	59.76 ± 1.03 c	23.32 ± 0.40 b	125.82 ± 2.17 c	66.79 ± 1.15 c
Control	2165.39 ± 37.50 b	10,154.85 ± 175.88 c	10,590.14 ± 183.42 c	2195.70 ± 38.03 b	623.94 ± 10.80 bc	30.65 ± 0.53 c	48.03 ± 0.83 d	70.94 ± 1.22 b	24.04 ± 0.41 b	132.83 ± 2.29 bc	42.63 ± 0.73 d
Significance	***	***	***	***	***	***	***	***	***	***	***

[1] Differences between means followed by different letters within the same column are statistically significant (N.S.: Non-significant, ***: $p < 0.001$).

3.4. Biochemical Composition of Fruits and Leaves

The fertilizer treatments significantly affected the biochemical characteristics of fruits and leaves (Table 5). The effects of fertilizer treatments on the biochemical composition of leaves and fruits varied depending on the treatments. The highest effects on leaves and fruits were observed with the T2 fertilizer treatment for TPC, the T1 treatment for TFlvC, and the T3 treatment for AA and fruit TAC.

Table 5. Effects of different fertilizer treatments on fruit and leaf biochemical content of 'Albion' strawberry cultivar.

Treatments	Fruit TPC	Leaf TPC	Fruit TFlvC	Leaf TFlvC	Fruit AA	Leaf AA	Fruit TAC
T1	426.84 ± 4.17 b [1]	1788.46 ± 12.95 b	74.78 ± 0.72 a	1767.11 ± 19.39 a	55.68 ± 0.47 b	76.56 ± 0.50 b	32.84 ± 0.36 b
T2	487.72 ± 3.72 a	2042.49 ± 16.35 a	39.98 ± 0.49 c	944.61 ± 12.36 c	53.76 ± 0.54 b	73.92 ± 0.73 c	26.31 ± 0.26 c
T3	358.89 ± 4.36 c	1503.98 ± 22.38 c	45.05 ± 0.46 b	1064.40 ± 15.27 b	69.89 ± 0.89 a	96.10 ± 0.85 a	35.02 ± 0.50 a
Control	338.00 ± 2.80 d	1416.22 ± 18.59 d	45.63 ± 0.37 b	1078.24 ± 10.74 b	55.30 ± 0.49 b	76.03 ± 0.62 bc	23.92 ± 0.28 d
Significance	***	***	***	***	***	***	***

[1] Differences between means followed by different letters within the same column are statistically significant (N.S.: Non-significant, ***: $p < 0.001$). TPC: Total Phenolic Content (mg GAE 100 g^{-1} FW), TFlvC: Total Flavonoid Content (mg QE 100 g^{-1} FW), AA: Antioxidant Activity (%), TAC: Total Anthocyanin Content (mg cyn 3-gluc 100 g^{-1} FW).

3.5. Multivariate Relationships: Principal Component Analysis (PCA), Heatmap Hierarchical Clustering, and Correlation Analysis

To comprehensively evaluate the effects of different fertilizer treatments and the relationships between the examined parameters of the 'Albion' strawberry cultivar, PCA, heatmap hierarchical clustering analysis, and correlation analysis were performed. According to the PCA results (Table 6), the first three principal components explained 100% of the total variance (PCA1: 50.85%, PCA2: 33.89%, and PCA3: 15.26%). On the PCA1 axis, the a* color value (0.23), leaf K (0.22), leaf B (0.21), fruit B (0.21), and fruit Al (0.20) parameters provided the highest positive contribution; while leaf Fe (−0.22), leaf Mn (−0.22), leaf Ca (−0.21), leaf Mg (−0.21), leaf S (−0.21), leaf P (−0.21), and the b* color value (−0.21) parameters provided the highest negative contribution. On the PCA2 axis, leaf Zn (0.27), fruit Mn (0.25), fruit Na (0.24), fruit P (0.24), fruit S (0.23), fruit Ca (0.23), fruit Mg (0.23), fruit TFlvC (0.23), leaf TFlvC (0.23), SPAD (0.22) and fruit Zn (0.22) parameters provided the highest positive contribution. On the PCA3 axis, fruit TFC (−0,36), leaf TFC (−0.36), and L* value (−0.33) parameters provided the highest negative contribution, while fruit AA (0.28), leaf AA (0.28), fruit TAC (0.23), fruit Zn (0.22), and yield per plant (0.20) parameters provided the highest positive contribution. Overall, PCA1 represented a contrast between leaf mineral characteristics and fruit color, particularly a*, whereas PCA2 was associated mainly with fruit mineral composition and flavonoid content. PCA3 was characterized primarily by phenolic variables, antioxidant activity, and L*.

The PCA biplot graph revealed the effectiveness of fertilizer treatments and the parameters examined (Figure 1). According to the analysis, PC1 (50.85%) and PC2 (33.89%) together explain 84.74% of the total variation. This ratio indicates that nearly all of the variability in the data can be effectively captured and summarized in two dimensions. Biplot graph reveals distinct clustering patterns among fertilizer treatments, providing valuable information about the effectiveness of different foliar fertilizers for strawberries. The T1 fertilizer treatment located on the positive side of PC1 and PC2, was associated with the fruit mineral contents (P, Mg, Mn, Na, S, K, Ca, Fe, Al, and B) as well as the fruit and leaf TFlvC contents, and a positive correlation was observed among these elements. The directional association of these parameters indicates that total flavonoid content increases in parallel with the increase in mineral content in the fruit. It was determined that T2 and T3 fertilizer treatments, located on the positive side of PC1 and the negative side of PC2,

were associated with leaf and fruit AA content, morphological characteristics of the fruit (weight, width, and length), yield, LB and LK elements, a* color value, and fruit TAC, and these characteristics exhibited a positive correlation. The proximity of these parameters can be interpreted to mean that the B and K content in the leaves plays a role in encouraging fruit size characteristics, as well as the antioxidant activity levels of the fruit and the leaves. It was observed that the control treatment, located on the negative side of PC1 and the positive side of PC2, was associated with leaf mineral contents (Fe, Mn, Mg, S, Ca, P, and Na), b* color value, and SPAD value, and these characteristics exhibited a positive correlation. It is noteworthy that fruit size, yield, and fruit mineral content remained at the lowest levels in the control treatment. This suggests that the mechanisms for transporting nutrients from the leaves to the fruit are inadequate in the control treatment.

