

## Article

# Influence of High Tunnel Microclimate on Fruit Quality and Calcium Concentration in 'Santina' Sweet Cherries in a Mediterranean Climate

Victor Blanco <sup>1</sup>, Juan Pablo Zoffoli <sup>2</sup> and Marlene Ayala <sup>2,\*</sup>

<sup>1</sup> Department of Horticulture, Tree Fruit Research and Extension Center, Washington State University, Wenatchee, WA 98801, USA; victor.blanco@wsu.edu

<sup>2</sup> Departamento de Fruticultura y Enología, Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Santiago 7820244, Chile; zoffolij@uc.cl

\* Correspondence: mayalaz@uc.cl

**Abstract:** The use of protective covers, such as high tunnels, is recognized as an effective technology to reduce rain-induced fruit cracking in sweet cherries; however, there is a lack of information concerning the effects of this production system on the fruit's mineral concentration, quality, and postharvest life. This study assesses the feasibility of using high tunnels on 'Santina' sweet cherries under the Mediterranean climate of the Central Valley of Chile to obtain earlier harvests of high-quality fruit with long storage life. The study included two plots: Plot 1 during the 2018/2019 growing season, and Plot 2 during the 2019/2020 growing season. High temperatures and relative humidity inside the high tunnels during bloom and fruit set decreased fruit yield, particularly in Plot 1. On average, trees inside the high tunnels were harvested 11 days earlier than those in the open. Fruit from covered trees were significantly larger (13%) and softer (10%) than those from the outside. Fruit quality characteristics, such as soluble solids concentration and titratable acidity, were not affected by high-tunnel-protected cultivation. Fruit from covered and uncovered trees maintained the firmness differences obtained at harvest between treatments, but showed similar postharvest quality after 45 days at 0 °C and a further 3 days at 20 °C on the other characteristics. The covered fruit had lower Ca concentrations (7.7 mg 100 g<sup>-1</sup>) and higher K:Ca, Mg:Ca, and N:Ca ratios. Significant relationships were found between Ca or K:Ca and fruit firmness at harvest. Lower Ca concentrations in the fruit may explain the lower firmness of fruit grown under plastic covers. There were no differences between covered and uncovered cherries in either cracking susceptibility or induced pitting. 'Santina' cherries were very sensitive to pitting damage, but this is not associated with the fruit's Ca concentration. The results obtained show that high tunnels influenced fruit yield, development, and quality, and emphasize that the fruit's Ca concentration under this growing condition plays a significant role in the firmness of 'Santina' sweet cherries.

**Keywords:** calcium; covers; fruit firmness; cracking; pitting; protected environment



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## 1. Introduction

Sweet cherry (*Prunus avium* L.) is one of the most popular fruits grown in temperate climates. High consumer demand and good grower returns have led to widespread increases in production, especially in the last two decades [1]. Consequently, sweet cherry orchards have expanded rapidly into many regions, including those in which it has not been a traditional crop. Some of these regions suffer insufficient winter chill or other adverse weather conditions. Moreover, some climates have advanced harvests in the early cultivars or delayed them in the late cultivars, with obvious market benefits [2].

One of the main limitations to sweet cherry production, and one of the greatest threats to its profitability, is rain-induced fruit cracking [3]. Cracking susceptibility increases during the last period of fruit development, shortly before harvest, and particularly after

(or during) rainfall. Failure in the extension of the cuticular membrane is induced by water uptake either by the fruit skin and/or via the root [4,5]. The use of plastic covers has been reported to be an effective way to reduce rain-induced cracking, since the covers present a physical barrier that prevents direct water contact with the fruit surface [6]. A range of plastic covering systems have been trialed by cherry growers, and high tunnels and tents have emerged as the most popular [7]. High tunnels are unheated and passively vented hoop structures of 2–3 m height, covered by flexible and removable plastic film [8]. In addition to keeping water from the fruit surface, high tunnels also significantly modify the microclimatic conditions, changing the trees' phenological and physiological properties, bloom and harvest dates, vegetative and fruit growth, yield, fruit quality, and water use efficiency [9–11].

As sweet cherry is a highly perishable, non-climacteric fruit, which is harvested at the ripe stage close to senescence, its potential for storage at low temperatures is rather limited [12,13]. Therefore, export to lucrative distant markets requires specific protocols for the selection of the most appropriate cultivar/rootstock combination, the training system, and preharvest managements to obtain high-quality fruit and, thus, slow postharvest fruit deterioration [14]. Sweet cherry deterioration during storage is characterized by dehydration, skin darkening, high susceptibility to mechanical damage (i.e., pitting and bruising), and decay. In addition, postharvest fruit cracking and pebbling are two other critical physiological disorders in some cultivars and seasons under saturated modified atmosphere packaging [15,16]. Pitting and bruising are expressed as sunken areas in the surface of the fruit that occur when cells in the epidermis–hypodermis collapse due to mechanical damage at harvest or during postharvest handling [17]. On the other hand, pebbling (i.e., orange-peel disorder) is a minor physiological disorder characterized by skin roughness caused by water loss from the fruit skin [18,19].

The storage potential of sweet cherries is influenced by preharvest environmental conditions, fruit mineral concentration, maturity at harvest, and postharvest handling [12,20]. Firm fruit is required, not only to achieve a desirable texture but also to ensure resistance to mechanical damage during picking and handling, thus minimizing postharvest pitting and bruising [20]. Calcium (Ca) has been shown to be a crucial mineral in many fruits, since it affects physiological responses associated with surface disorders and softening during storage [21]. In sweet cherries, the effects of Ca on firmness are uncertain. Moreover, there is almost no information on the effects of high tunnel production on fruit Ca concentration [22–25]. High tunnels are known to modify microenvironmental conditions, increasing both air temperature and relative humidity [26,27]. Hence, inappropriate management and ventilation can lead to reductions in fruit yield and quality, and can be associated with specific fruit mineral deficiencies induced by heat stress.

To our knowledge, there have been no formal reports that accurately define the effects of microclimate conditions under high tunnels on sweet cherry fruit quality, fruit mineral composition, and storage potential, particularly under Mediterranean conditions. However, a few reports have dealt with high tunnel cherry cultivation under continental and oceanic climates, such as in Michigan (USA), Norway, and Poland [10,11,28]. In an earlier report we found that sweet cherry fruit under high tunnels in Chile's Central Valley were larger and less firm than fruit grown out in the open, but their postharvest storage potential, mineral composition, and incidence of physiological disorders were not assessed [26]. In this two-year study, we hypothesize that the microclimate created within high tunnels will influence sweet cherry fruit quality both at harvest and postharvest, and that these changes are related to changes in fruit mineral composition, and especially to fruit Ca content. Accordingly, the main objective in this study was to assess the feasibility of using high tunnels on 'Santina' sweet cherry production in the Central Valley of Chile in order to obtain earlier harvests of high-quality fruit with long postharvest life.

## 2. Materials and Methods

### 2.1. Plant Material, Study Site and Treatments

The experiment was carried out on the sweet cherry cultivar ‘Santina’ on ‘Colt’ rootstock in the Central Valley of Chile during two consecutive growing seasons, 2018/2019 and 2019/2020 (a Southern Hemisphere growing season spans two calendar years). Two plots were considered. Plot 1 was located in the Maule region (34°59′ S, 71°22′ W), and consisted of 6-year-old sweet cherry trees trained as a Kym Green Bush (KGB) system at a tree density of 1136 plants ha<sup>-1</sup>. In Plot 1, the evaluations were carried out during the 2018/2019 growing season. Plot 2 was located in the O’Higgins region (34°20′ S, 71°07′ W), and consisted of 6-year-old sweet cherry trees trained as a Y-trellis system at a tree density of 1250 plants ha<sup>-1</sup>. In Plot 2, the evaluations were carried out during the 2019/2020 growing season. The climate in both plots was Mediterranean (Csb2Sa) according to the Köppen classification [29]. Temperatures ranged between maximum monthly values of 30 °C recorded in January, and minimum values of 5 °C in July. Mean annual precipitation was lower than 700 mm, and showed high seasonality, mostly during the fall and winter. Neither the 2018/2019 nor 2019/2020 growing seasons registered any frosts or rainy episodes. The soil in both plots was sedimentary–alluvial with a xeric moisture regime. The soil series were La Campana (Plot 1) and Cachapoal (Plot 2).

