

Article

Foliar Fertilization of Potassium Silicon Improved Postharvest Fruit Quality of Peach and Nectarine [*Prunus persica* (L.) Batsch] Cultivars

Walid Abidi ^{1,*} , Rawaa Akrimi ¹, Hichem Hajlaoui ¹ , Hichem Rejeb ²  and Yolanda Gogorcena ³ 

¹ Regional Center for Agricultural Research of Sidi Bouzid (CRRA) PB 357, Sidi Bouzid 9100, Tunisia

² Institut Supérieur Agronomique Chott Meriem, Université de Sousse, Sousse 4042, Tunisia

³ Departament of Pomology, Estación Experimental de Aula Dei (CSIC), Avda de Montañana 1005, 50059 Zaragoza, Spain

* Correspondence: walid.abidi@iresa.agrinet.tn

Abstract: Peach fruit quality is dependent on preharvest treatments and orchard practices. The aim of this study is to evaluate the effects of preharvest potassium silicon fertilization on fruit postharvest quality. Two peach cultivars (“Early Bomba” and “Plagold 17”) were sprayed with three concentrations of potassium silicon (K-Si) at fruit set, stone hardening, and physiological maturity stages. The applied treatments corresponded to control (T0 = 0% K-Si) pulverized with distilled water and two K-Si treatments (T1 = 3% K-Si and T2 = 4.5% K-Si). The blooming and harvesting dates, vegetative growth and agronomical parameters were analyzed over two growing seasons (2021–2022). Peach fruits were stored at 5 °C and 95% RH during two cold storage periods (2 and 4 weeks) followed by 2 days at room temperatures. The fruit weights (FW), color, firmness, soluble solids content (SSC), titratable acidity (TA), pulp stone ratio (P/S) and fruit weight loss (FWL) were evaluated. The anthocyanins, flavonoids, total phenolics, carotenoids and antioxidant capacity (DPPH) were determined. Vitamin B5 and vitamin C were analyzed by HPLC. The ethylene rate and the chilling injury symptoms (CI) were analyzed after two cold storage periods (2 and 4 weeks). Results showed that the applied potassium silicon treatments (3% K-Si and 4.5% K-Si) enhanced the FW, SSC, TA, FWL, fruit composition and CI. Anthocyanins and total phenolics increased after cold storage period under K-Si treatments. The nectarine cultivar (cv) Early Bomba showed low sensibility to chilling injury symptoms as compared to the cv Plagold 17.

Keywords: peach and nectarine; potassium silicon; storage; ethylene; fruit decay



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1. Introduction

Peach and nectarine fruits have an important economic value with a worldwide production of 24.5 million tons in a harvested area of around 1.5 million ha in 2020 [1]. In Tunisia, peach and nectarine production reached 150 thousand tons in a harvested area of around ha in 2022 [1].

Peach is a climacteric fruit which ripens and deteriorates quickly at ambient temperature, presenting a constraint for storage and handling [2]. Therefore, the postharvest quality and storability depends on the performed preharvest treatments and cold storage conditions. Foliar application of macro and micro-nutrients is the key to improving fruit set, productivity and quality of fruits, and also has a beneficial role in recovery of nutritional and physiological disorders in fruit trees [3].

Potassium silicon foliar application, as a source of highly soluble potassium and silicon, is an effective and fast fertilization, supplying the tree with the nutritional needs in critical periods away from soil–cation interactions [4]. Okba et al. [4] reported that potassium is involved in gas exchange, cell division, sugar translocation via the phloem to fruits, fruit coloration, soluble solids content, and increasing the fruit’s shelf life. Lester et al. [5]

reported that the potassium nutrient is related to enzyme synthesis and activation, sugar synthesis and the ripening process. It was reported that potassium and silicon nutrition contributes to enhancing yield, fruit size, color, soluble solids, ascorbic acid content and postharvest quality [6].

The beneficial effects of silicon were suggested through enhancing growth, yield, fruit quality, shelf life, photosynthetic activity, increasing the soluble substances of the plant xylem, and encouraging the antioxidant defense mechanism of plants [7]. In this respect, Zhang and Ervin [8] stated that silicon applications delayed fruit softening through a suppression effect on some enzymes as xylanase, cellulase, and polygalacturonase. In the same line, Mditshwa et al. [9] reported that silicon applications increased both phenolic and flavonoid antioxidants of fruit during cold storage.

Peach fruit undergo a rapid postharvest loss of firmness, weight loss and decay at room temperature [10]. The use of cold storage methods can slow the process of decay and extend the fruit shelf-life period [11]. The fruit maximum storage life can be achieved with temperature near 0 °C depending on the soluble solids content of the fruit [11]. However, when stored at temperatures between 2.2 and 7.6 °C, fruits can develop different chilling injury symptoms such as mealiness, flesh browning and bleeding [11].

An alternative to extend shelf life is to align refrigeration with potassium (K) and Silicon (Si) fertilization, influencing fruit resistance, pulp color, firmness, acidity and soluble solids content [12]. To our knowledge, there are few data regarding the evolution of physicochemical parameters and bioactive compound content of the fruits during storage under the combined effects of fertilization and storage temperature. The aim of this study is to investigate the impact of preharvest treatment of peach trees with potassium silicon on yield, vegetative growth, agronomical traits, physicochemical parameters, nutritional quality, fruit decay and chilling injury symptoms during two cold storage periods over two growing seasons (2021–2022).

2. Material and Methods

2.1. Plant Material

The experiment was conducted during two growing seasons (2021–2022) in ten-year-old drip-irrigated peach cultivars located in the region of Regueb (34°47′45.1″ N; 9°47′54.1″ E; 150 m above sea level), Sidi Bouzid, Tunisia. In this study, two peach cultivars (“Early Bomba” and “Plagold 17”) grafted onto ‘Garnem’ rootstock were used (Table 1). Irrigation was carried out by using a drip irrigation system with two emitters per tree, each delivering 8 L h^{−1}. Trees were trained to the standard open vase system, planted at a spacing of 6 m × 3 m. Early Bomba is a white-flesh freestone nectarine cultivar, whereas Plagold 17 is a yellow-flesh clingstone peach cultivar; the two cultivars have a red skin color. For physicochemical parameters, biochemical traits and chilling injury symptoms, a representative fruit sample (60 fruits) was taken over two consecutive years (2021–2022).

Table 1. Peach cultivars, fruit type, skin color, flesh color, flesh texture, stone adhesion, flower type and gland type for the studied peach and nectarine cultivars.

Traits	Plagold 17	Early Bomba
Fruit type	peach	nectarine
Fruit shape	round	round
Peel color	red	red
Flesh color	yellow	white
Flesh texture	non-melting	melting
Stone adherence	clingstone	freestone
Flower type	non-showy	showy
Petiol gland shape	reniform	reniform

The climate of the study area is typically Mediterranean with a seasonally irregular precipitations and a long dry summer period from May to September. During the exper-

imental period, the mean annual reference evapotranspiration (ETo) values were about 1300 mm y^{-1} . Daily average temperatures during the months of May and June are around 30°C . The annual precipitation is approximately 200 mm. The soil of the experimental site was sandy-loam in texture (75% sand, 20% silt, and 5% clay).