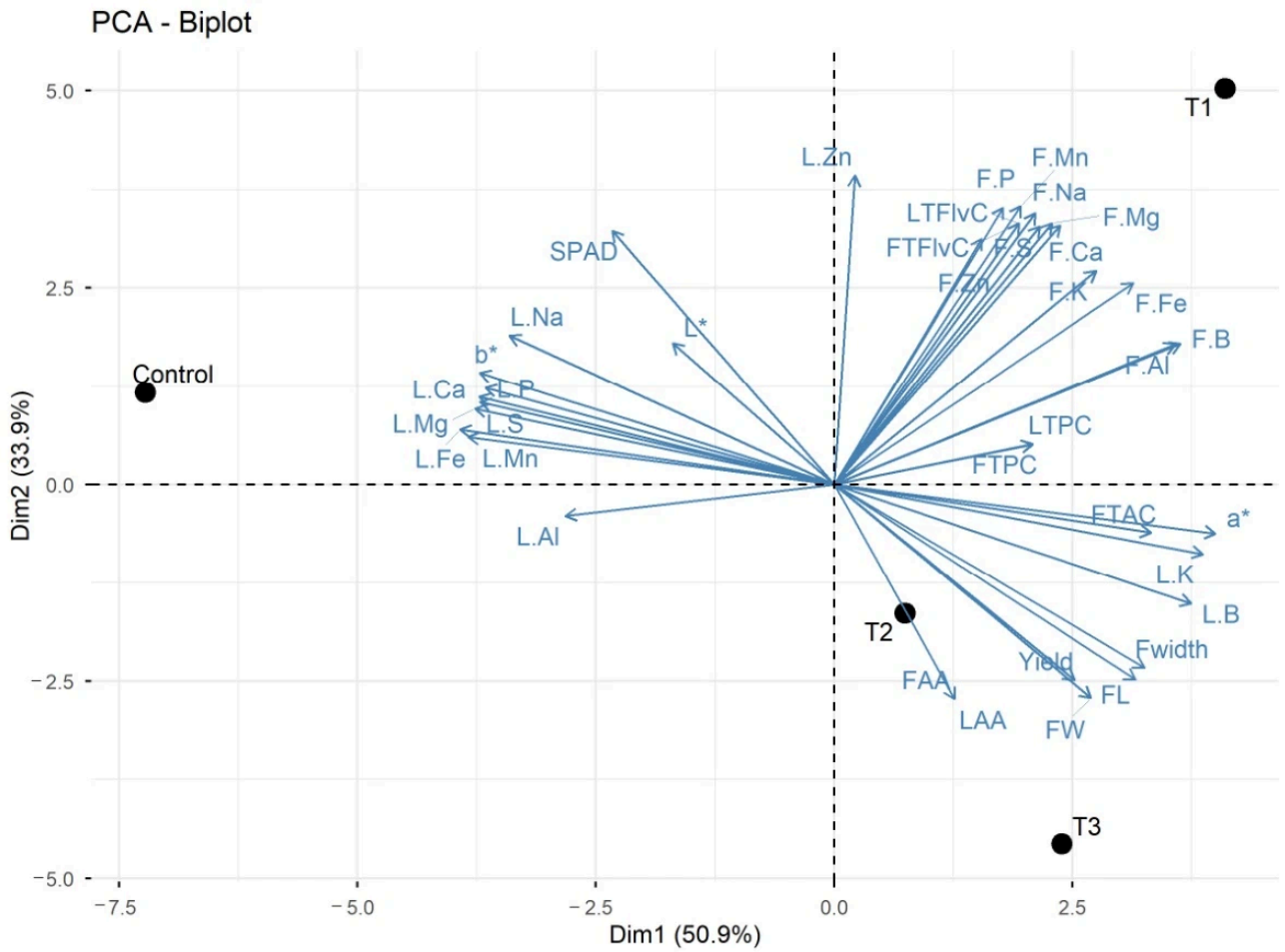


Figure 1. PCA biplot graph of fruit and leaf characteristics of the 'Albion' strawberry cultivar.

Hierarchical clustering analysis revealed distinct patterns among the fertilizer treatments and was broadly consistent with the PCA results (Figure 2). Heatmap hierarchical clustering analysis results support the PCA findings and separate fertilizer treatments into different groups. The control treatment was clearly separated from other fertilizer treatments in terms of Al, Mn, Fe, P, Mg, S, Ca and Na elements, L* and b* color values, and SPAD value. T1 formed a distinct cluster, characterized by relatively high values compared with other fertilizer treatments, exhibiting high values in a*, L.K, fruit TAC, SPAD, L.Zn, F.Ca, F.Mg, F.Mn, F.Na, F.K, F.P, F.S, fruit and leaf TFlvC, F.Zn, F.Al, F.B, and F.Fe. T2 fertilizer treatment showed high values in a*, L*, and fruit and leaf TPC characteristics, while T3 treatment showed high values in yield, fruit weight, fruit width, fruit length, a*, L.B, L.K, fruit TAC, and fruit and leaf AA characteristics. The characteristics examined

in the 'Albion' strawberry cultivar were divided into two groups. While the L.Al, L.Mn, L.Fe, L.P, L.Mg, L.S, L.Ca, L.Na, and b* color values are grouped separately from the other characteristics, the characteristics in the Y group are divided into two subgroups.

Table 6. PCA values of fruit and leaf characteristics of 'Albion' strawberry cultivar.

Traits	PCA1	% Cont. [1]	PCA2	% Cont.	PCA3	% Cont.
Yield per plant	0.14	2.05	−0.17	3.01	0.20	4.20
Fwidth	0.19	3.42	−0.16	2.63	0.07	0.46
FL	0.18	3.23	−0.17	2.99	0.06	0.33
FW	0.15	2.34	−0.19	3.57	0.14	1.98
L*	−0.10	0.93	0.13	1.58	−0.33	11.12
a*	0.23	5.17	−0.04	0.19	−0.02	0.06
b*	−0.21	4.47	0.10	0.98	0.08	0.64
SPAD	−0.13	1.75	0.22	5.03	−0.08	0.70
Leaf Al	−0.16	2.57	−0.03	0.08	0.30	8.98
Leaf B	0.21	4.53	−0.11	1.12	0.04	0.15
Leaf Ca	−0.21	4.48	0.08	0.61	0.12	1.43
Leaf Fe	−0.22	4.98	0.05	0.24	0.08	0.59
Leaf K	0.22	4.83	−0.06	0.38	0.09	0.76
Leaf Mg	−0.21	4.58	0.07	0.45	0.12	1.43
Leaf Mn	−0.22	4.77	0.04	0.18	0.12	1.41
Leaf Na	−0.19	3.75	0.13	1.75	0.12	1.35
Leaf P	−0.21	4.32	0.09	0.74	0.13	1.66
Leaf S	−0.21	4.47	0.07	0.54	0.13	1.63
Leaf Zn	0.01	0.02	0.27	7.49	0.10	1.03
Fruit Al	0.20	4.14	0.12	1.55	−0.07	0.49
Fruit B	0.21	4.26	0.13	1.57	0.02	0.04
Fruit Ca	0.13	1.81	0.23	5.25	0.01	0.01
Fruit Fe	0.18	3.18	0.18	3.19	−0.02	0.03
Fruit K	0.16	2.44	0.19	3.58	0.13	1.64
Fruit Mg	0.13	1.69	0.23	5.34	0.05	0.24
Fruit Mn	0.11	1.24	0.25	6.05	0.04	0.14
Fruit Na	0.12	1.44	0.24	5.74	0.04	0.15
Fruit P	0.10	1.01	0.24	5.99	0.10	1.04
Fruit S	0.12	1.50	0.23	5.21	0.11	1.13
Fruit Zn	0.09	0.77	0.22	4.73	0.22	4.64
Fruit TFC	0.12	1.40	0.04	0.13	−0.36	12.77
Leaf TFC	0.12	1.40	0.04	0.13	−0.36	12.75
Fruit TFlvC	0.11	1.22	0.23	5.32	0.14	1.83
Leaf TFlvC	0.11	1.22	0.23	5.32	0.14	1.83
Fruit AA	0.07	0.52	−0.19	3.60	0.28	7.99
Leaf AA	0.07	0.52	−0.19	3.60	0.28	7.99
Fruit TAC	0.19	3.58	−0.04	0.18	0.23	5.38
Eigenvalue	18.82		12.54		5.65	
Variance (%)	50.85		33.89		15.26	
Cumulative variance (%)	50.85		84.74		100.00	

