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SCIENTIFIC NOTE

Relationship between mineral content and fruit quality attributes firmness, size and weight of three sweet cherry cultivars

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ABSTRACT

The popularity and importance of sweet cherry (*Prunus avium* L.) is reflected in consumer preference, growing prices, and seasonal availability. Chile is the third worldwide producer with the largest area planted in cherry trees, and its main cultivars are Santina, Lapins and Regina. Fruit quality attributes such as weight, size and firmness, could also have a relation to better mineral nutritional composition. A study with these cultivars during season 2023-2024 showed that cherry firmness values fluctuated between 250 and 350 g mm^{-1}, being highest in 'Regina', followed by 'Lapins' and then 'Santina'. The fruit size fluctuated between 31 and 33 mm, and weight fluctuated between 13.0 and 14.2 g, and both were higher in 'Lapins' with no difference between the other two cultivars. There was a higher concentration of Ca, Mg, Mn and B in 'Lapins' and higher concentration of S in 'Santina'. The correlations of nutrients in fruits were not consistent between the three cultivars, and slight N-P and K-B correlation was found. Firmness of the fruits of the three cultivars presented a positive correlation with the concentration of N, and in two of the cultivars (Lapins and Regina) there was a correlation with the concentration of P. The DM content did not present a correlation with firmness, size or fruit weight in any of the three sweet cherry cultivars. Finally, as expected, there was a high positive correlation between size and fruit weight.

Key words: Fruit mineral composition, fruit quality attributes, *Prunus avium*, sweet cherry.

INTRODUCTION

Sweet cherry (*Prunus avium* L.) is one of the main fruit crops worldwide and Türkiye leads with 20.7% of the world's surface, both USA and Chile with 17.4% each, Spain with 4.6%, Italy with 3.4% and Greece with 3.0%. The cherry fruit is highlighted for its organoleptic characteristics, nutritional value and antioxidant content, being one of the fruits most preferred by consumers (Ballistreri et al., 2013; Clayton-Cuch et al., 2021). Its popularity in the world market, both in volume and price, has led to a constant development of improvement practices, generating better attributes such as sanitary conditions, firmness, size, weight, soluble solids, absence of cracking and other compounds (Ballistreri et al., 2013; Hayaloglu and Demir, 2015; Dong et al., 2019; Martins et al., 2021; Ockun et al., 2022). However, the main factor associated with these cherry fruit quality indicators is their genotype (Hayaloglu and Demir, 2015; Ockun et al., 2022; Radičević et al., 2022). Pereira et al. (2020) in Portugal indicated that the cracking of 'Lapins' and 'Early Bigi' cherry fruits, was more important in 'Lapins' and was related to greater size, firmness, total soluble solids, titratable acidity and lower wax content. Ozturk et al. (2024) indicated that the foliar application of biofilm in cherry orchards in stages prior to fruit harvest, could reduce fruit cracking, increase fruit firmness and improve post-harvest life.

Among the management factors that has commonly been related to the quality attributes of cherry fruit is nutritional management highlighting the applications of Ca (an important role in the mechanical resistance of the plasma membrane and cell walls) (Hocking et al., 2016; Michailidis et al., 2017; Correia et al., 2019; Dong et al., 2019; Winkler and Knoche, 2019; Yener and Altuntaş, 2020; Quiroz et al., 2023) and nutritional supplements such as biostimulants (Gonçalves et al., 2020; Sabir et al., 2021; Afonso et al., 2022; Serapicos et al., 2022). In this regard, Correia et al. (2019) indicated that foliar application of Ca during two consecutive seasons in 'Skeena' and 'Sweetheart' cherry orchards in Portugal, had no clear effect on the quality attributes epidermis rupture strength and flesh firmness of fruits. Dong et al. (2019) indicated that foliar applications of Ca in cherry orchards in moderate concentrations (0.3% to 0.6%) from pit hardening to 1 wk before harvest allowed an increase in Ca consumption, firmness, soluble solids content and titratable acidity in fruits. In addition, Quiroz et al. (2023) indicated that the firmness of 'Lapins' cherry fruits was positively correlated with the Ca concentration in the fruits, and negatively affected by the K:Ca and N:Ca ratios.