In each plot, two treatments were assessed: covered trees under high tunnels (treatment 1); and uncovered or open trees (treatment 2, control). The treatments were distributed in a completely randomized design with four replications. The high tunnel consisted of a multi-bay hoop house structure (pioneer model, Haygrove Ltd., Ledbury, UK) 8 m wide with 2.2 m side-wall height and a 150 µm thick polyethylene (PE) film roof (Luminal, Visqueen, bpi.films, London, UK). The PE film could be rolled up to achieve passive ventilation, decreasing the temperature and relative humidity inside the high tunnels. Horticultural practices such as irrigation, fertilization, pruning, and weed control were the same for both treatments. In order to characterize fruit location within the canopy, two canopy layers were identified: the upper canopy (above 1.5 m), and the lower canopy (below 1.5 m).

### 2.2. Environmental Monitoring, Fruit Development, and Fruit Quality

The environmental conditions—i.e., air temperature (°C) and relative humidity (%)—were monitored inside and outside the high tunnels, using three sensor devices (HOBO U12-012, OnsetComp, Bourne, MA, USA) per treatment. These were positioned 2.0 m above ground level.

Fruit size development was characterized during both seasons of the study (2018/2019 and 2019/2020) by measuring fruit diameter (mm) every 7 days on 10 labeled representative fruit per tree (40 fruit per treatment) with a digital caliper (Electronic Digital Caliper, Veto, Santiago, Chile). At commercial harvest, all fruit produced per tree (four trees per treatment) was harvested and weighed individually (B-40VA, Ventus Corp., Santiago, Chile) to obtain the tree yields inside and outside the high tunnels. Commercial harvest dates were determined by skin color and commercial judgement.

At harvest, based on color (cherry color chart scale, Pontificia Universidad Católica de Chile), 100 fruit per canopy layer and replicate were selected at random to assess fruit quality. Fruit quality characteristics analyzed included fruit unitary mass (g), fruit size (diameter, mm), soluble solids concentration (SSC) (%), PR32, Atago, Tokyo, Japan), titratable acidity (TA) (%), TitroMatic compact titrator; Crison, Barcelona, Spain), maturity index (MI, calculated as the ratio between SSC and TA), and fruit firmness. Fruit firmness was measured over the range 0 (soft) to 100 (firm) using a shore durometer (type A, Durofel Agrotechnologie, Tarascon, France) with a 2.5 mm tip. Fruit cracking sensitivity was assessed by determining the cracking index (CI). CI was measured in the laboratory 24 h after harvest by immersion of 50 fruit (from each treatment and canopy layer) in deionized water (pH 7) or in an acidic medium (pH 4; 0.1 M citric acid and 0.2 M disodium phosphate solutions in a ratio of 62:38). CI was calculated according to Christensen [30] as:

$CI = (5a + 3b + c)/(250)$ , where *a*, *b*, and *c* were the numbers of cracked fruit found and discarded after 2, 4, and 6 h of immersion, respectively.

In Plot 1, during the 2018/2019 growing season, postharvest storage evaluation consisted of 45 d at 0 °C (cold storage), with an additional 3 d of storage at 20 °C (shelf life). Fruit selected for this were free from defects and of similar size (26–28 mm) and ripening stage. These included fruit from the upper and lower parts of the canopy. Each replicate consisted of a bag of 1000 g of fruit from each of four replicates per treatment. The samples were packed under saturated conditions of modified atmosphere packaging (5–8% CO<sub>2</sub> and 10–15% O<sub>2</sub>, San Jorge packaging, Chile). Later, each 1000 g bag was divided, and 500 g of fruit was assessed immediately after cold storage (at 45 d), while the other 500 g was evaluated after a further three-day shelf life period at 20 °C (45 d + 3 d). In each case, fruit mass, size, color, firmness, SSC, TA, and MI were assessed for 20 fruit per replicate. After the shelf life period (45 d + 3 d), a visual evaluation ranked each fruit in term of the presence (%) of decay and physiological disorders (i.e., postharvest cracking, pitting, bruising, or pebbling), where incidence (%) was calculated.

In Plot 2, during the 2019/2020 season, a pitting induction experiment was carried out. The pitting induction procedure was conducted 24 h after harvest, on 20 fruit per replicate and for each canopy layer, using a similar procedure to that described by Toivonen et al. [31]. A controlled force of 0.011 N generated by a stainless steel probe rod with 4.91 mm<sup>2</sup> of contact surface and 10 g mass was dropped from a 0.06 m height on to the fruit surface (cheek). Each individual fruit was assessed in terms of the presence of damage after 14 d at 0 °C. Incidence was calculated as the proportion of affected fruit from the total, and expressed as a percentage.

### 2.3. Fruit Mineral Analysis

In Plot 2, a fruit mineral analysis was run at harvest using 500 g of fruit per replicate as samples. Fruit dry matter was calculated (DM, %) as the percentage of the dry weight of the sample (oven-dried at 65 °C for 48 h until constant weight) relative to its fresh weight. Mineral concentrations were determined by dry combustion until components were converted to ash (calcinated at 500 °C for 8 h). The following nutrients were determined using the methodology of Ryan et al. [32]: phosphorus (P), potassium (K), magnesium (Mg), and Ca. The ash tissue samples were then dissolved in HCl (2 M), and concentrations were determined via inductively coupled plasma optical emission spectroscopy (ICP-OES) (Agilent 720 ES axial—Varian, Mulgrave, Victoria, Australia). The nitrogen (N) concentrations were determined using a LECO CNS-2000 Elemental Analyzer (Leco, St. Joseph, MI, USA). From these measurements, fruit mineral concentration (mg/100 g of fresh fruit) was calculated.

Additionally, the stoichiometric ratios N:Ca, K:Ca, and Mg:Ca were also calculated.

### 2.4. Statistical Analysis

Analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) were carried out to determine significant ( $p = 0.05$ ) differences between the two treatments. The degree of agreement between the independent variables (Ca, N:Ca, K:Ca, maturity index, firmness) and the dependent variables (firmness, induced pitting) was assessed using regression analysis. The coefficient of determination ( $R^2$ ) and the mean square error (MSE) were also calculated. Statistical analyses were carried out using IBM SPSS Statistics v24 (Armonk, NY, USA). Principal component analysis (PCA) was carried out in RStudio package (RStudio Inc., Boston, MA, USA).

## 3. Results

### 3.1. Microclimate

The high tunnels modified the microclimate, altering both physiology and phenology. In general, differences in air temperature and relative humidity between high tunnels and open field conditions were more pronounced in Plot 1 than in Plot 2. Air temperature inside the high tunnels was higher than in the open fields in both plots, for the entire

period of fruit development. The high tunnels had a greater effect on the maximum air temperatures than on the minimum air temperatures. The greatest differences in maximum air temperature between inside and outside the high tunnels were recorded during full bloom and fruit set. In both plots, the covered trees were exposed to air temperatures higher than 27 °C during full bloom—5 °C higher than in the open field (Table 1). In Plot 1, the maximum air temperature averaged 32 °C inside the high tunnels, with the highest values reaching 42 °C during the period between the bloom and the fruit set due to inadequate ventilation (data not shown). As the season progressed, the differences between covered and uncovered trees became smaller, as the ventilation in the high tunnels was improved. Relative humidity showed a similar pattern with respect to covered and uncovered conditions, with higher values inside the high tunnels than outside. The mean values of maximum and minimum relative humidity differed between treatments by 8 and 13%, respectively, for Plot 1 (2018/2019), and 6 and 10%, respectively, for Plot 2 (2019/2020). The mean maximum relative humidity inside the high tunnels was 95%, while in the open plot it was 88% (Table 1).