[1] Cont.: Contribution.

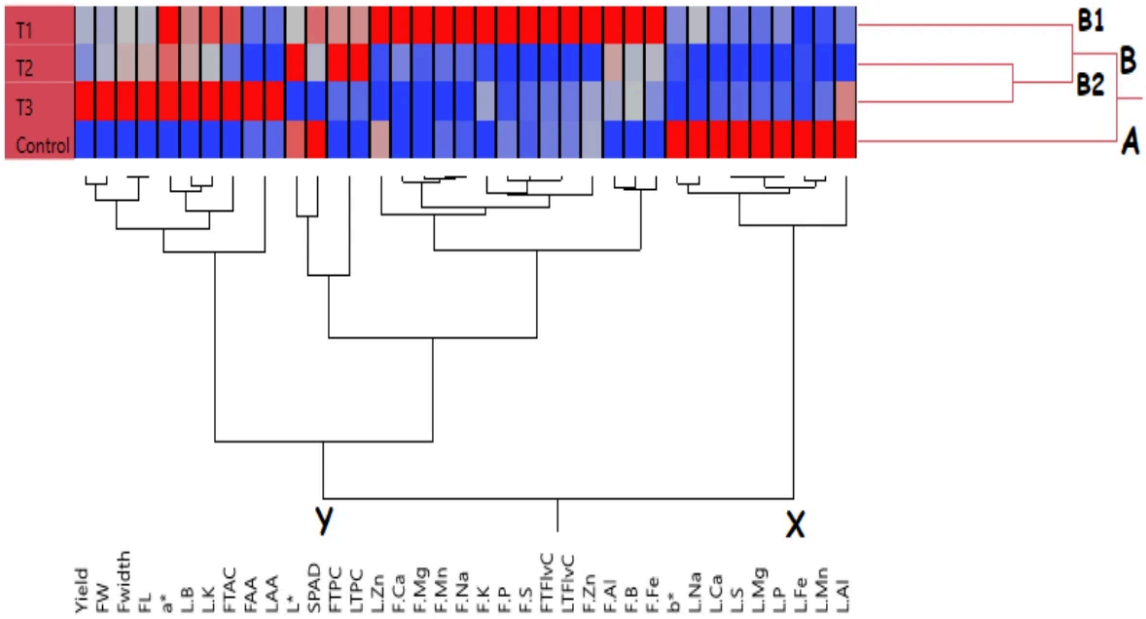


Figure 2. Heatmap hierarchical clustering graph of fruit and leaf characteristics of the 'Albion' strawberry cultivar.

The correlation analysis results revealed the direction and strength of the relationships between the morphological, mineral content, and biochemical characteristics examined (Figure 3). Strong positive correlations were observed among fruit width, fruit length, fruit weight, and yield per plant. Yield showed a strong positive correlation with fruit width (r = 0.66), fruit length (r = 0.75), and fruit weight (r = 0.71). Fruit width showed a strong positive correlation with fruit length and fruit weight (r = 0.96). Generally, negative correlations were observed between fruit morphological characteristics and leaf mineral content. Yield showed positive correlations with L.B (r = 0.82) and L.K (r = 0.81), and a negative correlation with L.Na (r = −0.64) and L.Fe (r = −0.59). The a* value showed very strong negative correlations ranging from −0.71 to −0.96, with almost all leaf nutrient elements (except L.B and L.K). In contrast, the b* value showed strong positive correlations with the same elements (except L.B and L.K). The a* value, which represents the redness of the fruit, showed positive correlations with F.Al (r = 0.81), F.B (r = 0.80), F.Fe (r = 0.66), and FTAC (r = 0.79). The mineral composition of the leaves showed very strong and significant synergistic relationships among themselves. L.B and L.K showed negative correlations with other leaf mineral contents, while other mineral contents showed positive correlations among themselves. L.B showed positive correlations with F.Al (r = 0.63) and F.B (r = 0.66), while L.K showed positive correlations with F.Al (r = 0.70), F.B (r = 0.76), and F.Fe (r = 0.58). L.B showed positive correlations with fruit AA (r = 0.60), leaf AA (r = 0.60), and fruit TAC (r = 0.86), while L.K showed positive correlations with fruit AA (r = 0.58), leaf AA (r = 0.58), and fruit TAC (r = 0.93). fruit and leaf AA, and fruit TAC showed positive correlations among themselves and with the morphological characteristics of the fruits. A negative correlation was observed between fruit TAC and b* value, L.Ca, L.Fe, L.Mg, L.Mn, L.Na, L.P, and L.S. Strong positive correlations have been observed between the mineral element contents of the fruits. Furthermore, fruit TPC and leaf TPC showed a negative correlation with leaf mineral element contents, while fruit and leaf TFlvC showed a positive correlation with fruit mineral element contents.