In relation to K applications, Palacios-Peralta et al. (2023) indicated that the foliar application of this nutrient (four or seven applications during fruit development) in 'Regina' cherry orchards in southern Chile, allowed increasing firmness, total soluble content, size, weight, and titratable acidity of fruits. Yener and Altuntaş (2020) indicated that the application of increasing K doses to the soil (0, 100, 200, 400 and 600 g tree^{-1} yr^{-1}) in cherry orchards '0900 Ziraat' on 'Gisela 6' during two consecutive seasons in Türkiye, improved fruit size, fruit firmness, total soluble solids, titratable acidity and decreased pH, antioxidant activity and total phenolic content.

Various studies indicate an effect of applications of nutrients in different doses on quality attributes in sweet cherry cultivars, with positive, null or negative effects. But, as has been reported for other fruit species such as apple (*Malus domestica* (Suckow) Borkh.) (Casero et al., 2004), pears (*Pyrus communis* L. 'Rocha') (Dias et al., 2024), and blueberry (*Vaccinium corymbosum* L.) (Hirzel et al., 2023), there is little information that indicates the interrelation or interdependence between the fruit mineral content and quality attributes.

Considering that many producers and consultants in cherry production estimate that fruit quality attributes could be related to increases or decreases in the concentration of mineral nutrients in the fruits, and that this interferes with the fertilization strategies carried out under field conditions, it is necessary to understand these inter-relationships.

As a contribution to agronomy, a descriptive study of mineral nutritional content and values of firmness, size and weight of fruits at harvest was carried out with the three main cultivars of sweet cherry trees grown in Chile; 'Santina', 'Lapins' and 'Regina', in a commercial orchard in the south-central zone, the main cherry production area. We hypothesized that quality attributes as firmness, size and weight of fruits are related to increases in nutrients and decreases in others, and that this mineral nutrient-quality attribute relationship may also be different between cultivars. The objective was to characterize values of firmness, size, weight and mineral nutritional content of fruits at harvest in three sweet cherry cultivars and to determine the existing correlations between the evaluated parameters.

MATERIAL AND METHODS

Locations and sweet cherry orchards

The study was conducted in sweet cherry (*Prunus avium* L.) commercial orchards during the 2023-2024 season; with 'Santina' (early season harvest) on 'Gisela 6' rootstock, 'Lapins' (medium season harvest) on sour cherry rootstock, 'Regina' (last season harvest) on 'Gisela 6' rootstock, collecting fruit samples at commercial maturity (mahogany red color). The orchard is located in south-central Chile (34°57'38" S, 71°11'20" W) and the soil corresponds to an Inceptisol (USDA, 2014). Orchards fluctuated between 6 to 10 yr, and the plantation distance in 'Santina' and 'Regina' was 3.5 m between rows and 1.8 m between plants on the row, while for 'Lapins' was 4 m between rows and 2 m between plants on the row. Climatic characteristics during the growth season are presented in the Table 1. In addition, 723 chill hours were accumulated between May and August 2023, which correspond to the 83% of the normal for the climatic zone (Agrometeorología INIA, 2024). The fruit load data (cumulative yield and fruit number per plant) are presented in the Table 2.

Table 1. Environmental condition during the growth season (flowering to late harvest) 2023 to 2024 in south central Chile.

Month	Phenological stage	Air temperature Mean	Min	Max	Rainfall	Solar radiation
		°C			mm	MJ m^{-2}
September	Flowering	11.9	7.6	16.2	90.0	11.3
October	Early fruit development	14.0	8.4	19.7	44.2	17.5
November	Fruit color change, start of	15.9	9.8	22.0	40.2	
	Harvest					22.1
December	Harvest	19.7	12.2	27.2	0.0	29.1
January	Late harvest	22.9	14.6	31.1	0.0	31.1
February	Late harvest	22.9	15.0	30.8	6.2	26.6
March	Late harvest	19.8	12.3	27.3	0.0	19.9

Table 2. Fruit load of three different sweet cherries cultivars cropped in south central Chile. SD: Standard deviation; SE: standard error.