**Table 1.** Environmental conditions under high tunnels, both covered and in the open, considering Plot 1 (season 2018/2019) and Plot 2 (season 2019/2020).

	Covered				Open			
	Plot 1		Plot 2		Plot 1		Plot 2	
Developmental Stage	T <sub>Mx</sub> (°C)	T <sub>min</sub> (°C)	T <sub>Mx</sub> (°C)	T <sub>min</sub> (°C)	T <sub>Mx</sub> (°C)	T <sub>min</sub> (°C)	T <sub>Mx</sub> (°C)	T <sub>min</sub> (°C)
Full Bloom	31.8	7.7	27.4	6.3	24.6	5.0	22.7	4.3
Fruit Set	28.6	9.6	28.1	5.4	23.5	7.9	24.2	4.9
Stage I	30.9	7.3	26.2	7.6	24.2	7.1	23.0	6.6
Stage II	32.8	8.2	28.3	8.0	29.0	8.0	26.3	7.5
Stage III	32.6	9.7	30.8	8.7	30.5	9.4	29.1	8.3

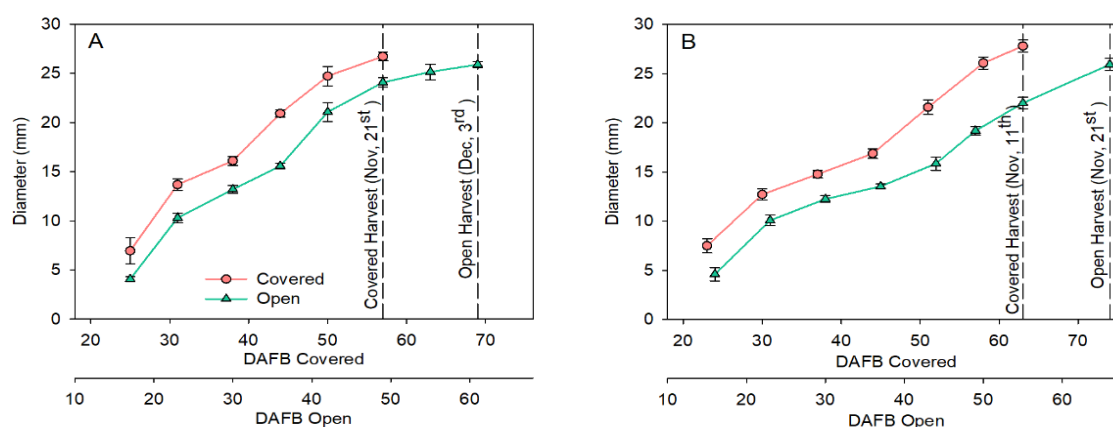
	Covered				Open			
	Plot 1		Plot 2		Plot 1		Plot 2	
Developmental Stage	RH <sub>Mx</sub> (%)	RH <sub>min</sub> (%)	RH <sub>Mx</sub> (%)	RH <sub>min</sub> (%)	RH <sub>Mx</sub> (%)	RH <sub>min</sub> (%)	RH <sub>Mx</sub> (%)	RH <sub>min</sub> (%)
Full Bloom	95.7	33.6	94.8	41.5	85.1	23.4	90.3	38.2
Fruit Set	92.6	47.4	94.9	37.5	84.7	30.3	89.8	32.6
Stage I	94.0	35.6	95.8	43.6	90.8	24.4	89.4	28.3
Stage II	97.6	47.1	93.8	48.4	89.3	24.9	88.5	31.2
Stage III	94.8	33.1	95.2	36.2	89.4	29.1	89.9	27.9

T<sub>Mx</sub>: maximum air temperature; T<sub>min</sub>: minimum air temperature; RH<sub>Mx</sub>: maximum relative humidity; RH<sub>min</sub>: minimum relative humidity.

### 3.2. Fruit Development and Fruit Quality at Harvest

The environmental conditions inside the high tunnels brought bloom and harvest forward by 8 and 12 d, respectively, in Plot 1 (2018/2019), and by 7 and 10 d, respectively, in Plot 2 (2019/2020), by accelerating the fruit development (Figure 1). Fruit development followed a typical double-sigmoid pattern, and was similar between treatments.

Fruit yield responded differently depending on the plot. In Plot 1, in the 2018/2019 growing season, the fruit yield of the covered trees was significantly lower (0.45–3.5 t ha<sup>-1</sup>) than that of the open trees (6.9 t ha<sup>-1</sup>). In Plot 2, in the 2019/2020 growing season, there were no significant differences in fruit yield between treatments (14.5 t ha<sup>-1</sup>), but a lower crop load was observed in the upper canopy of the covered trees (data not shown).



**Figure 1.** Seasonal patterns of the fruit diameter of ‘Santina’ cherries on ‘Colt’ rootstock from covered and open trees on Plot 1 ((A) growing season 2018/2019) and on Plot 2 ((B) growing season 2019/2020).

In terms of fruit quality, the high tunnels significantly altered fruit mass, size, and firmness. Fruit from covered trees had higher unitary mass and greater diameter than fruit from trees in the open, but were significantly less firm (Table 2). In Plot 1, fruit from the covered trees averaged 9.1 and 9.7 g for the upper and lower canopies, respectively. In Plot 2, fruit mass from the covered trees averaged 11.0 g for the upper and lower canopies. Fruit from trees under open field conditions, regardless of their position in the tree, had fruit unitary mass values that ranged between 8.6 and 9.2 g. Additionally, fruit from the covered trees was larger than fruit from the trees in the open.

Fruit firmness was influenced by the high tunnel conditions. Fruit from the outside trees averaged 83.5 Shore, while those from the high tunnel trees averaged 75.2 Shore (Table 2). SSC was not affected by covering, and TA did not show a clear trend.

**Table 2.** Effect of the treatment (covered and open) and fruit position (upper and lower canopy) on fruit quality characteristics of ‘Santina’ sweet cherries, Plot 1 (season 2018/2019) and Plot 2 (season 2019/2020).

			Mass (g)	Size (mm)	Firmness (Shore)	Color (1–5)	SSC (%)	TA (%)	MI
Plot 1	Upper	Covered	9.1	26.7	73.6	4.4	19.8	0.8	25.4
		Open	9.2	24.9	82.4	4.4	20.8	0.7	27.9
		<i>p</i> -value	0.717	0.013	0.021	0.722	0.153	0.013	0.079
	Lower	Covered	9.7	27.4	78.9	4.2	19.2	0.9	21.2
		Open	8.9	26.0	84.3	4.4	17.3	0.8	22.3
	<i>p</i> -value	0.042	0.088	0.015	0.194	0.026	0.145	0.312	
Plot 2	Upper	Covered	10.9	28.3	73.7	4.2	17.7	0.9	18.8
		Open	8.6	26.4	83.0	4.2	17.4	1.0	17.2
		<i>p</i> -value	0.008	0.041	0.001	0.671	0.763	0.055	0.108
	Lower	Covered	11.0	28.5	74.7	4.2	16.9	1.0	17.1
		Open	9.2	27.3	84.3	4.1	16.7	1.1	15.7
	<i>p</i> -value	0.039	0.048	0.007	0.592	0.652	0.037	0.023	

Size: diameter; SSC: soluble solid concentration; TA: titratable acidity; MI: maturity index. Each value is the mean of four blocks. Quality characteristics with *p*-values below 0.05 denote significant differences between treatments based on ANOVA ( $p < 0.05$ ).