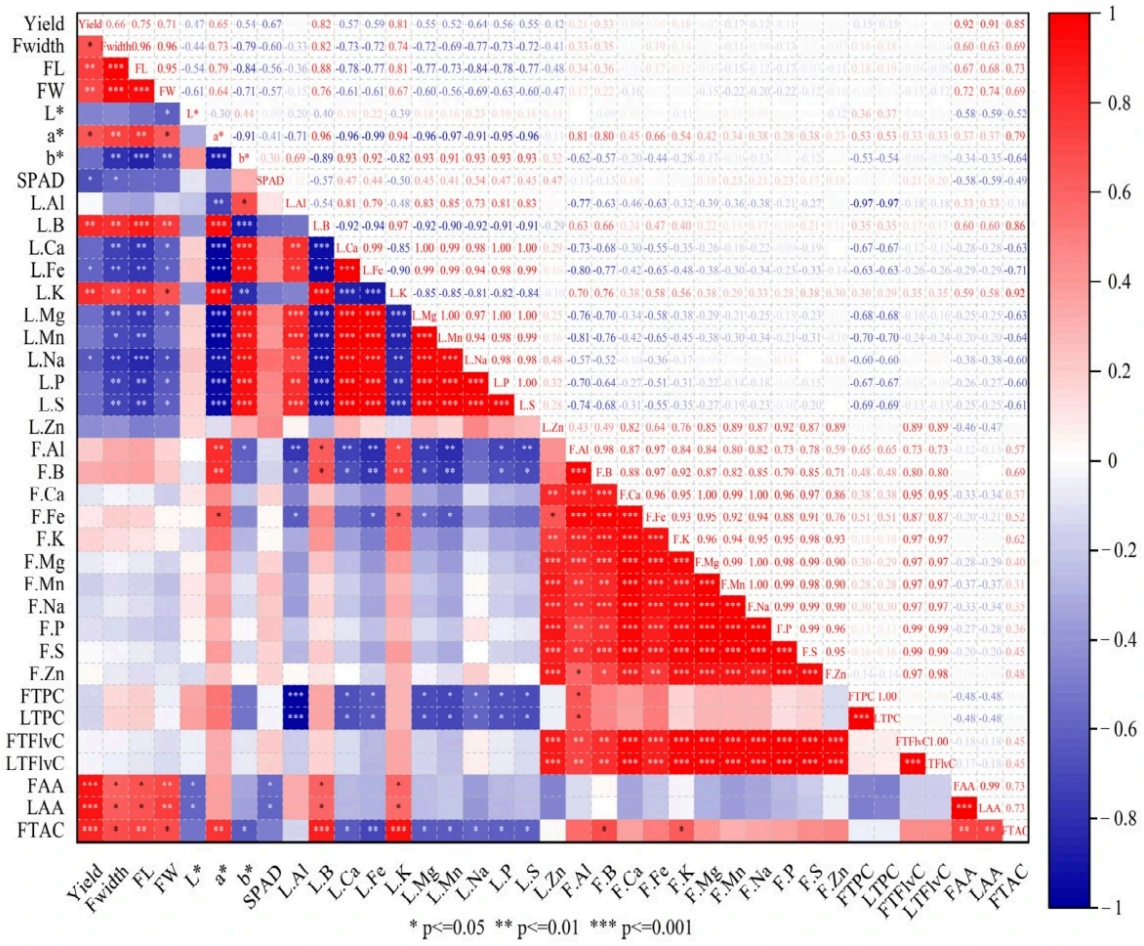


Figure 3. Correlation analysis of fruit and leaf characteristics of the 'Albion' strawberry cultivar.

4. Discussion

Foliar fertilization treatments are effective even at low treatment doses due to the rapid uptake of plant nutrients and provide the advantage of homogeneous distribution. Foliar fertilization is a suitable method for plants due to its high solubility even at low doses [37]. Foliar fertilizer treatments provide resistance to environmental stresses by promoting plant growth. As a result, crop yield and quality increase in plants [38].

In this study, different foliar fertilizer formulations significantly altered the pomological, mineral, and biochemical characteristics of the 'Albion' strawberry cultivar, thus demonstrating that the plant response is largely dependent on the fertilizer composition. Additionally, T1, T2, and T3 fertilizer treatments may contain surfactants and pH regulators, so effects may partly come from auxiliary components. Foliar fertilizer treatments significantly increased fruit size and yield in the 'Albion' strawberry cultivar. Plant yield is an important indicator of agricultural performance in strawberry cultivation. Characteristics such as fruit weight, fruit size, and fruit color, which are important indicators of fruit quality, are also important indicators of fruit yield. Plant yield is the most important objective for productivity per unit area in agricultural production [39].

Although fruit size and yield in strawberries are genetic traits, they vary depending on ecological factors, soil characteristics, and growing conditions (planting, cultural practices, and disease and pest control, etc.) [40]. The positive effect of boron and zinc-containing fertilizer treatments on fruit characteristics observed in our study results is consistent with findings reported in the literature. In a study investigating the effects of microelement treatments (B, Fe, Zn, and Cu) on the quality characteristics of Winter Dawn strawberry cultivar

fruits, it was reported that the treatments were more successful compared to the control. Researchers reported yields per plant ranging from 219.59 g/plant (control) to 451.89 g/plant (0.4% zinc sulfate treatment) [41]. In another study involving the application of boron, iron, and zinc foliar fertilizers, yield per plant for the Chandler strawberry cultivar was reported to range from 177.06 g/plant (control) to 253.33 g/plant (Zn + B + Fe 0.4%) [42]. In another study conducted on the 'Chandler' strawberry cultivar, iron, zinc, boron, and calcium were applied via foliar treatment. Yield per plant was reported to range from 105.12 g/plant (control) to 129.10 g/plant (0.6% $ZnSO_4$) [43]. Similar results regarding the treatment of boron and zinc have also been reported by Quddus et al. [44] and Alinejad Elahshah et al. [45]. Similar effects of B and Zn have also been observed in tomato [46], mandarin [47], date palm [48], and mango [49] species. It has also been reported that treatment B has a positive effect on yield by increasing the number of fruits in strawberries [50].Although the literature generally focuses on yield increases, our findings show that a balanced fertilizer formulation enriched with B increases fruit size more effectively than a balanced macro- and micronutrient formulation (T1) and a P-rich formulation (T2).

Fruit color parameters are known as cultivar characteristics, but ecological factors also influence color development. The positive effect on fruit color stems from balanced nutrition and optimal growth and development [51]. The distinctive red color of strawberries is due to their high anthocyanin content [52]. In the study, the significant increase in fruit redness (a* values) observed in T1 (111.84) and T3 (111.27) fertilizer treatments, compared to the control treatment (82.27), showed a strong correlation (r = 0.79) with total anthocyanin content. The lower a* and higher b* values of the fruits in the control treatment reflect that color development did not fully occur in the absence of fertilization treatments. The red color of strawberries is an important quality parameter for consumers. Anthocyanin, which is responsible for the formation of fruit color in strawberries, is influenced by mineral elements such as N, P, K, and Fe [53]. As a result of the study, we can say that balanced fertilization in terms of macro and micro content (T1 and T3) has a positive effect on color characteristics.