Cultivar	Yield		Yield		Fruit load	
	Mean ± SD	SE	Mean ± SD	SE	Mean ± SD	SE
	kg ha^{-1}		kg $plant^{-1}$		Fruits $plant^{-1}$	
Santina	9 162 ± 2 172	486	5.77 ± 1.32	0.30	443.8 ± 101.5	23.1
Lapins	22 333 ± 6 868	1536	17.87 ± 5.48	1.23	1276.4 ± 391.4	87.9
Regina	13 114 ± 3 284	734	8.26 ± 2.00	0.45	635.4 ± 153.8	34.6

Soil analysis, fertilization and irrigation management

The soil chemical properties from 0 to 0.3 m of the sectors where the fruit samples were collected are presented in the Table 3. Analyses were performed using the methodologies indicated by Sadzawka et al. (2006) in the soil laboratory of the Agricultural Research Institute (Instituto de Investigaciones Agropecuarias, INIA), INIA Quilamapu, Chillán, Chile, and the detail of each laboratory methodology was described by Hirzel et al. (2023).

The fertilization applied during the growth season in all the cultivars was 60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, 180 kg K_2O ha^{-1}, 25 kg CaO ha^{-1} and 40 kg MgO ha^{-1}. The irrigation was made considering the reposition of the water evaporation pan corrected by the crop coefficient (K_c).

Sampling of fruits and analysis procedure

Fruits were sampled at the beginning of harvest of each cultivar, routine practice in all Chilean commercial orchards. Each random sample consisted of 5 kg fruit from 30 plants from the middle section of each block or production unit (considering block from 10 000 to 30 000 m^2). For each cultivar 20 replicates were collected. The harvest criterion was fruit color, using the mahogany red color as an indicator. Fruit were collected between 08:00 and 10:00 h in plastic trays, transferred to a thermal isolation structure (144-L cooler, IGLOO Latitude, Katy, Texas, USA), and subsequently transported to both the fruits quality analysis and tissues chemical analysis laboratory of INIA Quilamapu, for immediate determination of fruit firmness, size, and weight, DM and mineral content: total N, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu and B. Firmness and size were measured individually from 60 fruits from each sample with a FirmPro instrument (HappyVolt, Santiago, Chile), and fruit weight was determined with a digital balance (model 100A-300M, Precisa, Dietikon, Switzerland). The DM was determined by recording fruit fresh weight of each sample on a digital balance (Precisa Model 100A-300M) and drying samples at 65 °C for 72 h in a drying oven (Memmert Model 600, Schwabach, Germany), dry weight was determined with digital balance. Fruit DM content was determined as the percentage relationship between dry weight and wet weight. To analyze mineral nutrient content, fruit samples were oven-dried at 70 °C to constant weight, milled and chemically analyzed. The methodologies described by Sadzawka et al. (2006) were used, and the detail of each methodology in laboratory was described by Hirzel et al. (2023).

Table 3. Soil physical and chemical properties at depth of 0 to 0.3 m.

Analysis	Minimum value	Maximum value
Sand, %	35.00	45.00
Loam, %	40.00	44.00
Clay, %	16.00	20.00
Organic matter content, g kg^{-1}	18.00	27.00
pH ($_{soil:water\ 1:2.5}$)	5.90	6.70
Electric conductivity, dS m^{-1}	0.34	0.48
Available N, mg kg^{-1}	18.00	24.00
Available P, mg kg^{-1}	18.00	40.00
Exchangeable Ca, $cmol_+$ kg^{-1}	6.80	8.50
Exchangeable Mg, $cmol_+$ kg^{-1}	1.50	2.40
Exchangeable K, $cmol_+$ kg^{-1}	0.43	0.85
Exchangeable Na, $cmol_+$ kg^{-1}	0.16	0.24
Available S, mg kg^{-1}	23.00	50.00
Available Fe, mg kg^{-1}	26.00	50.00
Available Mn, mg kg^{-1}	4.00	7.20
Available Zn, mg kg^{-1}	1.30	5.20
Available Cu, mg kg^{-1}	5.80	10.20
Available B, mg kg^{-1}	0.60	1.50

Statistical analysis
Considering that sweet cherries were grown in field condition of a farm under the same environmental and growing conditions, results were subjected to one way ANOVA among cultivars, using the same methodology as described by Ložienė et al. (2016), and Tukey's mean separation test at 5% level of significance. In addition, as the ANOVA indicated differences between cultivars, Pearson's multiple correlation analysis was performed separately for each cultivar. The SAS 6.0 (SAS Institute, Cary, North Carolina, USA) software was used.