2.2. Potassium Silicon Treatments

Three groups of ten trees were randomly selected within the orchard and sprayed with Kelik potassium silicon corrector (20% w/v potassium oxide (K_2O) and silicon oxide 13% w/v (SiO_2) and 2% w/v EDTA) at fruit set, stone hardening and physiological maturity stages. A manual backpack type sprayer was used to completely cover the tree canopy with the spray of freshly prepared K-Si treatments. Three potassium silicon treatments were performed. The untreated trees were sprayed with distilled water and served as control ($T0 = 0\%$ K-Si). In treatment T1 (3% K-Si), trees were sprayed with 3% potassium silicon (300 cc/100 L), whereas treatment T2 (4.5% K-Si) consisted of spraying trees with 4.5% of potassium silicon (450 cc/100 L).

2.3. Phenological and Pomological Traits

The initial blooming (BBCH = 57), full blooming (BBCH = 65), final blooming (BBCH = 67), harvesting (BBCH = 87) dates and fruit development period were recorded for each cultivar during the two years of study (2021–2022) according to the BBCH scale; then dates were converted into Julian days. The pomological traits such as leaf gland type (reniform/globose) and flower type (showy/non-showy) were measured directly in the tree. Fruit type (peach/nectarine), flesh color (yellow/white), flesh type (melting/non-melting), peel color (yellow/white) and stone type (clingstone/freestone) were determined in the laboratory immediately after harvest.

2.4. Agronomical Traits and Vegetative Growth

Annual yield (kg/tree), cumulative yield, yield efficiency (cumulative yield in kilograms per tree per final TCSA) were also recorded. Tree height, canopy and trunk cross-sectional area (TCSA, cm^2) were recorded at the beginning and end of each season during the study. Vegetative growth was measured every 15 days. Four representative shoots of similar length were selected in four orientations around the canopy and marked. Leaf area, shoot length, internodes number and shoot diameter were recorded regularly during the two growing seasons, from February to June on the tagged shoots. Fruits were hand-picked at commercial maturity and a representative fruit sample (60 fruits) was taken for fruit quality measurement and chilling injury symptom evaluation as described by [13].

2.5. Fruit Physicochemical Parameters

Fruit weight (g) and volume (cm^3) was measured in a sample of twenty fruits. Fruit peel color was measured using a CR-200 Minolta Chromameter (Chuo-Ku, Osaka, Japan) and measurements were displayed in L^* , a^* , and b^* values. Flesh firmness (Kg/cm^2) was measured with a penetrometer equipped with an 8 mm diameter flat-tip probe and expressed in Newton (N). Soluble solids content (SSC, $^\circ\text{Brix}$) was measured in the juice using a digital hand-held refractometer (Atago, Tokyo, Japan). The initial pH, juice conductivity, titratable acidity (TA, g malic acid per 100 g fresh weight sample) and the ripening index (RI) was determined as described in [14]. The juice yield and the pulp/pit ratio were also determined.

2.6. Fruit Composition Analysis

A subsample of ten fruits was weighed (fresh weight) and placed in an oven at 80°C to constant weight (dry weight). The water content was calculated as: $(\text{fresh weight} - \text{dry weight}) / \text{fresh weight} \times 100$. The ash was determined by muffle at 550°C . The protein concentration was determined according to the method of [15] using bovine serum albumin (BSA) as a standard (0, 0.0625, 0.125, 0.25, 0.5 and 1 g L^{-1}) and absorbance was read at

595 nm flesh fruit (0.5 g) frozen at liquid nitrogen was homogenized with 2.5 mL of tampon phosphate 50 mM (pH 7.2) containing 1 mM EDTA, 1 mM PMSF and 1% PVP. Then the solution was centrifuged at 5000 rpm for 15 min at 4 °C. The upper phase is put into a refrigerator at 4 °C for further analysis. Total protein content was expressed as mg/g of fresh weight. Total carbohydrate content was estimated by the difference from the total contents. The fiber content was determined according to [16].

2.7. Phenolic Compounds Extraction and Quantification

Fruits were washed, towel-dried and cut into small pieces, then 5 g of flesh fruit were frozen in liquid nitrogen and stored at (−20 °C) until analysis. Frozen flesh samples (5 g) were homogenized in a polytron with 10 mL of 0.5 N HCl in methanol/distilled water (80% v/v). The solution was then centrifuged for 20 min at 4 °C and 5000× g, and the supernatant was recovered and measured. Anthocyanins, flavonoids, total phenolics, and relative antioxidant capacity were measured using a spectrophotometer (Jenway 6300, UK). The anthocyanin content was evaluated for absorbance at 535 and 700 nm and the concentration was calculated using the molar extinction absorptivity coefficient $\epsilon = 25,965/\text{cm M}$ and expressed in mg of cyanidin 3-glucoside equivalents (C3GE) per kg of fresh weight (FW) [14]. Total flavonoid content was analyzed as described in Zhishen et al. [17]. The extract (1 mL) was diluted with 2 mL of distilled water and mixed with 0.3 mL of NaNO_2 for 5 min, incubated with 0.3 mL of AlCl_3 for 2 min, and then 2 mL of NaOH was added and mixed. Absorbance was measured at 510 nm, and the results were expressed in mg of catechin equivalents (CE) per 100 g of FW. Total phenolic content was determined as reported in Singleton and Rossi [18]. The method consisted of mixing 0.5 mL of the extract in 8 mL of distilled water and 0.5 mL of Folin–Ciocalteu reagent; the solution was incubated for 3 min, then 1 mL sodium carbonate (Na_2CO_3) was added and incubated at 25 °C in darkness for one hour. Absorbance was measured at 725 nm and the results were expressed in mg of gallic acid equivalents (GAE) per 100 g of FW. Free radical scavenging activity was assessed by the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay. The DPPH assay was performed using the method adapted from Williams et al. [19]. The method consisted of mixing 100 μL of extract with 2.9 mL of DPPH. The reaction was allowed to stand for 10 min in darkness at room temperature. Absorbance was measured at 515 nm and the results were expressed in μg of Trolox equivalents (TE) per g FW.

2.8. Vitamin B5, Vitamin C Extraction and Quantification

Flesh fruits (5 g) were mixed with 5 mL 5% metaphosphoric acid and frozen in liquid nitrogen, then stored at (−20 °C) until analysis. Thereafter, 5 mL 5% metaphosphoric acid were added to the frozen tissue, thawed on ice, homogenized with a polytron (T25D Turrax; IKA Works, Inc.; Wilmington, New Hanover) and centrifuged (SIGMA Laboratory centrifuges 3K18, UK) at 5000× g for 20 min at 4 °C. The supernatant was measured and used for vitamin B5 and vitamin C determination with HPLC.

The extract (20 μL) was injected into the HPLC system (Aminex HPX-87C column, 4.50 m × 15 cm; Bio-Rad, Barcelona, Spain) with a refractive index detector (Waters 2410). The flow rate of the mobile phase (deionized water) was 0.5 mL min^{−1} at 25 °C. The vitamin B5 and vitamin C contents were converted to the fresh weight of fruits and expressed as mg/100 g FW.

2.9. Decay Incidence, Ethylene Biosynthesis and Chilling Injury (CI) Symptoms

Two weeks after the final application of K-Si, fruits were manually harvested. For each fertilization treatment, three groups of twenty fruits were selected and stored in a private cold chamber at 5 °C and 95% RH. The rate of ethylene was assayed at harvest and after two cold storage periods (2 and 4 weeks) using an F-900 Portable Ethylene Gas Analyzer (Felix, Camas, WA, USA) and expressed as $\mu\text{mol kg}^{-1} \text{h}^{-1}$ in peach fruits as described in [20]. Chilling injury symptoms were evaluated in the studied cultivars during two growing seasons (2020–2021) as described in [13].