Fruit quality data were pooled and analyzed considering three factors: covering (A), fruit position (B), and plot (C, Table 3). The position within the canopy did not affect any of the fruit quality characteristics studied. On the other hand, the Plot influenced fruit size, color, SSC, TA, and MI. In Plot 1, the cherries were smaller, darker, sweeter, and more acidic than those in Plot 2. When the combination of factors was considered, quality characteristics such as fruit size, firmness, and color were not significantly affected by the

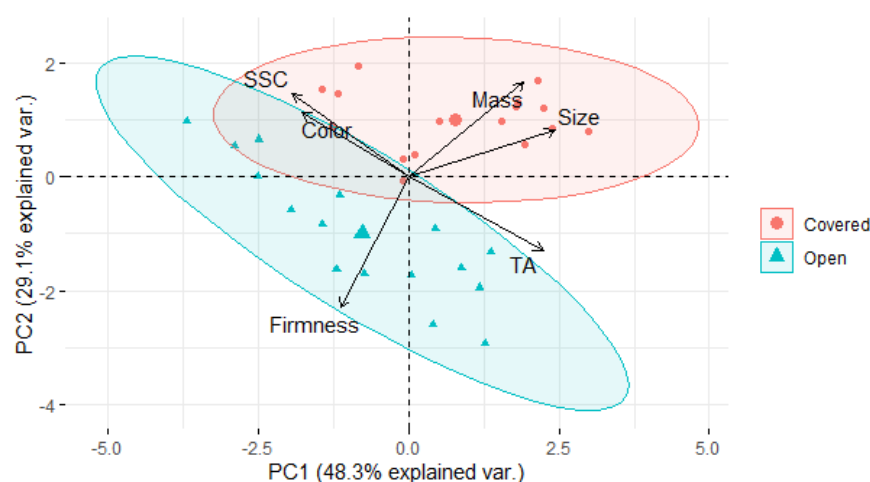
interaction of two or three factors. The interaction of the treatment and plot factors ( $A \times C$ ) affected the greatest number of quality characteristics (fruit mass, TA, and MI; Table 3). The SSC was the only fruit characteristic significantly affected by the interaction of the three factors.

**Table 3.** Effect of the treatment (covered and open), fruit position (upper and lower canopy) and plot (Plot 1 and Plot 2) on the fruit quality characteristics of ‘Santina’ sweet cherries on ‘Colt’ rootstock.

	<i>p</i> -Value	Mass (g)	Size (mm)	Firm (Shore)	Color (1–5)	SSC (%)	TA (%)	MI
<b>Covering</b>	A	<0.001	<0.001	<0.001	0.666	0.636	0.869	0.931
	B	0.494	0.222	0.239	0.202	0.075	0.254	0.059
<b>Position</b>	C	0.071	0.005	0.670	0.029	<0.001	<0.001	<0.001
	$A \times B$	0.546	0.223	0.191	0.670	0.035	0.644	0.508
<b>Plot</b>	$A \times C$	0.001	0.735	0.177	0.157	0.796	<0.001	0.001
	$B \times C$	0.571	0.303	0.379	0.607	0.052	0.490	0.001
	$A \times B \times C$	0.122	0.475	0.289	0.489	0.026	0.644	0.373

Size: diameter; Firm: fruit firmness; SSC: soluble solid content; TA: titratable acidity; MI: maturity index. Quality characteristics with *p*-values below 0.05 denote significant differences between treatments based on ANOVA. The analysis of the interaction effect of the different factors was calculated to each independent variable according to MANOVA ( $p < 0.05$ ).

The effect of high tunnel microclimate on the physicochemical characteristics studied in ‘Santina’ cultivars on ‘Colt’ rootstock is illustrated by a PCA biplot (Figure 2). Fruit from trees inside (covered) and outside (open) are differentiated by the ellipses enclosing the data for each plot.



**Figure 2.** Principal component analysis (PCA) biplot of the physicochemical properties of fruit obtained from Plots 1 and 2 of ‘Santina’ sweet cherry cultivars on ‘Colt’ rootstock, at harvest. The PCA biplot exhibits the PCA scores of the quality characteristics as vectors for fruit from both plots and vs. environmental conditions to the first and second principal components.

Together, the two principal components of the PCA explained 77.4% of the variation in the measured data (Figure 2). Quality characteristics such as unitary mass, fruit size, color, SSC, and TA contributed most to the first principal component (PC1), while fruit firmness contributed most to the second component (PC2).

Fruit from the covered trees are located on the same side as unitary mass and fruit size, indicating that fruit from trees under the high tunnels made a greater contribution to these characteristics than fruit from trees in the open. On the other hand, fruit from the open field made a higher contribution to fruit firmness. Mass and size vectors pointed in the same direction, indicating that both characteristics were positively correlated, as were color and SSC.

### 3.3. Cracking Incidence

It was not possible to assess the effects of rain-induced fruit cracking in either plot, since no rainfall events occurred close to harvest during the 2020/2019 or the 2019/2018 growing seasons. In the laboratory, induction of cracking indicated that fruit from the covered trees did not have a higher cracking potential in either Plot 1 or Plot 2. The values averaged 68 (pH 4) and 30 (pH 7), respectively. Fruit from the covered trees in Plot 1 showed a tendency for a lower CI, particularly at pH 7; however, in Plot 2, this trend was not observed (data not shown).

### 3.4. Postharvest Evaluation

After 45 d of cold storage, quality characteristics such as fruit firmness, SSC, AT, and MI decreased slightly in comparison with at harvest. After 45 d of cold storage and a further 3 d of shelf life at 20 °C, fruit color was unchanged, but fruit firmness, SSC, and TA all decreased. The SSC and TA did not show significant differences between treatments after 45 d or after 45 d + 3 d of shelf life storage.

Fruit firmness was the only quality characteristic that showed significant differences between the high tunnels and the open fields, at harvest (Table 2) and after 45 d of storage (Table 4). However, at the end of the experiment (45 d + 3 d), there were no significant differences in fruit firmness between fruit from covered and uncovered trees. The mean fruit firmness of the covered cherries was 10% lower than in the open (Table 4). At 45 d + 3 d, the fruit firmness, SSC, and TA of the covered cherries decreased by 7, 8 and 17%, respectively, compared to the values at harvest, while cherries from the trees in the open decreased by 10, 9 and 16%, respectively. For fruit mass and size, there were no significant differences between the values at harvest and after storage.

**Table 4.** Mean values for the physicochemical quality characteristics of ‘Santina’ sweet cherries grown under high tunnels (covered) or in the open after 45 days of cold storage (45 d) and 3 days of shelf life at 20 °C (45 d + 3 d) in the Central Valley of Chile. Plot 1, growing season 2018/2019.

		Firmness (Shore)	Color (1–5)	SSC (%)	TA (%)	MI
45 d	Covered	72.9	4.1	18.8	0.7	24.3
	Open	79.8	4.4	19.4	0.7	23.9
	<i>p</i> -value	0.040	0.277	0.582	0.322	0.736
45 d + 3 d	Covered	70.6	4.3	18.0	0.7	29.6
	Open	76.3	4.5	17.4	0.6	29.2
	<i>p</i> -value	0.072	0.412	0.413	0.312	0.848

SSC: soluble solid concentration; TA: titratable acidity; MI: maturity index. (n = 12). Quality characteristics with *p*-values below 0.05 denote significant differences between treatments based on ANOVA.

There were no significant differences between treatments in the proportion of fruit with physiological disorders after 45 d of cold storage plus 3 d of shelf life (Table 5). Treatments did not show symptoms of either decay or cracking. However, although there were no significant differences between treatments, there was high incidence of fruit with pitting (>50%) and pebbling (>30%), and a moderate presence of bruising (15%).

### 3.5. Fruit Mineral Concentration and Its Relationship with Fruit Firmness and Pitting Incidence

Fruit from covered and open trees had similar and normal ranges of mineral concentrations of N, P, K, and Mg. However, fruit from covered trees had significantly lower concentrations of Ca than fruit from trees in the open (Table 6).