RESULTS

Fruit quality attributes and mineral nutrient concentrations
The quality attribute analyses indicated differences in firmness between the three sweet cherry cultivars ($p < 0.05$) (Figure 1). The firmness of 'Regina' fruits was 15% larger than 'Lapins' and 37% larger than 'Santina'. In turn, the firmness of 'Lapins' fruits was 19% higher than 'Santina'. Fruit weight and size were greater in 'Lapins' ($p < 0.05$) without difference between the other two cultivars, in 'Lapins' were 3.7% and 11.4% higher, respectively, than average values for weight and size in 'Santina' and 'Regina' (Figures 2 and 3).

The mineral nutritional analyses of fruits only indicated a difference for the concentrations of Ca, Mg, S, Mn, Zn, Cu and B, and for the DM content ($p < 0.05$) (Table 4). In general, none of the three evaluated cultivars surpassed to the others two in all the values of the mineral nutrients evaluated, highlighting the highest concentration of Ca, Mg, Mn and B in 'Lapins' ($p < 0.05$) and higher S concentration in 'Santina' ($p < 0.05$). The DM content in 'Regina' was 9% higher than 'Lapins' and 17% higher than 'Santina', while this value in 'Lapins' was 8% higher than 'Santina' (Table 4).

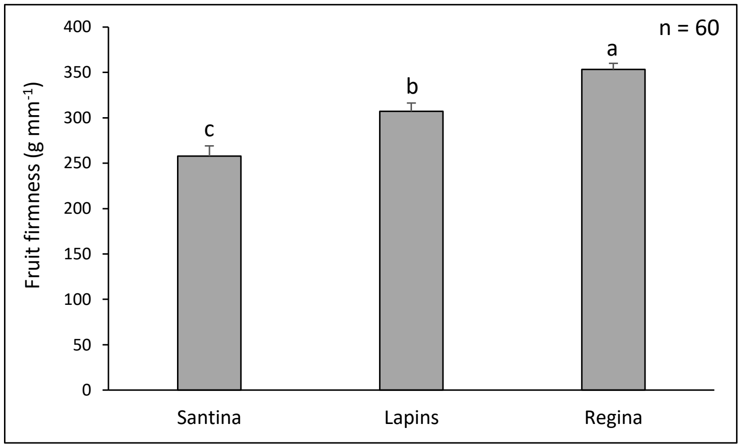

Figure 1. Fruits firmness of three sweet cherry cultivars. Lines over the bars indicate the standard error. Letter over the bars indicate significant difference according to Tukey' test ($p < 0.05$).

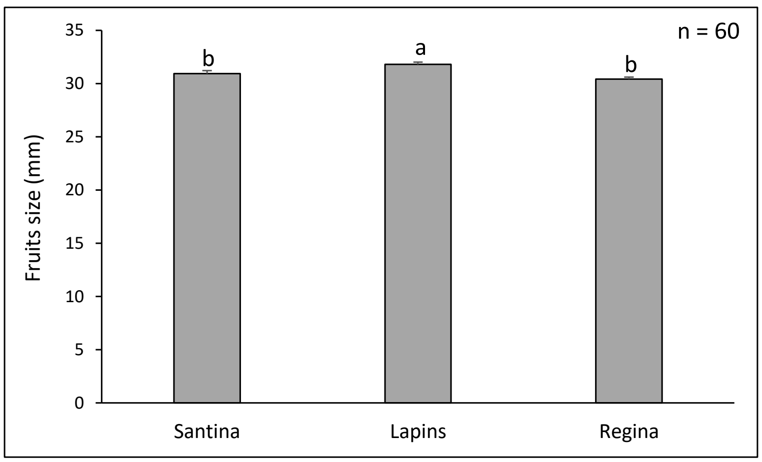

Figure 2. Fruits size of three sweet cherry cultivars. Lines over the bars indicate the standard error. Letter over the bars indicate significant difference according to Tukey' test ($p < 0.05$).