2.10. Statistical Analysis

For each cultivar, three replicates were considered to calculate the mean and standard error (SE) for each parameter using SPSS 20.0 (SPSS, Chicago, IL, USA). All data were subjected to one-way analysis of variance (ANOVA, San Francisco, CA, USA) to test the effect of fertilization treatments, cold storage period and interaction (Fertilization $\times$ storage period) for the linear model. When analysis of variance showed significant differences ($p < 0.05$), means were separated by Scheffe's multiple range tests.

3. Results

3.1. Phenological Traits

The blooming dates, harvesting dates and fruit development period of the cvs "Early Bomba" and "Plagold 17" during the two growing seasons (2021–2022) are shown in Table 2. The initial blooming dates of the cv "Early Bomba" were 1 and 6 February in 2021 and 2022, respectively. The peach cv "Plagold 17" has initial blooming dates on 10 and 18 February in 2021 and 2022, respectively. Differences were observed for the initial and full blooming dates between the two cultivars among the two years of study. The harvest dates ranged from 15 to 25 May for the cv "Early Bomba" in 2021 and 2022, respectively, whereas the cv "Plagold 17" showed harvesting dates from 20 May to 5 June in 2021 and 2022, respectively. The fruit development period (from fruit set to harvest) in 2021 ranged from 80 to 84 days for the cvs "Plagold 17" and "Early Bomba", respectively. During the 2022 growing season, fruit development days were 87 and 91 days for "Plagold 17" and "Early Bomba", respectively. The annual variability of blooming dates was in a 10-day range, depending on the climatic conditions. The applied fertilization treatments showed no statistically significant differences in blooming and harvesting dates.

Table 2. Blooming and harvesting time for the two peach and nectarine cultivars. Bloom beginning, full bloom and bloom end dates, were determined. Data are means of two consecutive years for each peach cultivar.

Cultivars	cv Early Bomba		cv Plagold 17	
	2021	2022	2021	2022
Seasons				
Traits				
Initial blooming	01/02	06/02	10/02	18/02
Full blooming	05/02	10/02	15/02	24/02
End blooming	20/02	23/02	01/03	10/03
Harvest	15/05	25/05	20/05	05/06
Fruit development	84	91	80	87

Initial blooming: 2% of flowers are open. Full blooming: 50% of flowers are open. End blooming: 2% of petals have fallen. Fruit development period: from fruit set to harvest (Julian days).

3.2. Tree Vigor, Vegetative Growth, Yield and Nutritional Composition

The tree vigor parameters such as tree height, canopy and trunk cross-sectional area are shown in Table 3. The tree height ranged from 2.3 to 2.7 m with less variation between cultivar and years of study. The tree canopy presented the same behavior and ranged from 1.9 to 2.5 m. The trunk cross-sectional area (TCSA) ranged from 56.7 to 61.7 cm² for the cv "Early Bomba" and from 49.3 to 58.7 cm² for the cv "Plagold 17". Results showed no statistically significant differences between the three potassium silicon treatments over the two growing seasons.

The variation in average shoot elongation, shoot diameter, internode number and leaf area for the two peach cultivars over the two growing seasons are shown in Table 3. Results showed that the treatments T1 (3% K-Si) and T2 (4.5% K-Si) presented similar trending and showed significant differences ($p < 0.05$) with the treatment T0 (0% K-Si). The cv "Early Bomba" showed a shoot length from 53.3 to 61.6 cm under the treatments T0 and T2, respectively. The cv Plagold 17 showed a shoot length in the range of 29.3–33.3 cm. Over the experimental period, the growth pattern of current-year vegetative shoot did not

vary among seasons and the shoot length was not affected by year of study. The shoot diameter ranged from 0.3 to 0.5 cm in the cvs “Early Bomba” and “Plagold 17”, respectively. The leaf area varied from 22.5 to 34.5 cm² in the cvs “Early Bomba” and “Plagold 17”, respectively. The node number and internode length presented similar behavior during the two growing seasons.

Table 3. Impact of potassium silicon treatments on tree vigor, vegetative growth, and fruit nutritional composition (%) for the peach and nectarine cultivars during two growing seasons. Values are means of three measurements $\pm$ SE. Mean separation within columns by Scheffe’s multiple range tests ($p \leq 0.05$). In each row, within each cultivar, values with the same letter are not significantly different.

Peach and Nectarine Cultivars						
Traits	Early Bomba			Plagold 17		
	T0	T1	T2	T0	T1	T2
Tree vigor						
Height (m)	2.7 $\pm$ 0.1 ^a	2.4 $\pm$ 0.2 ^b	2.5 $\pm$ 0.3 ^b	2.7 $\pm$ 0.1 ^a	2.3 $\pm$ 0.1 ^b	2.6 $\pm$ 0.2 ^a
Canopy (m)	2.4 $\pm$ 0.2 ^a	2.5 $\pm$ 0.4 ^a	2.3 $\pm$ 0.3 ^a	1.9 $\pm$ 0.4 ^b	2.2 $\pm$ 0.2 ^a	2.2 $\pm$ 0.2 ^a
TCSA (cm ²)	56.7 $\pm$ 2.5 ^b	59.0 $\pm$ 5.3 ^a	61.7 $\pm$ 4.9 ^a	52.3 $\pm$ 2.9 ^a	49.3 $\pm$ 1.5 ^a	58.7 $\pm$ 9.8 ^a
Yield						
Yield (ton/ha)	25.3 $\pm$ 0.5 ^b	28.5 $\pm$ 0.2 ^a	30.0 $\pm$ 0.1 ^a	20.0 $\pm$ 0.5 ^a	20.5 $\pm$ 0.3 ^a	22.0 $\pm$ 0.4 ^a
C.Y (ton/ha)	48.3 $\pm$ 0.5 ^b	50.0 $\pm$ 0.2 ^a	55.6 $\pm$ 0.3 ^a	38.1 $\pm$ 0.5 ^a	40.3 $\pm$ 0.2 ^a	42.5 $\pm$ 0.7 ^a
Y.E (kg/cm ²)	0.81 $\pm$ 0.1 ^a	0.88 $\pm$ 0.2 ^a	0.88 $\pm$ 0.2 ^a	0.70 $\pm$ 0.2 ^a	0.76 $\pm$ 0.1 ^a	0.68 $\pm$ 0.2 ^a
Vegetative growth						
Shoot lenght (cm)	53.3 $\pm$ 5 ^a	55.0 $\pm$ 5 ^a	61.6 $\pm$ 7 ^b	32.7 $\pm$ 4 ^a	29.3 $\pm$ 1 ^b	33.3 $\pm$ 3 ^a
Internode number	14.3 $\pm$ 2.0 ^a	16.7 $\pm$ 1.5 ^a	15.3 $\pm$ 2.5 ^a	20 $\pm$ 1 ^a	19.7 $\pm$ 1.5 ^a	15 $\pm$ 1 ^b
Shoot D (cm)	0.4 $\pm$ 0.1 ^b	0.50 $\pm$ 0.1 ^a	0.60 $\pm$ 0.1 ^b	0.4 $\pm$ 0.1 ^a	0.4 $\pm$ 0.1 ^a	0.5 $\pm$ 0.2 ^a
Internode L (cm)	1.70 $\pm$ 0.1 ^a	1.8 $\pm$ 0.2 ^a	1.5 $\pm$ 0.3 ^b	2.1 $\pm$ 0.4 ^a	2.0 $\pm$ 0.1 ^a	1.5 $\pm$ 0.3 ^b
Leaf Area (cm ²)	22.5 $\pm$ 0.2 ^b	24.7 $\pm$ 0.1 ^b	30.4 $\pm$ 0.1 ^a	27.5 $\pm$ 0.2 ^b	30.8 $\pm$ 0.1 ^a	34.5 $\pm$ 0.2 ^a
Fruit composition						
Water content (%)	83.50 $\pm$ 3 ^b	87.20 $\pm$ 3 ^a	85.50 $\pm$ 3 ^a	82.50 $\pm$ 2 ^b	85.80 $\pm$ 2 ^a	87.80 $\pm$ 2 ^a
Carbohydrates (%)	6.50 $\pm$ 1 ^b	7.20 $\pm$ 1 ^a	8.30 $\pm$ 1 ^a	7.20 $\pm$ 1 ^b	8.20 $\pm$ 1 ^a	10.20 $\pm$ 1 ^a
Ash (%)	0.39 $\pm$ 0.1 ^a	0.42 $\pm$ 0.1 ^a	0.45 $\pm$ 0.1 ^a	0.45 $\pm$ 0.1 ^a	0.50 $\pm$ 0.1 ^a	0.52 $\pm$ 0.1 ^a
Protein (%)	0.50 $\pm$ 0.1 ^a	0.55 $\pm$ 0.1 ^a	0.58 $\pm$ 0.1 ^a	0.51 $\pm$ 0.2 ^a	0.53 $\pm$ 0.2 ^a	0.56 $\pm$ 0.2 ^a
Fiber (%)	1.65 $\pm$ 0.2 ^a	1.72 $\pm$ 0.2 ^a	1.85 $\pm$ 0.2 ^a	1.60 $\pm$ 0.2 ^a	1.70 $\pm$ 0.1 ^a	1.80 $\pm$ 0.2 ^a