**Table 5.** Mean values for physiological storage disorders of ‘Santina’ sweet cherries grown under high tunnels (covered) or in the open in the Central Valley of Chile. Plot 1, growing season 2018/2019, after 45 days of cold storage and 3 days of shelf life.

	Pitting (%)	Bruising (%)	Pebbling (%)
Covered	55.0	17.5	44.0
Open	71.3	15.0	30.0
<i>p</i> -value	0.093	0.689	0.356

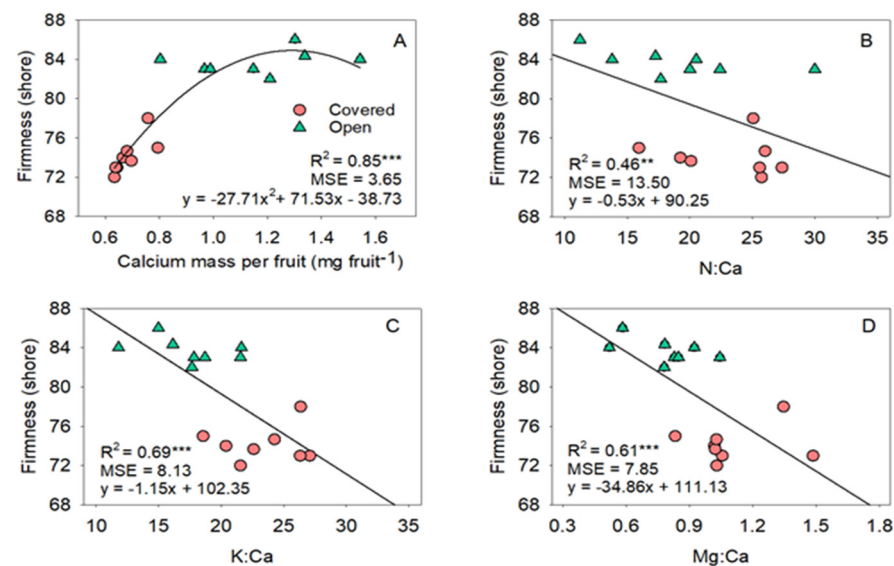
Each value is the mean of four blocks. Characteristics with *p*-values below 0.05 denote significant differences between treatments based on ANOVA.

**Table 6.** Mean values of the dry matter content (DM) and mineral composition of ‘Santina’ sweet cherries grown outside (open) and inside high tunnels (covered) in the Central Valley of Chile. Plot 2, season 2019/2020.

	DM (%)	N (mg 100 g <sup>-1</sup> )	P (mg 100 g <sup>-1</sup> )	K (mg 100 g <sup>-1</sup> )	Mg (mg 100 g <sup>-1</sup> )	Ca (mg 100 g <sup>-1</sup> )
Covered	18.0	195.8	24.5	180.7	7.9	7.7
Open	17.4	177.0	22.5	179.1	8.6	10.6
<i>p</i> -value	0.181	0.453	0.209	0.859	0.292	0.016

Each value is the mean of four blocks. N: nitrogen; P: phosphorus; K: potassium; Mg: magnesium; Ca: calcium. Variables with *p*-values below 0.05 denote significant differences between treatments based on ANOVA.

When the fruit mineral concentration of each element was associated with the physico-chemical quality characteristics measured at harvest, Ca concentration was strongly related to fruit firmness ( $p = 0.0001$ ,  $R^2 = 0.85$ ) (Figure 3).

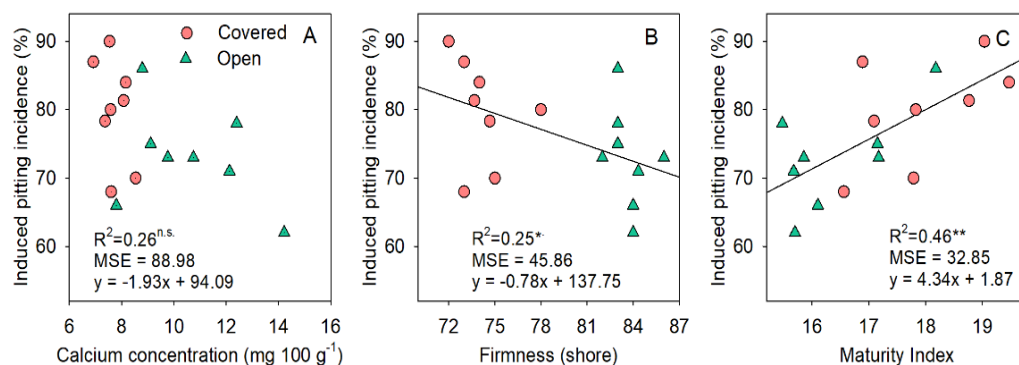


**Figure 3.** Relationship between fruit firmness and Ca mass per fruit (A), N:Ca (B), K:Ca (C), and Mg:Ca (D) for ‘Santina’ sweet cherries grown inside and outside high tunnels in the Central Valley of Chile. Plot 2, season 2019/2020. \*\* and \*\*\* correspond to the *p*-values  $\leq 0.01$  and  $0.001$ ; MSE: mean square error.

Fruit firmness increased as fruit Ca concentration increased from 0.6 mg Ca mass per fruit to a threshold value of around 1.3 mg Ca mass per fruit, which corresponded to 85 Shores. Above that threshold, Ca mass increments in the fruit were not directly related to higher fruit firmness. Fruit firmness was negatively correlated to the ratios N:Ca ( $R^2 = 0.46$ ;  $p = 0.004$ ), K:Ca ( $R^2 = 0.69$ ;  $p = 0.0001$ ), and Mg:Ca ( $R^2 = 0.61$ ;  $p = 0.0007$ ). N:Ca was the weakest indicator of fruit firmness; while K:Ca and Mg:Ca showed linear relationships with similar trends (Figure 3).

There were no significant differences in pitting damage between the fruit from the high tunnels and the fruit from the open fields, with values that ranged between 60 and 90% incidence. A trend was observed for higher pitting in fruit from the upper canopy, in both covered and uncovered trees.

Despite fruit firmness at harvest being strongly correlated with Ca concentration (Figure 3), pitting incidence did not seem to be associated with Ca concentration (Figure 4). However, fruit firmness at harvest was significantly correlated with pitting. A negative linear model described this association ( $R^2 = 0.25$ ;  $p = 0.041$ ). Similarly, the value of MI was significantly and positively correlated with the incidence of pitting ( $R^2 = 0.46$ ;  $p = 0.006$ ).



**Figure 4.** Relationships between induced pitting of ‘Santina’ sweet cherries from trees under high tunnels and those in the open in the Central Valley of Chile, season 2019/2020, after 14 d of cold storage, and Ca concentration (A), fruit firmness (B), and maturity index (C), at harvest. ( $n = 16$ ). n.s.: not significant; \* and \*\* correspond to the  $p$ -values  $\leq 0.05$  and  $0.01$ ; MSE: mean square error.

#### 4. Discussion

The environmental conditions inside the high tunnels affected both fruit yield and fruit quality in the early sweet cherry cultivar ‘Santina’ on ‘Colt’ rootstock in the Central Valley of Chile. Careful management of the ventilation in high tunnels is required during the bloom and fruit set stages in order to avoid significant crop losses. In Plot 1, during the bloom in 2018, the maximum temperature and relative humidity averaged 32 °C and 96%, respectively. A number of studies [33,34] have reported that high air temperatures during bloom and fruit set have negative effects on stigma receptivity and ovule longevity in sweet cherry flowers. Moreover, decreases of up to 70% in the activity of pollinators have also been reported when air temperatures in the covered environments exceed 24 °C [35]. The combination of high temperature and high relative humidity may have reduced fruit set in Plot 1, and led to the lower yield in the high tunnels, since both flowers and honey bees were observed in both covered and open trees during pollination. In Plot 2, an improved ventilation strategy for the high tunnels prevented such extreme temperatures during bloom. However, ventilation was still not enough to avoid temperatures above 27 °C, which might have led to slight negative effects on the fruit yield in the upper canopy of the covered trees.