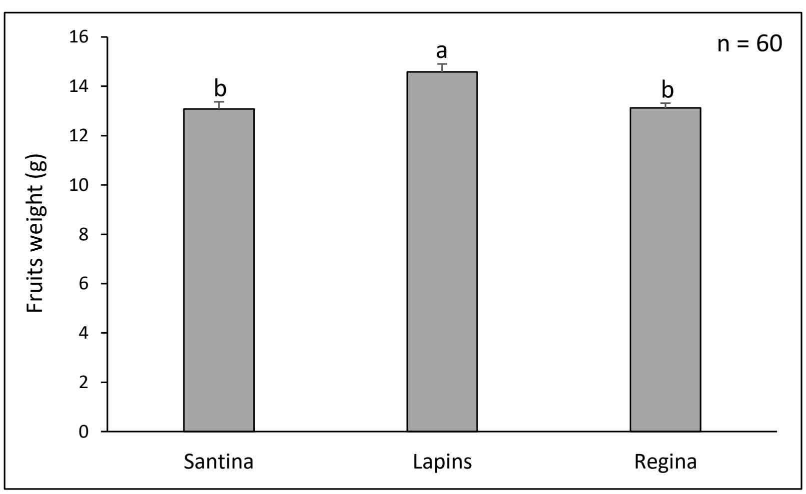

Figure 3. Fruits weight of three sweet cherry cultivars. Lines over the bars indicate the standard error. Letter over the bars indicate significant difference according to Tukey' test ($p < 0.05$).

Table 4. Quality and mineral nutritional characteristics of three sweet cherry cultivars. Different letters in the same row indicate significant differences between sweet cherry cultivars according to Tukey's test ($p < 0.05$).

Fruit attribute o content	Santina	Lapins	Regina	CV (%)	Significance value
Dry matter, %	17.2^{c}	18.5^{b}	20.2^{a}	7.4	0.0001
N, mg 100 g^{-1} fresh fruit	246.9^{a}	230.6^{a}	231.0^{a}	16.1	0.350
P, mg 100 g^{-1} fresh fruit	27.0^{a}	26.1^{a}	26.7^{a}	11.4	0.770
K, mg 100 g^{-1} fresh fruit	221.6^{a}	216.9^{a}	232.3^{a}	11.1	0.210
Ca, mg 100 g^{-1} fresh fruit	10.1^{b}	12.2^{a}	8.2^{c}	20.4	0.0001
Mg, mg 100 g^{-1} fresh fruit	11.2^{a}	11.4^{a}	9.4^{b}	9.6	0.0001
S, mg 100 g^{-1} fresh fruit	11.5^{a}	10.3^{b}	7.3^{c}	14.3	0.0001
Na, mg 100 g^{-1} fresh fruit	0.88^{a}	0.82^{a}	0.76^{a}	31.8	0.370
Fe, mg 100 g^{-1} fresh fruit	0.41^{a}	0.45^{a}	0.46^{a}	32.4	0.570
Mn, mg 100 g^{-1} fresh fruit	0.075^{b}	0.096^{a}	0.079^{b}	22.2	0.018
Zn, mg 100 g^{-1} fresh fruit	0.068^{b}	0.080^{ab}	0.081^{a}	17.7	0.0096
Cu, mg 100 g^{-1} fresh fruit	0.079^{a}	0.042^{b}	0.082^{a}	45.0	0.017
B, mg 100 g^{-1} fresh fruit	0.45^{b}	0.59^{a}	0.53^{ab}	31.0	0.050

Correlation between fruit quality attributes and mineral nutrient contents

There was a moderate and significant correlation for fruit firmness with concentration of N and B in 'Santina', high positive correlations with N and P in 'Lapins', and moderate significant correlations with N and P in 'Regina' (Tables 5, 6 and 7).

Table 5. Correlation matrix of different fruit quality attributes and mineral composition of the 'Santina' sweet cherry. *Significant at $p \leq 0.05$; **Significant at $p \leq 0.01$. n = 20. FF: Fruit firmness; FS: fruit size; FW: fruit weight; DM: dry matter percentage.