The absence of statistically significant differences in SPAD values suggests that the basic chlorophyll capacity of plants may have been preserved even in the control treatment during the vegetative growth phase, but the main effect of fertilizer treatments becomes apparent during generative phases such as fruit set and development. Similar results have been reported in the literature [18,54].

The study results show that fertilizer treatments dynamically alter the mineral balance of the leaf. Foliar fertilization applications affected the mineral composition of the leaves to varying degrees depending on the nutrient content. The increase in K and B elements in fertilized plants depends on the direct effect of these elements on vegetative growth and fruit quality. The role of K in carbohydrate transport and the regulation of turgor pressure during fruit development has been highlighted as an important factor in increasing strawberry yield [55,56]. Therefore, it can be said that the high K content detected in the leaves during fertilizer treatments is consistent with high yield values. Notably, the levels of elements such as Al, Ca, Fe, Mg, Mn, Na, P, and S in the leaves were significantly higher in the control plants than in the fertilized plants. Given the high mineral content of the leaves in the control treatment, it can be said that the low fruit yield in the control treatment reduced the demand for mineral content and caused the minerals to accumulate in the leaves. The high Al content in the control treatment suggests that plants may be more susceptible to soil-related stress factors in the absence of fertilization.

Fruit mineralization is critically important for both human nutrition and the storage life and quality of the fruit. The study results show that T1 fertilizer treatments (multi-nutrient formulation) is highly effective in increasing the mineral richness of fruit. The fact that the

T1 fertilizer application enriches the mineral content of the fruit highlights the effectiveness of broad-spectrum foliar fertilizer applications in increasing nutrient density. This finding suggests that applications with a balanced macronutrient and micronutrient content more effectively support the transport of mineral elements from the leaves to the fruit. An increase in the number of fruits creates competition among the fruits for assimilates [57]. It is known that mineral nutrition in strawberries reduces competition among fruits and increases fruit size [58]. While T2 and T3 treatments showed similar intermediate values, the control treatment generally showed the lowest fruit mineral content. This result can be attributed to the fruit's direct response to fertilizers as an organ for the accumulation of mineral elements.

The data obtained from the study demonstrate that fertilization strategies dramatically alter not only the yield of the strawberry plant but also the composition of health-related bioactive compounds. Responses of plant organs and fertilizer applications to biochemical components varied with fertilizer composition, application rate, and biochemical content. The antioxidant activities and phenolic compound content of the leaves were found to be higher (approximately 4–5 times) compared to the fruits. Strawberry leaves have a richer bioactive compound content compared to the strawberry fruit [59,60]. The study revealed that phenolic compounds, flavonoids, antioxidant activity, and anthocyanin content exhibit different biosynthetic responses to fertilizer treatments. This finding has also been reported by other researchers. Pešaković et al. [61] reported that different fertilizers applied to strawberries could have independent effects on total phenolic content, antioxidant capacity, and, in particular, anthocyanin accumulation, and that chemical fertilizer treatments yielded the best results for anthocyanin content. Similarly, Zahid et al. [54] reported that different fertilizer sources applied to strawberries selectively affected the secondary metabolite profile of the plant. The decrease in total flavonoid content resulting from foliar fertilizer applications may be related to the mineral element levels in the leaves and fruits. Indeed, it is known that a decrease in N content increases flavonoid content [62] and a decrease in P content decreases flavonoid content [63]. Foliar fertilization may have contributed to a decrease in flavonoid concentrations by altering the mineral content associated with plant growth. Therefore, the observed decrease in total flavonoid content may reflect changes in plant growth, but further physiological and biochemical research is needed to determine the underlying mechanisms.

Multivariate statistical approaches significantly contribute to the interpretation of fertilization studies by revealing patterns that cannot be observed through comparisons of individual variables [64]. In the study, PCA1 and PCA2 explained 84.74% of the variance. This ratio demonstrates that differences between treatments can be reliably interpreted using a two-dimensional biplot graph. A total variation exceeding 25% in the first three components is considered an indicator of heterogeneity in the dataset's variation [65]. In similar studies, the two main components were reported as 64.90% by Kouam et al. [18], 69.50% by Elikara et al. [23] and 83.82% by Pak and Güneş [24]. The first two components therefore accounted for a larger share of the total variance than in these earlier reports, which probably reflects the contrasting nutrient profiles of the formulations compared here. Furthermore, by examining more components in the study, the effects of foliar fertilization on nutrient content, biochemical properties, and fruit quality were characterized in more detail. In conclusion, the clear separation of the T1, T3, and control treatments in the PCA biplot graph confirms the need to select targeted foliar fertilization strategies based on specific production objectives.

In the overall correlation matrix, strong positive correlations were identified between fruit size, fruit weight, and yield per plant. In strawberries, fruit growth directly translates into increased yield [44]. When the correlations among mineral contents of fruits were

examined, strong positive relationships were observed among mineral elements such as K, Mg, Mn, Na, P, and S. Since these elements are transported together via the phloem and reflect a common nutritional status in the plant [56], positive correlations between similar element groups have also been reported in different fruit types [66].

We can list no soil analysis was carried out before the experiment was established, the soil analysis of the study area was carried out in 2021, the failure to determine the B and S content in the soil analysis, the use of commercial mixtures, which do not allow for the separate evaluation of the effects of individual nutrients, the lack of plant biomass data, and the study was conducted at only one location and during a single growing season, among the study's limitations.

5. Conclusions

This study comprehensively evaluated the effects of different foliar fertilizers applied to the 'Albion' strawberry variety on plant performance, fruit quality, and nutrient content. The findings clearly demonstrate that foliar fertilizers can increase yield and quality in strawberry cultivation and affect nutritional value. The T3 treatment, containing B and Zn, showed the greatest effect on fruit size, fruit weight, and yield per plant. Foliar fertilizers with combined element content have been found to be important in transporting nutrients to the fruit and enriching the fruit with elements such as Ca, K, and Zn. In Albion strawberry cultivation, the use of nutrient-rich fertilizers like T1 optimizes the mineral quality of the fruit, maximizing economic yield and nutritional value. Biochemical analyses have shown that foliar fertilizer treatments dynamically alter the levels of health-related bioactive compounds, such as phenolics, flavonoids, anthocyanins, and antioxidant activity in strawberry fruits. The effect of fertilizer applications on biochemical components varied depending on the mineral content. These findings demonstrate that nutritional management of the strawberry plant is important for functional food production. Multivariate analysis methods (PCA, heatmap hierarchical clustering, and correlation) have proven powerful tools for visualizing the complex interactions of different fertilization strategies, interpreting complex plant nutrition data, and determining the most appropriate fertilization protocols. This study makes a significant contribution to the development of optimized foliar fertilization strategies for sustainable strawberry cultivation practices. In conclusion, it is recommended to select a fertilizer suitable for the production purpose.