Abbreviations: TCSA: Trunk cross-sectional area. CY: cumulative yield. Y.E: Yield efficiency. D: diameter. L: length. T0: (0% K-Si). T2: (3% K-Si). T3: (4.5% K-Si).

The yield, cumulative yield and yield efficiency over the two growing seasons are shown in Table 3. The two treatments T1 (3% K-Si) and T2 (4.5% K-Si) presented similar behavior and showed statistically significant differences ($p < 0.05$) with the control (T0). The mean annual yield varied from 25.3 to 30.0 tons/ha in the cv “Early Bomba” and from 20 to 22 tons/ha in the cv “Plagold 17”. The cumulative yield ranged from 48.3 to 55.6 tons/ha for the cv “Early Bomba” and from 38.1 to 42.5 tons/ha for the cv “Plagold 17”. The yield efficiency varied from 0.81 to 0.88 kg/cm² in the cv “Early Bomba” and from 0.68 to 0.76 kg/cm² in the cv “Plagold 17”.

The fruit nutritional composition is shown in Table 3. The applied treatment enhanced water and carbohydrates content in the two studied cultivars. Hence, the treatments T1 and T2 presented statistically significant differences ($p < 0.05$) with the control (0% K-Si). The water content ranged from 83.5 to 87.2% in the cv “Early Bomba”, under the treatments T0 and T1, respectively. The cv Plagold 17 showed values of water content in the range of 82.5–87.8% under treatments T0 and T2, respectively. The carbohydrates content varied from 6.5% in the cv “Early Bomba” to 10.2% in the cv “Plagold 17” showing significant ($p < 0.05$) differences between the control and the two applied potassium silicon treatments. The amount of ash varied from 0.39% in the cv “Early Bomba” to 0.52% in the cv “Plagold

17". The protein content varied from 0.51% in the cv "Plagold 17" to 0.61% in the cv "Early Bomba". The fiber content of peach pulp varied from 1.6% in "Plagold 17" to 1.85% in "Early Bomba" with no significant differences between fertilization treatments.

3.3. Physicochemical Parameters

The impact of potassium silicon pretreatment on fruit weight (a), firmness (b), soluble solids content (SSC) (c), titratable acidity (TA) (d), ripening index (RI) (e), pulp stone ratio (f), fruit volume (g), and conductivity (CE) (f) in peach cultivars at harvest and after 2 or 4 weeks of cold storage (5 °C and 95% Relative Humidity) during two growing seasons (2021/2022) were summarized in the Figure 1a–h.

The applied K-Si treatments improved the fruit weight (Figure 1a), flesh fruit firmness (Figure 1b), and SSC (Figure 1c), under the two treatments T1 and T2 and showed significant differences ($p < 0.05$) with the treatment T0. The potassium silicon treatment reduced the titratable acidity (TA) values in the fruits (Figure 1d), which showed a gradual decrease during the storage period. The observed differences in SSC and titratable acidity resulted in a remarkable increase in the fruit ripening index (Figure 1e) over the cold storage period, presenting significant differences ($p < 0.05$) with the values obtained at harvest. The pulp/stone ratio was improved by the potassium silicon application as shown in Figure 1f. However, the cold storage period negatively affected the pulp stone ratio. The fruit volume (Figure 1g) decreased among storage periods and showed significant differences between the control and the two K-Si treatments. The juice conductivity was not affected by the fertilization treatment and the cold storage periods in the two studied cultivars (Figure 1h).