	FF	FS	FW	DM	N	P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Zn	B
FF	1	-0.13	-0.17	0.24	0.42*	0.38	-0.04	-0.23	0.03	-0.04	0.33	0.25	0.22	0.24	0.22	0.43*
FS		1	0.97**	0.03	-0.09	0.17	0.24	-0.13	0.31	-0.07	0.15	-0.60**	-0.44	0.02	-0.49*	-0.02
FW			1	0.04	-0.13	0.13	0.12	-0.11	0.17	-0.07	0.14	-0.50*	-0.40	-0.07	-0.52*	-0.10
DM				1	0.44	0.22	0.43	-0.38	-0.19	0.44	0.53*	0.08	0.42	0.05	-0.09	0.69**
N					1	0.51*	0.35	0.13	0.41	0.15	0.65**	0.22	0.29	0.65**	0.57**	0.65**
P						1	0.33	0.26	0.38	0.35	0.59**	0.15	0.16	0.33	0.44*	0.41
K							1	0.02	0.30	0.25	0.46*	-0.43*	0.19	0.36	0.01	0.41*
Ca								1	0.45*	0.01	0.31	0.36	0.09	0.33	0.50*	0.08
Mg									1	-0.07	0.22	-0.29	-0.19	0.75**	0.40	0.26
Na										1	0.37	0.31	0.14	0.05	0.16	0.24
S											1	0.30	0.28	0.34	0.27	0.66**
Cu												1	0.29	-0.03	0.52*	0.19
Fe													1	0.05	0.31	0.20
Mn														1	0.59**	0.36
Zn															1	0.26
B																1

Table 6. Correlation matrix of different fruit quality attributes and mineral composition of the 'Lapins' sweet cherry. *Significant at $p \le 0.05$; **Significant at $p \le 0.01$. n = 20. FF: Fruit firmness; FS: fruit size; FW: fruit weight; DM: dry matter percentage.

	FF	FS	FW	DM	N	P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Zn	B
FF	1	-0.32	-0.26	-0.05	0.64*	0.81**	0.26	0.31	0.13	-0.02	0.12	-0.24	0.49	0.08	0.26	-0.09
FS		1	0.97**	-0.19	0.03	-0.02	-0.01	0.12	0.60	0.33	0.28	0.26	0.21	0.13	-0.01	-0.26
FW			1	-0.26	-0.05	-0.05	-0.11	0.13	0.55	0.30	0.24	0.17	0.23	0.16	-0.12	-0.28
DM				1	0.15	0.19	0.75*	-0.51	0.45	-0.42	0.18	0.06	-0.29	-0.38	0.15	0.91**
N					1	0.79**	0.66*	0.26	0.56	0.23	0.60	0.14	0.56	-0.14	0.36	-0.09
P						1	0.54	0.11	0.52	-0.21	0.09	-0.26	0.29	-0.05	0.30	0.09
K							1	0.03	0.67*	-0.05	0.46	-0.05	0.11	-0.23	0.44	0.45*
Ca								1	-0.16	0.65*	0.15	-0.21	0.49	0.51	0.61	-0.77**
Mg									1	0.06	0.54	0.19	0.17	-0.34	0.04	0.31
Na										1	0.62	0.51	0.43	-0.05	0.31	-0.61
S											1	0.67*	0.62	-0.22	0.15	-0.03
Cu												1	0.25	-0.34	0.03	0.07
Fe													1	0.51	0.31	-0.46
Mn														1	0.39	-0.47
Zn															1	-0.14
B																1

Table 7. Correlation matrix of different fruit quality attributes and mineral composition of the 'Regina' sweet cherry. *Significant at $p \le 0.05$; **Significant at $p \le 0.01$. n = 20. FF: Fruit firmness; FS: fruit size; FW: fruit weight; DM: dry matter percentage.