Author Contributions: Conceptualization, A.S. (Ahmet Sümbül) and M.Y.; Methodology, A.S. (Ahmet Sümbül) and M.Y.; Validation, A.S. (Ahmet Sümbül), F.K., M.Y., A.E., F.D., S.D. and A.S. (Ahmet Say); Formal Analysis, A.S. (Ahmet Sümbül); Investigation, F.K., A.E., A.S. (Ahmet Say) and M.G.; Resources, M.Y., F.D., S.D. and A.S. (Ahmet Say); Data Curation, A.S. (Ahmet Sümbül), F.K., M.Y., A.E., F.D., S.D., A.S. (Ahmet Say), M.G.; Writing—Original Draft Preparation, A.S. (Ahmet Sümbül) and M.Y.; Writing—Review and Editing, A.S. (Ahmet Sümbül), M.Y., M.P. and C.G.P.; Visualization, A.S. (Ahmet Sümbül), M.Y., M.P. and C.G.P.; Supervision, A.S. and M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

Acknowledgments: AI tools were used to enhance the graphical abstract, resulting in a more polished and clear final image. During the preparation of this manuscript/study, the author(s) used [Gemini Notebook (formerly NotebookLM), 2026] for the purposes of [to enhance the graphical abstract and clear final image]. The authors have reviewed and edited the output and take full responsibility for the content of this publication. Dogatech company provided support in the supply of fertilizer and did not provide any financial or commercial support. We would like to thank Dogatech company for their support in supplying the fertilizers used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Giampieri, F.; Alvarez-Suarez, J.M.; Battino, M. Strawberry and human health: Effects beyond antioxidant activity. *J. Agric. Food Chem.* **2014**, *62*, 3867–3876. [CrossRef] [PubMed]
2. Rahman, M.H.; Hasan, M.N.; Khan, M.Z.H. Study on different nano fertilizers influencing the growth, proximate composition and antioxidant properties of strawberry fruits. *J. Agric. Food Res.* **2021**, *6*, 100246. [CrossRef]
3. Yaman, M.; Sümbül, A.; Say, A. Effects of Plant Growth Promoting Rhizobacteria (PGPR) Treatments on Biochemical Activity and Enzyme Activity in Strawberries. *Erzincan Univ. J. Sci. Technol.* **2025**, *18*, 951–962.
4. Basu, A.; Nguyen, A.; Betts, N.M.; Lyons, T.J. Strawberry as a functional food: An evidence-based review. *Crit. Rev. Food Sci. Nutr.* **2014**, *54*, 790–806. [CrossRef] [PubMed]
5. FAO. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 15 July 2026).
6. Kilic, N.; Burgut, A.; Gündesli, M.A.; Nogay, G.; Ercisli, S.; Kafkas, N.E.; Szopa, A. The effect of organic, inorganic fertilizers and their combinations on fruit quality parameters in strawberry. *Horticulturae* **2021**, *7*, 354. [CrossRef]
7. Bai, X.; Liu, K.; Ning, T.; Deng, C.; Wang, L.; Li, D.; Li, J. Effects of multiple N, P, and K fertilizer combinations on strawberry growth and the microbial community. *PLoS ONE* **2023**, *18*, e0293088. [CrossRef] [PubMed]
8. Cvelbar Weber, N.; Koron, D.; Jakopič, J.; Veberič, R.; Hudina, M.; Baša Česnik, H. Influence of nitrogen, calcium and nano-fertilizer on strawberry (*Fragaria× ananassa* Duch.) fruit inner and outer quality. *Agronomy* **2021**, *11*, 997. [CrossRef]
9. Trejo-Téllez, L.I.; Gómez-Merino, F.C. Nutrient management in strawberry: Effects on yield, quality and plant health. In *Strawberries: Cultivation, Antioxidant Properties and Health Benefits*; Nova Science Publishers: Hauppauge, NY, USA, 2014; pp. 239–267.
10. Al-Mamun, M.R.; Hasan, M.R.; Ahommed, M.S.; Bacchu, M.S.; Ali, M.R.; Khan, M.Z.H. Nanofertilizers towards sustainable agriculture and environment. *Environ. Technol. Innov.* **2021**, *23*, 101658. [CrossRef]
11. Ali, S.; Moon, Y.S.; Hamayun, M.; Khan, M.A.; Bibi, K.; Lee, I.J. Pragmatic role of microbial plant biostimulants in abiotic stress relief in crop plants. *J. Plant Interact.* **2022**, *17*, 705–718. [CrossRef]
12. Farid, M.Z.; Qureshi, K.M.; Shah, S.H.; Qureshi, A.A.; Umair, M.; Shafiq, H. Foliar treatment of micronutrients improves growth, productivity and fruit quality of strawberry (*Fragaria ananassa* Duch). *JAPS J. Anim. Plant Sci.* **2020**, *30*, 905–912. [CrossRef]
13. Mohamed, M.H.; Petropoulos, S.A.; Ali, M.M.E. The treatment of nitrogen fertilization and foliar spraying with calcium and boron affects growth aspects, chemical composition, productivity and fruit quality of strawberry plants. *Horticulturae* **2021**, *7*, 257. [CrossRef]
14. Alshaal, T.; El-Ramady, H. Foliar treatment: From plant nutrition to biofortification. *Environ. Biodivers. Soil Secur.* **2017**, *1*, 71–83. [CrossRef]
15. Soppelsa, S.; Kelderer, M.; Casera, C.; Bassi, M.; Robatscher, P.; Matteazzi, A.; Andreotti, C. Foliar treatments of biostimulants promote growth, yield and fruit quality of strawberry plants grown under nutrient limitation. *Agronomy* **2019**, *9*, 483. [CrossRef]
16. Mufty, R.K.; Taha, S.M. Response two strawberry cultivars (*Fragaria* x *ananassa* Duch.) for foliar treatment of two organic fertilizers. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *910*, 012033. [CrossRef]
17. Salman, M.; Ullah, S.; Razzaq, K.; Rajwana, I.A.; Akhtar, G.; Faried, H.N.; Khalid, S. Combined foliar treatment of calcium, zinc, boron and time influence leaf nutrient status, vegetative growth, fruit yield, fruit biochemical and anti-oxidative attributes of "Chandler" strawberry. *J. Plant Nutr.* **2022**, *45*, 1837–1848. [CrossRef]
18. Kouam, I.D.; Moungang, S.; Koulagna, H.I.; Ntsoli, G.P.; Titti, R.W.; Yaouba, A. Influence of organic and mineral fertilizers and a foliar biostimulant on the yield and nutritional quality of strawberries (*Fragaria* × *ananassa* Duch.) under field conditions. *Biochem. Syst. Ecol.* **2024**, *117*, 104917. [CrossRef]
19. Takehisa, H.; Sato, Y.; Antonio, B.A.; Nagamura, Y. Global transcriptome profile of rice root in response to essential macronutrient deficiency. *Plant Signal. Behav.* **2013**, *8*, e24409. [CrossRef] [PubMed]
20. Jat, M.K.; Sarangthem, I.; Devi, N.S.; Singh, S.D.; Singh, G.M.; Singh, S.R. Growth and Yield Improvement in Strawberry through Foliar Treatment of Boron and Zinc. *Int. Innov. J. Appl. Sci.* **2026**, *3*. [CrossRef]
21. Gunes, A.; Turan, M.; Kitir, N.; Tufenkci, M.S.; Cimrin, K.M.; Yildirim, E.; Ercisli, S. Effects of bio-bor fertilizer applications on fruit yield, antioxidant enzyme activity and freeze injury of strawberry. *Erwerbs-Obstbau* **2016**, *58*, 177–184. [CrossRef]