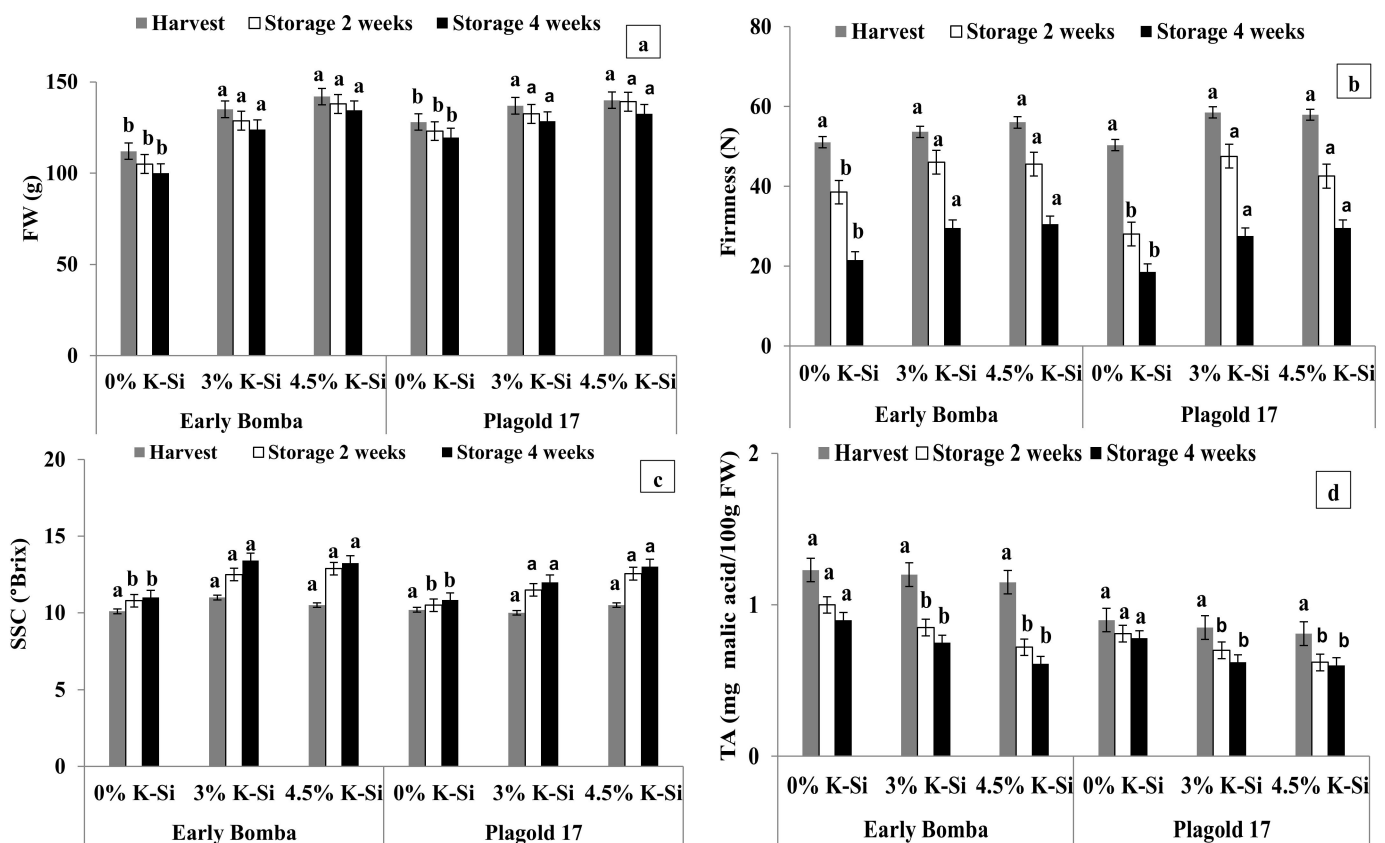


Figure 1. Cont.

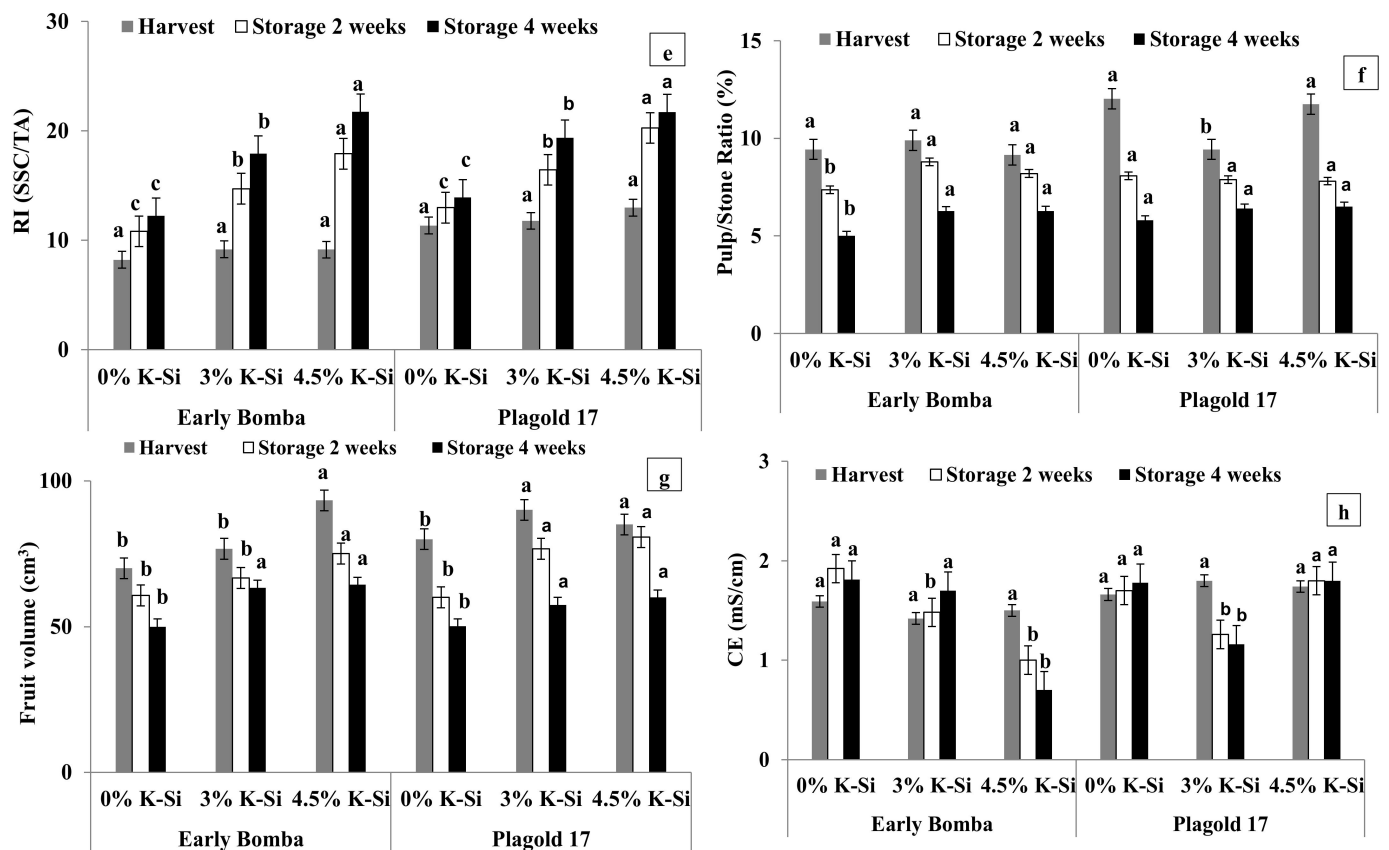


Figure 1. Impact of potassium silicon pretreatment and storage period on fruit weight (a), firmness (b), soluble solids content (SSC) (c), titratable acidity (TA) (d), ripening index (RI) (e), pulp stone ratio (f), fruit volume (g), and conductivity (CE) (h) in peach cultivars at harvest and after 2 or 4 weeks of cold storage (5 °C and 95% Relative Humidity) during two growing seasons (2021/2022). Values are means ($n = 3$) $\pm$ SE. Different letters a, b, indicate significant difference among K-Si treatments in each cultivar according to Scheffe's multiple range test.

Values of L^* , a^* , b^* , C^* and h° of fruit color at harvest and during cold storage were evaluated in the 2021 and 2022 growing seasons, and results are shown in Table 4. Our study showed that the brightness (L^* value) in the cv “Plagold 17” increased after the two cold storage periods whereas the cv “Early Bomba” remained stable. The degree of red blush (a^* value) was maintained during the cold storage periods. The degree of yellow blush (b^* value) in the peel of peach fruit was higher after 4 weeks of cold storage.

3.4. Phenolic Compounds Content

The analysis of anthocyanins, flavonoids, total phenolics and antioxidant capacity in fruits of the two cultivars “Early Bomba” and “Plagold 17” over the two storage periods are shown in Figure 2. The anthocyanin content varied between treatments, showing statistically significant differences ($p < 0.05$) between the control and the treatments T1 and T2 (Figure 2a). Hence, fruits presented high anthocyanin values after the two cold storage periods. The potassium silicon treatments did not affect the flavonoid content (Figure 2b). The flavonoid content decreased after cold storage in both peach cultivars, showing statistically significant ($p < 0.05$) differences with values obtained at harvest. The total phenolic content (Figure 2c) did not presented a clear increase under the K-Si treatments. After storage, the total phenolic content increased in all the studied cultivars, showing significant difference ($p < 0.05$) with the values obtained at harvest. The applied treatment of fertilization did not affect significantly the antioxidant capacity of fruits (Figure 2d). After 2 weeks of cold storage, the values of antioxidant capacity were higher

than those observed at harvest. The storage period clearly affected the antioxidant capacity of the studied cultivars as compared to the control treatment.