	FF	FS	FW	DM	N	P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Zn	B
FF	1	0.29	0.21	-0.13	0.44*	0.46*	0.20	0.06	0.26	-0.46*	0.08	0.14	-0.35	0.26	-0.22	-0.02
FS		1	0.97**	0.10	0.42*	0.15	-0.13	-0.13	0.03	0.03	0.29	0.23	0.06	0.01	0.06	-0.18
FW			1	0.05	0.33	0.12	-0.18	-0.06	0.09	0.03	0.26	0.34	0.04	-0.01	0.14	-0.21
DM				1	0.21	-0.03	0.16	-0.59**	-0.07	0.37	0.36	-0.21	0.53**	-0.45*	-0.52**	0.06
N					1	0.41*	0.19	-0.36	0.07	-0.09	0.67**	0.01	-0.22	0.10	-0.20	-0.07
P						1	0.62**	0.03	0.73**	-0.53**	0.39*	0.37	-0.03	0.13	0.09	0.20
K							1	-0.30	0.57**	-0.28	0.37	0.01	0.12	-0.16	0.01	0.46*
Ca								1	0.02	-0.30	-0.65**	0.40*	-0.24	0.30	0.30	-0.02
Mg									1	-0.31	0.37	0.36	-0.06	0.24	0.24	0.47*
Na										1	0.27	-0.07	0.57**	-0.08	0.06	0.01
S											1	0.04	0.19	0.01	0.02	0.13
Cu												1	0.13	0.27	0.54**	-0.20
Fe													1	-0.47*	0.01	0.02
Mn														1	0.35	-0.08
Zn															1	-0.07
B																1

As expected, there was a high and significant positive correlation between weight and size (0.97) in the three cultivars (Tables 5, 6 and 7). The fruit size only presented significant correlations with mineral nutrient content in 'Santina' and 'Regina' (Tables 5 and 7). In the case of 'Santina' there was a negative correlation with Cu and Zn concentrations, while for 'Regina' there was a moderate positive correlation with N concentration.

Fruit weight only presented significant correlations with the concentration of mineral nutrients in 'Santina' (Table 5), which, like the size, was negatively affected by Cu and Zn concentrations.

The DM content in 'Santina' was positively affected by S and B concentrations, highlighting the high correlation obtained with B (Table 5). For 'Lapins' there was a high positive correlation with K and B concentrations (Table 6). In 'Regina' a negative correlation was obtained with Ca, Mn and Zn concentrations, and a positive correlation with Fe concentration (Table 7).

Mineral nutrient concentrations in fruits presented some correlations that were consistent in the three cultivars of sweet cherry (Tables 5, 6 and 7), such as the N-P, and K-B correlation. A consistent N-S, P-S and Zn-Cu correlation was also observed in 'Santina' and 'Regina', and K-Mg in 'Lapins' and 'Regina'. Other positive and negative correlations were observed between mineral nutrients, but they were specific for one or another cultivar, highlighting the high negative correlation between Ca-B in 'Lapins' (Tables 5, 6 and 7).

DISCUSSION

The climatic conditions in which the orchards are developed are suitable for sweet cherry trees, which is consistent with obtained yields (Table 1), despite the insufficient number of chilling hours recorded during the season (Salvadores and Bastías, 2023). The soil physical-chemical properties are also suitable for the normal development and production of the sweet cherry orchards, taking into account that a fertilization applied is also carried out to meet the annual nutrient extraction of each orchard (Hirzel, 2014). Only the organic matter content could be a limiting factor for the vegetative development of the orchards, but modern management systems are oriented to control the vegetative vigor and maximize the light input (Scofield et al., 2022), so it is preferred to work on soils with low organic matter content.

Nevertheless, a work carried out in 'Regina' using the FirmPro equipment for commercial orchards in southern Chile, indicated fruit firmness values between 323.4 and 373.3 g mm^{-1} (Palacios-Peralta et al., 2023), which was similar to what was obtained herein. Regarding the differences found in the three cultivars evaluated in this study, higher firmness values were expected. With longer development time of fruits like 'Regina', carbohydrates are accumulated and then used in secondary metabolism, necessary to improve the texture of fruits and their mechanical resistance. In this regard, Facteau et al. (1983) indicated a direct relationship between accumulation of soluble solids and firmness of 'Lambert' and 'Bing' cherry fruits.