In this study, quality characteristics such as fruit size and fruit firmness were greatly affected in the high tunnels, regardless of position within the canopy and the plot. Fruit grown under the high tunnels was consistently larger but less firm. Interestingly, although the covered fruit showed a shorter developmental period, they were still larger than fruit grown in the open. Our results are consistent with the finding of Lang et al. [7] and Blanke et al. [6], who reported larger fruit under covers in the combinations ‘Rainier’ on ‘Gisela 5’ rootstock, ‘Rainier’ on ‘Gisela 6’, and ‘Burlat’ on ‘Gisela 5’. We suggest that the larger fruit size inside the high tunnels is the result of higher fruit water potential and turgor potential, as reported for covered peaches (*Prunus persica* L.) [36]. In cherry trees, fruit water potential has been described as being highly dependent on stem water potential [37] which, in turn, is highly dependent on environmental variables, such as the vapor pressure deficit [38,39]. Recently, Blanco et al. [9] reported that high tunnel cultivation enhanced sweet cherry tree

water status by decreasing the vapor pressure deficit and water evaporation losses, which increased midday stem water potential. Thus, the high midday stem water potential may have increased the fruit water potential and fruit turgor potential, promoting higher fruit growth rates in the trees in the high tunnels.

The fruit characteristics of both the covered and uncovered trees at harvest are consistent with those values reported as optimal for ‘Santina’ sweet cherries [40]. Therefore, it is expected that fruit from both treatments would be equally acceptable to the consumer; however, more research is required in order to assess the effects of high tunnels on fruit’s acceptability and sensory perception to consumers. Significant differences in quality characteristics such as SSC between plots might be explained as an effect of the different crop loads. Higher SSC values have been associated with lower crop loads [41–43]. As no rain events registered during either season, rain-induced cracking was negligible. Unlike other studies, in which covered fruit were less prone to cracking under cover than fruit from uncovered trees [26,44], CI was significantly lower than reported, and the high tunnels did not affect CI in either Plot 1 (season 2018/2019) or Plot 2 (season 2019/2020).

The effect of the environmental conditions inside the high tunnels on the storage performance of fruit has important implications for sweet cherry growers exporting to distant markets [12,45]. As expected, fruit firmness decreased postharvest in fruit from both covered and open trees. Most sweet cherry cultivars suffer quality losses [37,46] during cold storage, particularly firmness loss. In this study, fruit from the high tunnels were softer than that from open trees, both at harvest and after 45 d of cold storage. There were no significant differences in fruit firmness between covered and uncovered trees after 45 d + 3 d of shelf life. Consequently, ‘Santina’ fruit firmness during storage and shelf life were not significantly affected by the covers.

The incidence of physiological disorders after storage (i.e., postharvest cracking, pebbling, and pitting) was not significantly different between covered and uncovered fruit. Of the physiological disorders, pitting was the one with the highest incidence both inside and outside the high tunnels. Our pebbling results for ‘Santina’ were lower than those reported by Cliff et al. [47] (i.e., 80% with ‘Skeena’ sweet cherries after 28 d at 0.5 °C) but similar to those reported by Zoffoli et al. [12] with ‘Santina’, which is highly susceptible to this disorder. Water loss from the skin has been proposed as the main cause of pebbling, but the problem was not ameliorated under saturated storage conditions such as modified atmosphere packaging [19]. More research is required in order to identify the preharvest practices that affect the fruit epidermal properties controlling skin conductance.

Fruit mineral composition was in the normal range in both covered and uncovered trees for N, P, K, Ca, and Mg [48], but Ca concentration was significantly lower in fruit from inside the high tunnels. The lower Ca concentration in covered trees may be explained by the environmental conditions in the high tunnels. Sweet cherries grown under conditions of high relative humidity (similar to those reported inside the high tunnels) usually have lower Ca concentrations than those grown outside under lower relative humidity. This may be the result of lower fruit transpiration rates [49]. In apples (*Malus domestica* Borkh.), higher stomatal conductance and excessive shoot growth have been related to higher Ca concentration in the leaves and lower Ca concentration in the fruit [50,51]. Ca distribution in the tree is influenced by the evapotranspiration rate as well as by the competition between vegetative organs and fruit [51]. In this study, sweet cherry trees under high tunnels were exposed to higher relative humidity and lower vapor pressure deficit than those in the open, which may have influenced Ca uptake and distribution during fruit development. Furthermore, sweet cherry trees under high tunnels have been reported to have higher transpiration rates than those in the open [9,26], which may favor Ca mobilization to the vegetative organs.

A positive linear relationship between Ca concentration and fruit firmness was found; similar results have been reported for apples and peaches [52,53]. Several studies on sweet cherries have related Ca concentration to fruit quality, particularly fruit firmness [21,22,49]. Sweet cherry firmness is considered one of the most important quality attributes for export.

Consumers prefer fruit in the range between 2.5 and 4.7 N, and values below 2.5 N are considered soft [54]. In this study, average firmness was always higher than 70 Shores, which is in the range of 70–75 Shores for high quality fruit [55]. Fruit from covered trees had significantly lower Ca concentrations and fruit firmness than fruit from uncovered trees, which highlights Ca partitioning as being key to fruit firmness. Foliar applications of Ca during early fruit development have been suggested as being effective, as Ca import is promoted by fruit transpiration, and Ca uptake by the fruit is reduced during the later stages of fruit growth [49].

The optimal fruit Ca concentration to ensure the highest firmness in ‘Santina’ fruit at harvest and after storage is  $>10 \text{ mg } 100 \text{ g}^{-1}$  ( $>1.04 \text{ mg Ca mass per fruit}$ ). A negative relationship between the stoichiometric ratios and fruit firmness, particularly with K, was observed for ‘Santina’ sweet cherries in this study. High K:Ca ratios have been associated with low fruit firmness in strawberries (*Fragaria × Ananassa* Duch.), kiwifruit (*Actinidia deliciosa*), and apples [56–58]. High K:Ca likely results from the fact that K is phloem-mobile, whereas Ca is phloem-immobile and cannot be remobilized from vegetative organs to the fruit to compensate for mineral deficiencies, leading to mineral imbalances in the fruit [59].

## 5. Conclusions

High tunnels increase both air temperature and relative humidity compared to open fields. They also advance the dates of bloom by 7 d and of harvest by 11 d. However, the microclimate under the high tunnels reduced fruit yield when proper ventilation was not implemented, particularly with the mean air temperature higher than 32 °C during bloom and fruit set. The use of high tunnels improved fruit size and negatively affected fruit firmness compared with fruit from the open, but the fruit was still exportable. Compared with the uncovered fruit, the covered fruit were similarly sensitive to postharvest physiological disorders, such as cracking, pitting, pebbling, and bruising.

The results of this research support the hypothesis that lower firmness in ‘Santina’ sweet cherries under plastic covers is associated with lower fruit Ca concentrations, probably induced by the high tunnel microclimate that reduces fruit transpiration and increases vegetative growth, resulting in Ca imbalances in the fruit.

Future research on rain protective covering management, different cultivars and climate, and sustainable agronomic practices might extend the current knowledge of the role of Ca in fruit firmness in covered cherries.