Table 4. Impact of potassium silicon pretreatment and storage period on fruit peel color indices L*, a*, b*, C* and h° of the peach cultivars during harvest and after two cold storage periods (2 and 4 weeks). L* means the brightness of the sample while a* and b* represent the color directions. Values are the means ($n = 5$) $\pm$ SE. Different letters a, b, indicate difference ($p < 0.05$) among storage periods in each treatment for the same cultivar.

Storage Period	L*	a*	b*	C*	h°
T0 (0% K-Si)					
Early Bomba					
Harvest	46.32 ^a	35.12 ^a	16.93 ^b	38.98 ^a	25.64 ^b
2 weeks storage	46.18 ^a	31.83 ^a	21.13 ^a	38.20 ^a	33.42 ^a
4 weeks storage	43.52 ^a	33.90 ^a	19.98 ^a	39.34 ^a	30.54 ^a
Plagold 17					
Harvest	28.05 ^b	24.52 ^a	16.18 ^a	29.37 ^a	33.42 ^a
2 weeks storage	38.15 ^a	23.35 ^a	14.88 ^a	27.68 ^a	32.61 ^a
4 weeks storage	36.35 ^a	24.98 ^a	12.43 ^b	27.90 ^a	26.65 ^b
T1 (3% K-Si)					
Early Bomba					
Harvest	50.90 ^a	27.70 ^a	23.30 ^a	36.19 ^a	40.03 ^a
2 weeks storage	44.32 ^b	27.13 ^a	19.23 ^a	33.25 ^a	35.37 ^a
4 weeks storage	46.90 ^b	27.50 ^a	14.20 ^b	27.81 ^b	38.53 ^a
Plagold 17					
Harvest	34.30 ^b	25.40 ^a	10.70 ^b	27.56 ^b	22.78 ^b
2 weeks storage	42.25 ^a	22.92 ^a	23.40 ^a	32.75 ^a	45.56 ^a
4 weeks storage	31.40 ^b	25.20 ^a	12.10 ^b	27.95 ^b	25.64 ^b
T2 (4.5% K-Si)					
Early Bomba					
Harvest	47.90 ^a	41.50 ^a	24.60 ^a	48.24 ^a	30.54 ^a
2 weeks storage	42.58 ^a	31.92 ^b	17.73 ^b	36.51 ^b	29.24 ^a
4 weeks storage	41.20 ^a	33.30 ^b	14.00 ^b	36.12 ^b	22.78 ^b
Plagold 17					
Harvest	35.30 ^b	25.40 ^a	16.40 ^b	30.23 ^b	33.02 ^b
2 weeks storage	41.48 ^a	25.68 ^a	21.47 ^a	33.47 ^b	40.03 ^a
4 weeks storage	40.40 ^a	24.50 ^a	25.50 ^a	42.90 ^a	36.50 ^a

3.5. Vitamin B5 and Vitamin C Analysis

The vitamin B5 (Figure 3a) and vitamin C (Figure 3b) content showed high variability between fertilization treatments and cold storage periods. The fertilization treatments clearly improved the vitamin B5 and vitamin C content in the cv “Early Bomba”. The cv “Plagold 17” showed high values of vitamin B5 and vitamin C under the treatment T1 (3% K-Si). The storage period negatively affected the vitamin B5 and vitamin C content, showing high values at harvest.

3.6. Ethylene Biosynthesis, Fruit Decay and Chilling Injury

Figure 4 showed the visual appearance of peach fruits during storage periods. The postharvest application of potassium silicon was found to be effective and reduced significantly the rate of disease/decay occurrence in the peach fruit.

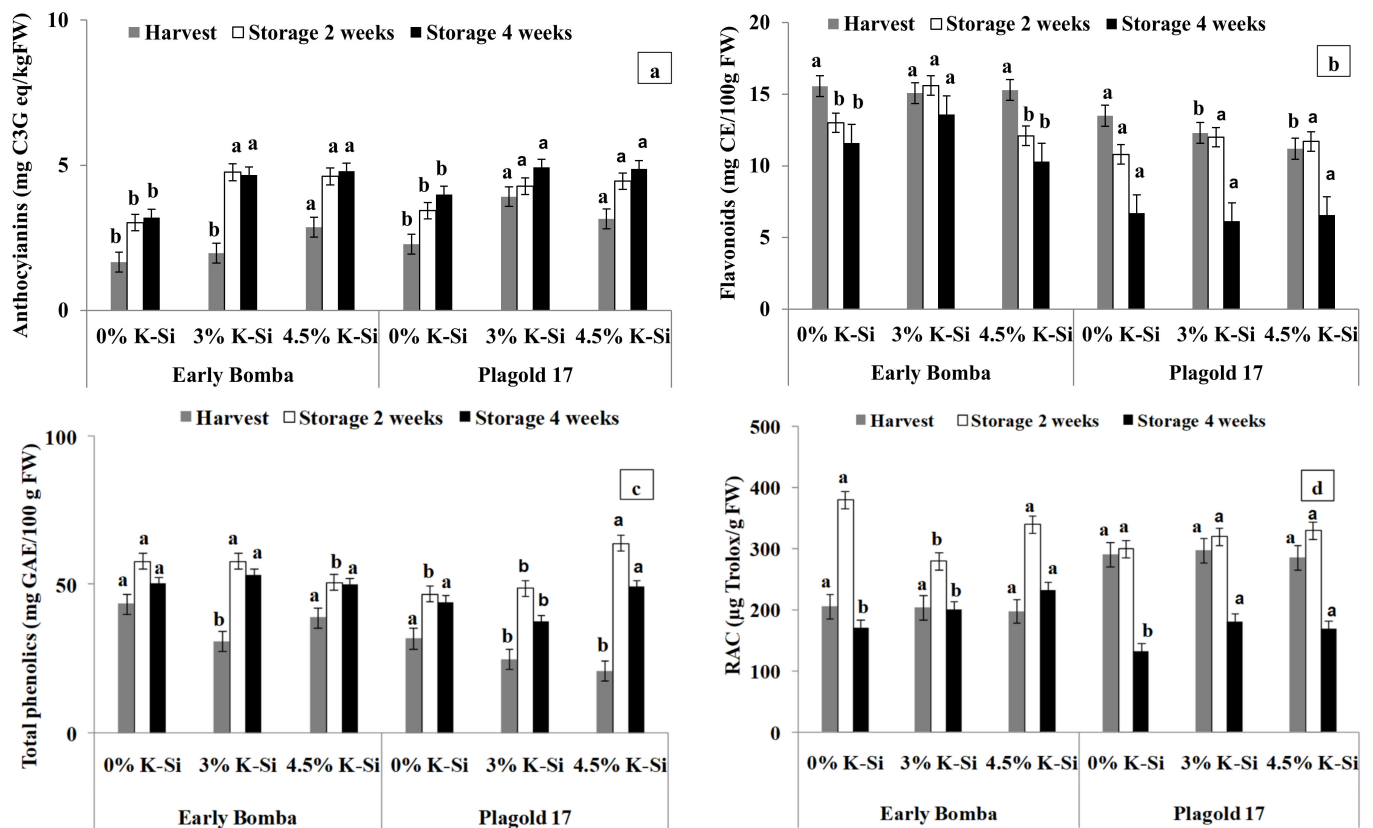


Figure 2. Influence of potassium silicon spray and storage period on contents of anthocyanins (a), flavonoids (b), total phenolics (c), and relative antioxidant capacity (RAC) (d), among two peach cultivars at harvest and after 2- and 4-week cold storage periods during the growing seasons (2021–2022). Abbreviations: Values are the means ($n = 3$) $\pm$ standard error. Different letters a, b, indicate difference ($p < 0.05$) among K-Si treatments in each cultivar according to Scheffe's multiple range test.