22. Wójcik, P.; Lewandowski, M. Effect of calcium and boron sprays on yield and quality of "Elsanta" strawberry. *J. Plant Nutr.* **2003**, *26*, 671–682. [CrossRef]
23. Elikara, A.U.; Popescu, G.C.; Demirel, S.; Sümbül, A.; Yaman, M.; Demirel, F.; Günes, A. Effect of rhizobacteria treatment on nutrient content, bioactive compounds, antioxidant activity, color properties and fruit characteristics of strawberry cultivars. *Processes* **2024**, *12*, 2242. [CrossRef]
24. Pak, E.; Güneş, A. Determination of the Effect of Inhibitor Fertilizers on the Production and Quality Parameters of Strawberry (*Fragaria x ananassa*). *Erwerbs-Obstbau* **2023**, *65*, 1421–1427. [CrossRef]
25. Umar, S.; Bansal, S.K.; Imas, P.; Magen, H. Effect of foliar fertilization of potassium on yield, quality, and nutrient uptake of groundnut. *J. Plant Nutr.* **1999**, *22*, 1785–1795. [CrossRef]
26. Vishekaii, Z.R.; Soleimani, A.; Fallahi, E.; Ghasemnezhad, M.; Hasani, A. The impact of foliar treatment of boron nano-chelated fertilizer and boric acid on fruit yield, oil content, and quality attributes in olive (*Olea europaea* L.). *Sci. Hortic.* **2019**, *257*, 108689. [CrossRef]
27. Ali, B.; Babar, M.; Fatima, R.N.; Mahmood, A.; Sher, A.; Siddique, T.; Aslam, M.S.; Afzal, S.; Luqman, M.; Shahzad, K.; et al. Effect of Different Doses of NPK at Different Time Intervals on Growth, Yield and Quality of Strawberry CV. Chandler (*Fragaria ananassa*). *J. Surv. Fish. Sci.* **2023**, *10*, 4095–4108.
28. Yaman, M.; Yilmaz, K.U. The effects of different chemicals on runner yield and quality of 'Kabarla'strawberry young plants grown in Cappadocia region. *Erwerbs-Obstbau* **2022**, *64*, 85–90. [CrossRef]
29. Hannachi, H.; Elfalleh, W.; Laajel, M.; Ennajeh, I.; Mechlouch, R.F.; Nagaz, K. Chemical profiles and antioxidant activities of leaf, pulp, and stone of cultivated and wild olive trees (*Olea europaea* L.). *Int. J. Fruit Sci.* **2020**, *20*, 350–370. [CrossRef]
30. Slinkard, K.; Singleton, V.L. Total phenol analysis: Automation and comparison with manual methods. *Am. J. Enol. Vitic.* **1977**, *28*, 49–55. [CrossRef]
31. Chang, C.C.; Yang, M.H.; Wen, H.M.; Chern, J.C. Estimation of total flavonoid content in propolis by two complementary colorimetric methods. *J. Food Drug Anal.* **2022**, *10*, 13–21.
32. Brand-Williams, W.; Cuvelier, M.E.; Berset, C.L.W.T. Use of a free radical method to evaluate antioxidant activity. *LWT Food Sci. Technol.* **1995**, *28*, 25–30. [CrossRef]
33. Giusti, M.M.; Rodríguez-Saona, L.E.; Wrolstad, R.E. Molar absorptivity and color characteristics of acylated and non-acylated pelargonidin-based anthocyanins. *J. Agric. Food Chem.* **1999**, *47*, 4631–4637. [CrossRef] [PubMed]
34. Miller, R.O. Nitric-perchloric acid wet digestion in an open vessel. In *Handbook of Reference Methods for Plant Analysis*; CRC Press: Boca Raton, FL, USA, 2019.
35. Kacar, B.; İnal, A. *Plant Analysis*; Nobel Press: Stockholm, Sweden, 2008; Volume 1241, p. 891. (In Turkish)
36. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2024; Available online: http://www.R-project.org/ (accessed on 15 June 2026).
37. Çolak Esetlili, B.; Pekcan, T.; Bayız, O.; Telli Karaman, H.; Ayata, M.; Sarı, G. Optimizing olive production: The role of foliar fertilizers in boosting yield and quality. *Horticulturae* **2024**, *10*, 1147. [CrossRef]
38. Makale, A.R.; Mourice, S.K.; Kapinga, F.A. Assessment of farmers' knowledge on the foliar fertilizer use for improved cashew (*Anacardium occidentale* L) productivity in south-eastern Tanzania. *J. Agric. Food Res.* **2024**, *16*, 101092. [CrossRef]
39. Sayğı, H. Effects of organic fertilizer treatment on strawberry (*Fragaria vesca* L.) cultivation. *Agronomy* **2022**, *12*, 1233. [CrossRef]
40. Hancock, J.F. *Strawberries Crop Production Science in Horticulture*; CABI, Publishing: Oxon, UK, 1999; Volume 109, p. 112.
41. Saha, T.; Ghosh, B.; Debnath, S.; Bhattacharjee, A. Effect of micronutrients on growth, yield and quality of strawberry (*Fragaria× ananassa* Duch.) cv. Winter Dawn in the Gangetic alluvial region of West Bengal. *J. Crop Weed* **2019**, *15*, 92–95.
42. Verma, S.; Bairwa, R.K.; Rana, D.K.; Dimri, T.; Dotaniya, C.K. Influence of different concentrations of zinc, boron and iron on yield characters of strawberry (*Fragaria x ananassa* Duch.) cv. Chandler under valley condition of Garhwal Himalaya. *J. Pharmacogn. Phytochem.* **2018**, *7*, 3881–3884.
43. Singh, G.; Kachwaya, D.S.; Kuchi, V.S.; Singh, M.; Singh, J.; Singh, B. Influence of foliar application of mineral nutrients on vegetative and fruit quality of strawberry (*Fragaria× ananassa* Duch.) cv. Chandler. *J. Plant Sci. Res.* **2020**, *36*, 323–328. [CrossRef]
44. Quddus, M.A.; Siddiky, M.A.; Ali, M.R.; Ahmed, R.; Sarker, K.K.; Arfin, M.S. Influence of boron and zinc on yield, nutrient uptake and quality of strawberry. *J. Plant Nutr.* **2022**, *45*, 866–882. [CrossRef]
45. Alinejad Elahshah, A.; Moradi, H.; Sadeghi, H. Boron and zinc foliar application enhanced the morpho-physiological responses and mineral absorption in the hydroponically grown 'Aromas' strawberry. *J. Plant Nutr.* **2023**, *46*, 3487–3498. [CrossRef]
46. Haleema, B.; Rab, A.; Hussain, S.A. Effect of Calcium, Boron and Zinc Foliar Treatment on Growth and Fruit Production of Tomato. *Sarhad J. Agric.* **2018**, *34*, 19–30. [CrossRef]
47. Rana, G.S. The Effect of Foliar Treatment of Zinc, Potassium, and Boron on Fruit Set and Retention in Kinnow Mandarin. *Asian J. Soil Sci. Plant Nutr.* **2024**, *10*, 627–638. [CrossRef]
48. El-Kosary, S.; Rashedy, A.; El-Sharabasy, S.; Abd Allah, A.M. Treatments of Calcium Boron or Potassium Phosphite Combined with Different Fruit Thinning Styles to Enhance Fruit Quality of Barhee date palm. *Egypt. J. Chem.* **2023**, *66*, 427–438. [CrossRef]