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## References

1. FAOSTAT–Food and Agriculture Organization of the United Nations Statistics Division. Agricultural Production. Cherries. 2020. Available online: <http://www.fao.org/faostat/en/#data/QC/visualize> (accessed on 31 January 2021).
2. Bujdosó, G.; Hrotkó, K. Chapter 1: Cherry production. In *Cherries: Botany, Production and Uses*, 1st ed.; Quero-García, J., Iezzoni, A., Pulawska, J., Lang, G., Eds.; CABI: Oxfordshire, UK, 2017; pp. 1–13.
3. Balbotin, C.; Ayala, H.; Bastías, R.M.; Tapia, G.; Ellena, M.; Torres, C.; Yuri, J.A.; Quero-García, J.; Ríos, J.C.; Silva, H. Cracking in sweet cherries: A comprehensive review from a physiological, molecular, and genomic perspective. *Chil. J. Agric. Res.* **2013**, *73*, 66–72. [[CrossRef](#)]

4. Correia, S.; Schouten, R.; Silva, A.P.; Gonçalves, B. Sweet cherry fruit cracking mechanisms and prevention strategies: A review. *Sci. Hortic.* **2018**, *240*, 369–377. [[CrossRef](#)]
5. Brüggewirth, M.; Knoche, M. Mechanical properties of skins of sweet cherry fruit of differing susceptibilities to cracking. *J. Amer. Soc. Hort. Sci.* **2016**, *141*, 162–168. [[CrossRef](#)]
6. Blanke, M.M.; Lang, G.A.; Meland, M. Chapter 11: Orchard microclimate modification. In *Cherries: Botany, Production and Uses*, 1st ed.; Quero-García, J., Iezzoni, A., Pulawska, J., Lang, G., Eds.; CABI: Oxfordshire, UK, 2017; pp. 244–268.
7. Lang, G.A. High Tunnel Tree Fruit Production: The Final Frontier? *HortTechnology* **2009**, *19*, 50–55. [[CrossRef](#)]
8. Lamont, W.J. Overview of the Use of High Tunnels Worldwide. *HortTechnology* **2009**, *19*, 25–29. [[CrossRef](#)]
9. Blanco, V.; Zoffoli, J.P.; Ayala, M. Eco-physiological response, water productivity and fruit quality of sweet cherry trees under high tunnels. *Sci. Hortic.* **2021**, *286*, 110180. [[CrossRef](#)]
10. Meland, M.; Frøynes, O.; Kaiser, C. High tunnel production systems improve yields and fruit size of sweet cherry. *Acta Hortic.* **2017**, *1161*, 117–124. [[CrossRef](#)]
11. Lang, G.A. Growing sweet cherries under plastic covers and tunnels: Physiological aspects and practical considerations. *Acta Hortic.* **2014**, *1020*, 303–312. [[CrossRef](#)]
12. Zoffoli, J.P.; Toivonen, P.; Wang, Y. Chapter 19: Postharvest biology and handling for fresh markets. In *Cherries: Botany, Production and Uses*, 1st ed.; Quero-García, J., Iezzoni, A., Pulawska, J., Lang, G., Eds.; CABI: Oxfordshire, UK, 2017; pp. 460–484.
13. Chockchaisawasdee, S.; Golding, J.B.; Vuong, Q.V.; Papoutsis, K.; Stathopoulos, C.E. Sweet cherry: Composition, postharvest preservation, processing and trends for its future use. *Trends Food Sci. Technol.* **2016**, *55*, 72–83. [[CrossRef](#)]
14. Mitchell, F.G.; Mayer, G.; Kader, A.A. Injuries cause deterioration of sweet cherries. *California Agric.* **1980**, *34*, 14–15.
15. Mattheis, J.P.; Roberts, R.G. Fumigation of sweet cherry (*Prunus avium* ‘Bing’) fruit with low molecular weight aldehydes for postharvest decay control. *Plant Dis.* **1993**, *77*, 810–814. [[CrossRef](#)]
16. Shao, Y.; Xuan, G.; Hu, Z.; Gao, Z.; Liu, L. Determination of the bruise degree for cherry using Vis-NIR reflection spectroscopy coupled with multivariate analysis. *PLoS ONE* **2019**, *14*, e0222633. [[CrossRef](#)]
17. Param, N.; Zoffoli, J.P. Genotypic differences in sweet cherries are associated with the susceptibility to mechanical damage. *Sci. Hortic.* **2016**, *211*, 410–419. [[CrossRef](#)]
18. Toivonen, P.M.A.; Manganaris, G.A. Chapter 15.2: Stone fruits: Sweet cherries (*Prunus avium* L.). In *Controlled and Modified Atmospheres for Fresh and Fresh-Cut Produce. Part II: CA/MA Requirements and Recommendations for Fresh and Fresh-Cut Fruits*, 1st ed.; Gil, M.I., Beaudry, R., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 323–329.
19. Schlegel, H.J.; Grimm, E.; Winkler, A.; Knoche, M. Orange peel disorder in sweet cherry: Mechanism and triggers. *Postharvest Biol. Technol.* **2018**, *137*, 119–128. [[CrossRef](#)]
20. Mitcham, E.J.; Crisosto, C.H. Postharvest handling systems: Stone fruits. III Sweet cherry. In *Postharvest Technology of Horticultural Crops*, 3rd ed.; Kader, A.A., Ed.; University of California, Division of Agricultural and Natural Resources: Richmond, CA, USA, 2002; pp. 353–356.
21. Winkler, A.; Knoche, M. Calcium and the physiology of sweet cherries: A review. *Sci. Hortic.* **2019**, *245*, 107–115. [[CrossRef](#)]
22. Measham, P.F.; Richardson, A.; Townsend, A. Calcium application and impacts on cherry fruit quality. *Acta Hortic.* **2017**, *1161*, 375–382. [[CrossRef](#)]
23. Wang, Y.; Long, L.E. Physiological and biochemical changes relating to postharvest splitting of sweet cherries affected by calcium application in hydrocooling water. *Food Chem.* **2015**, *181*, 241–247. [[CrossRef](#)] [[PubMed](#)]
24. Candan, A.P.; Raffo, M.D.; Calvo, G.; Gomila, T. Study of the main points of impact during cherry handling and factors affecting pitting sensitivity. *Acta Hortic.* **2014**, *1020*, 137–141. [[CrossRef](#)]
25. Clayton, M.; Biasi, W.V.; Agar, I.T.; Southwick, S.M.; Mitcham, E.J. Sensory quality of ‘bing’ sweet cherries following preharvest treatment with hydrogen cyanamide, calcium ammonium nitrate, or gibberellic acid. *HortScience* **2006**, *41*, 745–748. [[CrossRef](#)]
26. Blanco, V.; Zoffoli, J.P.; Ayala, M. High tunnel cultivation of sweet cherry (*Prunus avium* L.): Physiological and production variables. *Sci. Hortic.* **2019**, *251*, 108–117. [[CrossRef](#)]
27. Lang, G.A.; Sage, L.; Wilkinson, T. Ten years of studies on systems to modify sweet cherry production environments: Retractable roofs, high tunnels, and rain-shelters. *Acta Hortic.* **2016**, *1130*, 83–90. [[CrossRef](#)]
28. Mika, A.; Buler, Z.; Wójcik, K.; Konopacka, D. Influence of the Plastic Cover on the Protection of Sweet Cherry Fruit Against Cracking, on the Microclimate under Cover and Fruit Quality. *J. Hort. Res.* **2019**, *27*, 31–38. [[CrossRef](#)]
29. Santibáñez, F.; Santibáñez, P.; Caroca, C.; González, P. Tomo III: Regiones de Valparaíso, Metropolitana, O’Higgins y Maule. In *Atlas Agroclimático de Chile Estado Actual y Tendencias del Clima*, 1st ed.; Universidad de Chile, Ed.; FIA: Santiago, Chile, 2017; pp. 157–163.
30. Christensen, J.V. Cracking in cherries. III. Determination of cracking susceptibility. *Acta Agric. Scand.* **1972**, *22*, 128–136. [[CrossRef](#)]
31. Toivonen, P.M.A.; Kappel, F.; Stan, S.; McKenzie, D.-L.; Hocking, R. Firmness, Respiration, and Weight Loss of ‘Bing’, ‘Lapins’ and ‘Sweetheart’ Cherries in Relation to Fruit Maturity and Susceptibility to Surface Pitting. *HortScience* **2004**, *39*, 1066–1069. [[CrossRef](#)]
32. Ryan, J.; Estefan, G.; Rashid, A. *Soil and Plant Analysis Laboratory Manual*; International Center for Agricultural Research in the Dry Areas (ICARDA): Islamabad, Pakistan, 2001.
33. Hedhly, A.; Hormaza, J.L.; Herrero, M. Warm temperatures at bloom reduce fruit set in sweet cherry. *J. Appl. Bot. Food Qual.* **2007**, *81*, 158–164.