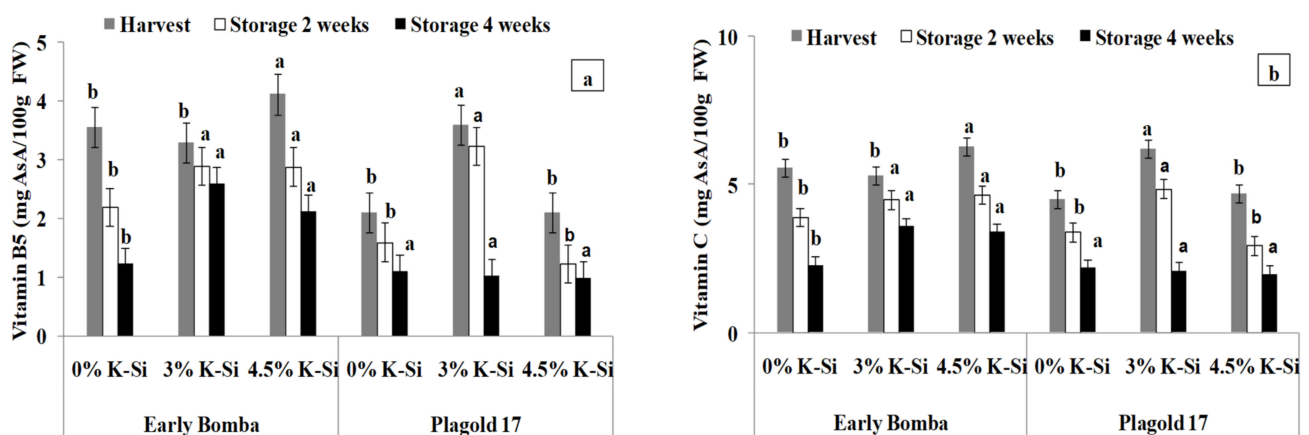


Figure 3. Influence of potassium silicon spray and storage period on vitamin B5 (a) and vitamin C (b) contents among two peach cultivars at harvest and after 2- and 4-week cold storage periods during the growing seasons 2021–2022. Abbreviations: Values are the means ($n = 3$) $\pm$ standard error. Different letters a, b, indicate differences ($p < 0.05$) among K-Si treatments in each cultivar according to Scheffe's multiple range test.

cv. Early Bomba			cv. Plagold 17		
Harvest	2 weeks	4 weeks	Harvest	2 weeks	4 weeks
					
control					
					
3% K-Si					
					
4.5% K-Si					

Figure 4. Impact of potassium silicon pretreatment and storage period on fruit decay in peach cultivars after 2 or 4 weeks of cold storage.

The results in Figure 5a showed an inverse relationship between the fertilization treatments and the rate of ethylene production of peach fruit at harvest and during the entire period of cold storage. The maximum ethylene measured at harvest was observed in the control treatment, while the 3% K-Si and the 4.5% K-Si treatments showed significantly ($p < 0.05$) lower values. Hence, at harvest the ethylene production was $5.2 \text{ nL g}^{-1} \text{FW h}^{-1}$ in the cv “Early Bomba” and $4.48 \text{ nL g}^{-1} \text{FW h}^{-1}$ in the cv “Plagold 17”. During storage, the 3% K-Si and the 4.5% K-Si application significantly ($p < 0.05$) reduced the ethylene climacteric peak of the peach fruit as compared to control.

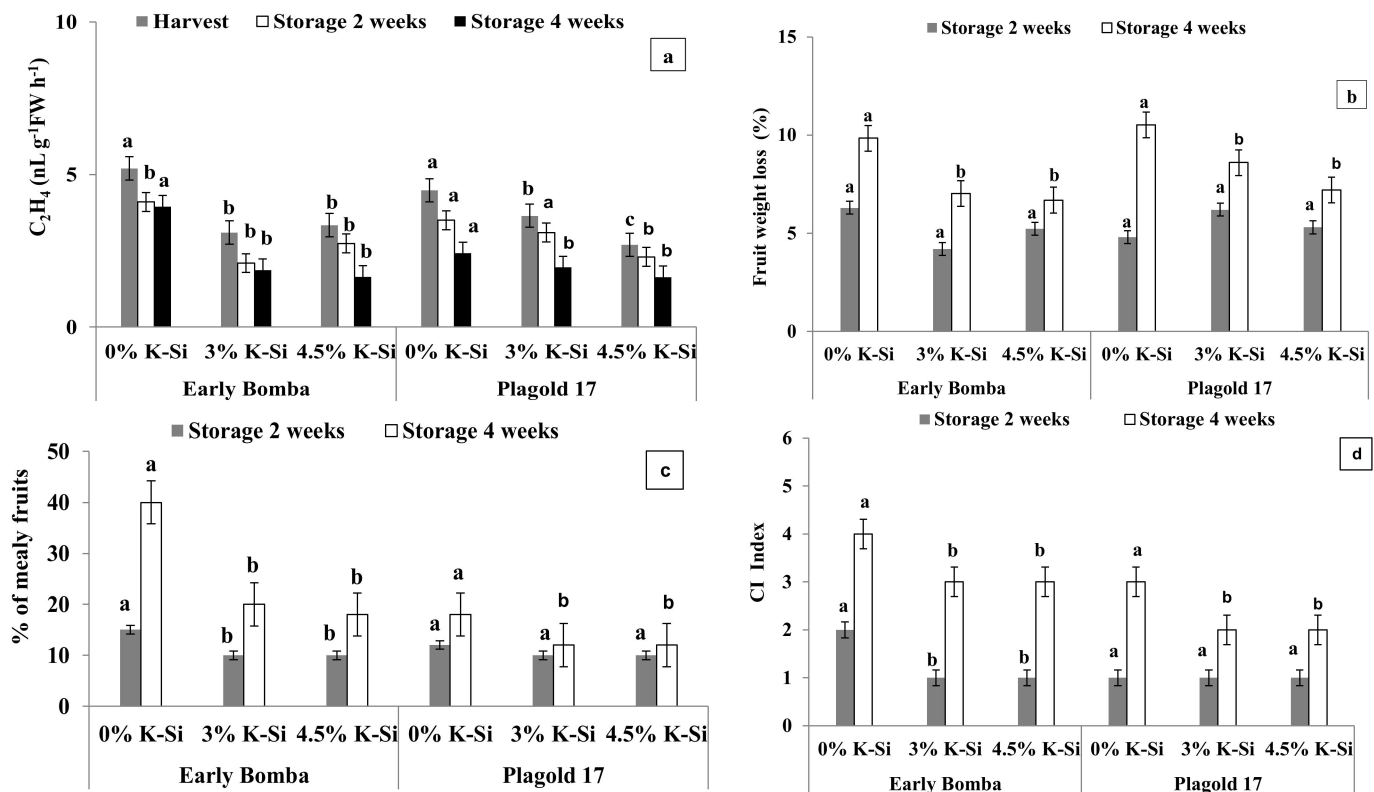


Figure 5. Impact of the potassium silicon spray and storage period on ethylene (a), fruit weight loss (b), mealiness (c) and chilling injury index (d) in peach cultivars after storage at 5°C for 2 and 4 weeks and then ripening at room temperature for 2 days. Units and abbreviations: CI (CI index) was visually assessed according to the global fruit appearance of each genotype, from healthy fruit with no symptoms (1) to extremely injured fruit with severe CI symptoms (6). Values are means ($n = 3$) $\pm$ SE. Letters a, b, c letters indicate difference ($p < 0.05$) among K-Si treatments after 2 weeks of cold storage according to Scheffé's multiple range test.