49. El-Motaium, R.A.E.; Shaban, A.E.S.; Badawy, E.S.H.; Ibrahim, A.S. The potential role of nano-calcium and boron in increasing mango fruits productivity, quality and antioxidant content. *J. Plant Nutr.* **2025**, *48*, 1529–1546. [CrossRef]
50. Hussein, S.A.; Al-Doori, M.F. The effect of spraying with calcium, boron and benzyl adenine on the quantity and quality of yield for strawberry plants (Fragaria Ananassa Duch) CV. Rubygem. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *910*, 012066. [CrossRef]
51. Ağgün, Z.; Geçer, M.K.; Aslantaş, R. The effects on fruit yield and fruit properties of plant growth promoting bacteria treatments on some strawberry cultivars. *Int. J. Agric. Wildl. Sci.* **2018**, *4*, 20–25. [CrossRef]
52. López-Valencia, D.; Sánchez-Gómez, M.; Acuña-Caita, J.F.; Fischer, G. Physicochemical properties of seven outstanding strawberry (*Fragaria x ananassa* Duch.) varieties cultivated in Cundinamarca (Colombia) during maturation. *Cienc. Tecnol. Agropecu.* **2018**, *19*, 147–162. [CrossRef]
53. Bai, Q.; Shen, Y.; Huang, Y. Advances in mineral nutrition transport and signal transduction in Rosaceae fruit quality and postharvest storage. *Front. Plant Sci.* **2021**, *12*, 620018. [CrossRef] [PubMed]
54. Zahid, N.; Maqbool, M.; Tahir, M.M.; Horvitz, S.; Hamid, A.; Khalid, M.S.; Ali, A. Influence of organic and inorganic fertilizer regimes on growth patterns and antioxidants capacity of strawberry (*Fragaria* × *ananassa* Duch.) cv. Chandler. *J. Food Qual.* **2022**, *2022*, 8618854. [CrossRef]
55. Vago, I.; Tolner, L.; Loch, J. Effect of chloride anionic stress on the yield amount and some quality parameters of strawberry (*Fragaria ananassa*). *Cereal Res. Commun.* **2009**, *37*, 81–84.
56. Marschner, H. (Ed.) *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK, 2011.
57. Hassan, A.H. Effect of nitrogen fertilizer levels in the form of organic, inorganic and bio fertilizer applications on growth, yield and quality of strawberry. *Middle East J. Appl. Sci.* **2015**, *5*, 604–617.
58. Khalil, N.H.; Agah, R.J. Effect of chemical, organic and bio fertilization on growth and yield of strawberry plant. *Int. J. Adv. Chem. Eng. Biol. Sci.* **2017**, *4*, 167–171.
59. Wang, S.Y.; Lin, H.S. Antioxidant activity in fruits and leaves of blackberry, raspberry, and strawberry varies with cultivar and developmental stage. *J. Agric. Food Chem.* **2000**, *48*, 140–146. [CrossRef] [PubMed]
60. Michalska, A.; Carlen, C.; Heritier, J.; Andlauer, W. Profiles of bioactive compounds in fruits and leaves of strawberry cultivars. *J. Berry Res.* **2017**, *7*, 71–84. [CrossRef]
61. Pešaković, M.; Milenković, S.; Đukić, D.; Mandić, L.; Karaklajić-Stajić, Ž.; Tomić, J.; Miletić, N. Phenolic composition and antioxidant capacity of integrated and conventionally grown strawberry (*Fragaria*× *ananassa* Duch.). *Hort. Sci.* **2016**, *43*, 17–24. [CrossRef]
62. Narvekar, A.S.; Tharayil, N. Nitrogen fertilization influences the quantity, composition, and tissue associ-ation of foliar phenolics in strawberries. *Front. Plant Sci.* **2021**, *12*, 613839. [CrossRef] [PubMed]
63. Shabani, E.; Zivdar, S.; Rahnama Ghahfarokhi, A.; Danaeifar, A.; Davoudi Arshad, M. Foliar application of Si-aminochelate: A strategy for increasing P uptake and antioxidant properties of strawberry. *BMC Plant Biol.* **2025**, *25*, 1690. [CrossRef] [PubMed]
64. Granato, D.; Santos, J.S.; Escher, G.B.; Ferreira, B.L.; Maggio, R.M. Use of principal component analysis (PCA) and hierarchical cluster analysis (HCA) for multivariate association between bioactive compounds and functional properties in foods: A critical perspective. *Trends Food Sci. Technol.* **2018**, *72*, 83–90. [CrossRef]
65. Mohammadi, S.A.; Prasanna, B.M. Analysis of genetic diversity in crop plants—Salient statistical tools and considerations. *Crop Sci.* **2003**, *43*, 1235–1248. [CrossRef]
66. White, P.J.; Broadley, M.R.; Gregory, P.J. Managing the nutrition of plants and people. *Appl. Environ. Soil Sci.* **2012**, *2012*, 104826. [CrossRef]

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