34. Zhang, L.; Ferguson, L.; Whiting, M.D. Temperature effects on pistil viability and fruit set in sweet cherry. *Sci. Hortic.* **2018**, *241*, 8–17. [[CrossRef](#)]
35. Kwon, T.J.; Saeed, S. Effect of temperature on the foraging activity of *Bombus terrestris* L. (Hymenoptera: Apidae) on greenhouse hot pepper (*Capsicum annuum* L.). *Appl. Entomol. Zool.* **2003**, *38*, 275–280. [[CrossRef](#)]
36. Najla, S.; Vercambre, G.; Gérard, M. Effects of water deficit and variations of fruit microclimate on peach fruit growth and quality. *Plant Stress* **2011**, *6*, 33–38.
37. Blanco, V.; Martínez-Hernández, G.B.; Artés-Hernández, F.; Blaya-Ros, P.J.; Torres-Sánchez, R.; Domingo, R. Water relations and quality changes throughout fruit development and shelf life of sweet cherry grown under regulated deficit irrigation. *Agric. Water Manag.* **2019**, *217*, 243–254. [[CrossRef](#)]
38. Measham, P.F.; Wilson, S.J.; Gracie, A.J.; Bound, S.A. Tree water relations: Flow and fruit. *Agric. Water Manag.* **2014**, *137*, 59–67. [[CrossRef](#)]
39. Blanco, V.; Domingo, R.; Pérez-Pastor, A.; Blaya-Ros, P.J.; Torres-Sánchez, R. Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees. *Agric. Water Manag.* **2018**, *208*, 83–94. [[CrossRef](#)]
40. Kappel, F.; Lane, W.D.; MacDonald, R.; Lapins, K.; Schmidt, H. ‘Santina’, ‘Sumpaca Celeste’ and ‘Sumnue Cristalina’ Sweet Cherries. *HortScience* **1998**, *33*, 1087–1089. [[CrossRef](#)]
41. Neilsen, G.H.; Neilsen, D.; Kappel, F.; Forge, T. Interaction of irrigation and soil management on sweet cherry productivity and fruit quality at different crop loads that simulate those occurring by environmental extremes. *HortScience* **2014**, *49*, 215–220. [[CrossRef](#)]
42. Bound, S.A.; Close, D.C.; Quentin, A.G.; Measham, P.F.; Whiting, M.D. Crop load and time of thinning interact to affect fruit quality in sweet cherry. *J. Agric. Sci.* **2013**, *5*, 216–230. [[CrossRef](#)]
43. Blanco, V.; Torres-Sánchez, R.; Blaya-Ros, P.J.; Pérez-Pastor, A.; Domingo, R. Vegetative and reproductive response of ‘Prime Giant’ sweet cherry trees to regulated deficit irrigation. *Sci. Hortic.* **2019**, *249*, 478–489. [[CrossRef](#)]
44. Mucha-Pelzer, T.; Müller, S.; Rohr, F.; Mewis, I. Cracking susceptibility of sweet cherries (*Prunus avium* L.) under different conditions. *Commun. Agric. Appl. Biol. Sci.* **2006**, *71*, 215–223.
45. Lemus, G.; Valenzuela, J. Survey of the Chilean sweet cherry industry. *Acta Hortic.* **2006**, *667*, 379–387. [[CrossRef](#)]
46. Wang, Y.; Long, L.E. Respiration and quality responses of sweet cherry to different atmospheres during cold storage and shipping. *Postharvest Biol. Technol.* **2014**, *92*, 62–69. [[CrossRef](#)]
47. Cliff, M.A.; Stanich, K.; Toivonen, P.M.A. Evaluation of the Sensory, Physicochemical, and Visual Characteristics of a Sweet Cherry Cultivar Treated in a Commercial Orchard with a Cherry Cuticle Supplement when a Rainfall Event Does Not Occur. *HortTechnology* **2017**, *27*, 416–423. [[CrossRef](#)]
48. Neilsen, G.H.; Neilsen, D.; Forge, T. Chapter 9: Environmental limiting factors for Cherry production. In *Cherries: Botany, Production and Uses*, 1st ed.; Quero-García, J., Iezzoni, A., Pulawska, J., Lang, G., Eds.; CABI: Oxfordshire, UK, 2017; pp. 189–222.
49. Winkler, A.; Fiedler, B.; Knoche, M. Calcium physiology of sweet cherry fruits. *Trees* **2020**, *34*, 1157–1167. [[CrossRef](#)]
50. Gomez, R.; Kalcsits, L. Physiological Factors Affecting Nutrient Uptake and Distribution and Fruit Quality in ‘Honeycrisp’ and ‘WA 38’ Apple (*Malus × domestica* Borkh.). *HortScience* **2020**, *55*, 1327–1336. [[CrossRef](#)]
51. Saure, M.C. Calcium translocation to fleshy fruit: Its mechanism and endogenous control. *Sci. Hortic.* **2005**, *105*, 65–89. [[CrossRef](#)]
52. Beavers, W.B.; Sams, C.E.; Conway, W.S.; Brown, G.A. Calcium Source Affects Calcium Content, Firmness, and Degree of Injury of Apples during Storage. *HortScience* **1994**, *29*, 1520–1523. [[CrossRef](#)]
53. Shah, S.T.; Sajid, M. Influence of Calcium Sources and Concentrations on the Quality and Storage Performance of Peach. *SJA* **2017**, *33*, 532–539. [[CrossRef](#)]
54. Hampson, C.R.; Stanich, K.; McKenzie, D.L.; Herbert, L.; Lu, R.; Li, J.; Cliff, M.A. Determining the optimum firmness for sweet cherries using Just-About-Right sensory methodology. *Postharvest Biol. Technol.* **2014**, *91*, 104–111. [[CrossRef](#)]
55. Kappel, F.; Fisher-Fleming, B.; Hogue, E. Fruit characteristics and sensory attributes of an ideal sweet cherry. *HortScience* **1996**, *31*, 443–446. [[CrossRef](#)]
56. Masoud, H.; Mousa, A.; Javad, N.M. Different K:Ca ratios affected fruit color and quality of strawberry ‘Selva’ in soilless system. *J. Plant Nutr.* **2018**, *41*, 243–252.
57. Torkashvand, A.M.; Ahmadi, A.; Nikraves, N.L. Prediction of kiwifruit firmness using fruit mineral nutrient concentration by artificial neural network (ANN) and multiple linear regressions (MLR). *J. Integr. Agric.* **2017**, *16*, 1634–1644. [[CrossRef](#)]
58. Dilmaghani, M.R.; Malakouti, M.J.; Neilsen, G.H.; Fallahi, E. Interactive Effects of Potassium and Calcium on K/Ca Ratio and Its Consequences on Apple Fruit Quality in Calcareous Soils of Iran. *J. Plant Nutr.* **2005**, *27*, 1149–1162. [[CrossRef](#)]
59. Kalcsits, L.; van der Heijden, G.; Reid, M.; Mullin, K. Calcium Absorption during Fruit Development in ‘Honeycrisp’ Apple Measured Using <sup>44</sup>Ca as a Stable Isotope Tracer. *HortScience* **2017**, *52*, 1804–1809. [[CrossRef](#)]