The potassium silicon application improved the flesh texture and the external fruit quality, resulting in a clear reduction of fruit weight loss during the two cold storage periods as compared to the control (Figure 5b). The fruit weight loss increased progressively with storage, and significant differences ($p < 0.05$) were observed among the two cold storage periods.

The storage period (2 or 4 weeks at 5°C) increased the severity of mealiness (Figure 5c) in the flesh fruit of the studied varieties. The applied fertilization treatments enhanced the flesh texture, showing significantly ($p < 0.05$) lower values of mealiness as compared to control.

The chilling injury index (Figure 5d) increased greatly after four weeks of cold storage and varied differently between cultivars. A considerably higher proportion of fruit was significantly affected by CI symptoms in the control treatment, while the treated fruits with potassium silicon showed significantly lower values of CI.

4. Discussion

The two studied cvs “Early Bomba” and “Plagold 17” presented mid-season harvesting dates. The cv “Early Bomba” presented early blooming dates as compared to the peach cv “Plagold 17”. The harvesting dates of the two cultivars were very close, showing the short development period of the cv “Plagold 17”. The blooming and the harvesting dates showed statistically significant differences ($p < 0.05$) between the two growing seasons assessed in terms of Julian days. Hence, the blooming dates were 10 days later in the 2022 growing season as compared to 2021, due to annual variation in climatic conditions. In this same context, [21], studying the variability of phenological traits and fruit development periods between years among peach progenies, reported that bloom and harvest dates may change depending on the temperature and that the fruit development period remained more or less stable for each seedling over the years of study.

The vegetative growth showed no statistically significant difference among treatments. Hence, a slight improvement of shoot length and diameter was observed in the two studied cultivars under both treatment T1 (3% K-Si) and T2 (4.5% K-Si) as compared to the control. Our results are in accordance with [22], who reported that the differential foliar silicon fertilization had no significant effect on the studied growth parameters of apple (*Malus domestica* Borkh.) trees. However, [23] reported that foliar application of K_2SiO_3 increased trunk diameter and the number of second-order lateral branches in apple trees.

The cv “Early Bomba” presented clearly higher yield as compared to the cv “Plagold 17”. The applied foliar fertilization of K-Si enhanced the yield of the two studied cultivars presenting high production in T1 and T2 treatments as compared to control (T0). Soppelsa et al. [24] obtained an improvement in the yield of apple trees as shown by the yield and number of fruits per tree after application of Siliforce silicon fertilizer. Our findings are in line with [25], who stated an improvement of yield in fig trees after foliar application of potassium silicate at concentrations of 1 and 2%.

The agronomical and basic biochemical fruit quality traits such as fruit weight, firmness, SSC, TA, RI were improved under the K-Si fertilization. Our results are in accordance with [26], who reported an improvement in fruit weight, SSC and TA of Anna apple with foliar potassium silicate (3%) fertilization. Moreover, [27] reported that potassium silicate applications enhanced fruit quality parameters, such as fruit weight, fruit dimensions, fruit pulp, fruit firmness and total soluble solids. Abdrabboh [28] revealed that higher fruit firmness of the Amal apricot cultivar was obtained by a higher concentration of potassium silicate than the non-treated trees. Kaur et al. [29] reported that pre-harvest spraying of peach trees with potassium nitrate at 2% increased fruit weight, TSS and ripening index (TSS: acid), whereas firmness and acidity decreased. In the same line Gill et al. [30], applying three sprays with potassium nitrate 1.5%, significantly improved the fruit size of pear as compared to control. Furthermore, [31] stated that the highest fruit firmness of Anna apple was obtained by potassium silicate application at 0.2%. However, the interaction effect between preharvest K-salts treatments and storage periods on fruit firmness was significant in both seasons. Moreover, silicon application prevents fruit softening by affecting activities of major cell wall degrading enzymes such as cellulase, polygalacturonase, and xylanase [8].

Our results showed an improvement of fruit peel color under K-Si fertilization. These findings were supported by the results of [24], who reported that the intensity of red color increased in apple after silicon fertilization. El Kholy et al. [27] revealed that the shining of fruits (hue angle) value was increased with the application of potassium silicate (K_2SiO_3); however, the accumulation of pigments in fruits during cold storage was retarded.

The fruit composition was also affected by the K-Si fertilization. Hence, fruits under T1 and T2 presented an improved fruit nutritional composition regarding protein, ash, fiber, and carbohydrates as compared to control. Jia et al. [32] reported that silicon applications enhanced protein content in fruits.

The potassium silicon improved the antioxidant compounds content. The increase in anthocyanin content reported in this study was supported by [33], who reported an

increase in this phenolic compound during ripening. The decrease in vitamin B5 and vitamin C observed in our study was in accordance with [34], who reported that the highest vitamin C content of peach fruits was observed at harvest. The decrease of antioxidant capacity observed after 4 weeks of storage could be explained by the decrease in phenolic compounds [35].

Potassium silicon treatments decreased ethylene biosynthesis in fruit during storage. These results are in line with the study of [31] on “Anna” apple. Our findings in ethylene reduction under K-Si application were also supported by [27], who reported that K-silicate application reduced ethylene production and chlorophyll degradation. Our results are in the range [0.56 to 15.26 nL g⁻¹ FW h⁻¹] reported by [36] for ethylene biosynthesis in peach fruits.

The reduction of fruit weight loss observed in our study was also reported in the study of [37], which stated that Si treatments delayed fruit weight loss by maintaining fruit water content. In this line, [38] reported that Si decreased fruit decay by controlling fungal diseases. El Kholy et al. [27] reported that the potassium silicate-treated fruits showed lower weight loss (%) as compared to the control and that this might be due to the suppression of the transpiration and respiration rates of fruits by closing of the stomata. The interaction effect of storage period and potassium silicon treatments showed a high reductive effect on fruit decay percentage in both seasons.

5. Conclusions

This work showed the impact of potassium silicon application during three phenological stages on the agronomic, physicochemical and biochemical peach fruit parameters during cold storage. Potassium silicon fertilization applied in this experiment did not improve the tree vigor and the vegetative growth parameters. However, it increased the yield of trees as well as the quality of fruit expressed by fruit weight, firmness, SSC, TA, RI and biochemical traits. Trees under the treatments T1 (3% K-Si) and T2 (4.5% K-Si) presented significant differences with the control (0% K-Si) for the major analyzed fruit quality traits. The antioxidant capacity, vitamin B5 and vitamin C were not affected by the fertilization application, but rather by the cold storage periods. The fruit weight loss and chilling injury symptoms were clearly reduced by the K-Si application. The treatment T1 (3% K-Si) was effective in improving fruit firmness and postharvest quality. Further studies are needed to elucidate and fill gaps in the physiological mechanisms that explain the impact of K and Si fertilization on fruit physicochemical and biochemical parameters.

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