Regarding fruit weight references for the productive conditions of Chile, Palacios-Peralta et al. (2023) indicated 9.5 to 9.8 g for 'Regina', while Quiroz et al. (2023) indicated 8.1 to 11.7 g for 'Lapins'. The values indicated by these authors are lower than those obtained in this study. In relation to fruit size, Palacios-Peralta et al. (2023) indicated 26.6 to 27.3 mm for 'Regina', while Quiroz et al. (2023) indicated 27.4 to 29.5 mm for 'Lapins', which are also lower than ours. The discrepancies may be due to the different evaluation areas within Chile, as well as seasonal variables, considering that in seasons with less cold accumulation, there is less fruit production, which generates an increase in both weight and size.

Regarding DM content, it was normal to expect higher values in the cultivars with longer fruit development time, given its higher accumulation of fruit carbohydrates (Escribano et al., 2017), in decreasing order 'Regina' > 'Lapins' > 'Santina'. Kovács et al. (2009) working with four cultivars of sweet cherry ('Vera', 'Carmen', 'Linda' and 'Krupnoplodnaja') at different maturity, indicated a directly proportional relationship between development time of fruit and accumulation of soluble solids and DM. The DM values for 'Lapins' were similar to those reported by Quiroz et al. (2023) for productive conditions in Chile.

The differences in mineral nutrient concentration in fruits of the three evaluated cultivars of sweet cherry are normal for fruit species, as has been pointed out for example for berries (Vance et al., 2017; Hirzel et al., 2023) and for apple trees (Kumar et al., 2018); however, there is little information for other fruit species, especially for sweet cherry. These differences depend on genotype and genotype-environment interaction; however, for this study the environment was stable, therefore the differences are mainly due to the genotype, as was pointed out for quality attributes of sweet cherry by Calle et al. (2020). Although Quiroz et al. (2023) indicate a direct relationship between Ca concentration in fruits and their firmness, it is noticeable that the highest Ca concentration obtained in 'Lapins' fruits was not consistent with the greater comparative firmness between cultivars. Similarly, the lowest Ca concentration in fruits was obtained in 'Regina', which in turn presented the highest firmness value, showing that relationships between fruit Ca concentration and firmness cannot be generalized and should be cultivar dependent. Considering that there is no standard to evaluate nutritional condition of sweet cherry fruits, values generated by this study for 'Santina', 'Lapins' and 'Regina' can be a contribution for productive purposes or future research.

Regarding relationships between firmness and weight or size of sweet cherry fruits, little has been published. Demirsoy and Demirsoy (2004) indicated very moderate correlation between firmness and fruit weight for 35 cultivars of sweet cherry evaluated in Türkiye (R = 0.52). In relation to the correlations obtained between quality attributes and mineral nutrient concentration in fruits, an inversely proportional relationship between fruit weight and firmness has been described for some cultivars of sweet cherry (Campoy et al., 2015); however, Calle et al. (2020) mention that this correlation is genotype dependent, and positive or negative relationships may exist.

For the correlation between fruits size and weight in sweet cherry, Calle et al. (2020) indicated values between 0.95 and 0.96 for 'Ambrunés', data also found in our three evaluated cultivars.

The negative correlation between Cu concentration with size and weight of 'Santina' fruits was also reported for sweet cherry fruits at different stages of development by Gruber et al. (2010). In a laboratory study working with sweet cherry flower buds and increasing doses of heavy metals (Cu, Cd, Pb and Hg), Sharafi et al. (2017) indicated than the pollen germination and tube growth of all the cultivars were reduced with increasing metals concentrations.

In this study, fruit firmness presented a consistent although moderate correlation with N concentration in the three cultivars evaluated, and with P concentration in two of the cultivars, which can be explained by the protein structures and phospholipids present in the cell wall (Marschner, 2012), mainly in the peripheral cells that generate the textural condition of the fruits (Giongo et al., 2013). Other studies that have determined the correlation between fruit firmness and nutrient concentration in cherry fruits have described positive relationships with K (Ates et al., 2021; Palacios-Peralta et al., 2023), Ca (Winkler and Knoche, 2019; Quiroz et al., 2023), which contrasts with the results of the present study. For apple fruits, Casero et al. (2004) reported positive correlation between fruit firmness and P content. In pear fruits, Dias et al. (2024) indicated that no relationship was found between fruit firmness and the concentration of any nutrient. Similarly, Hirzel et al. (2023) did not find relationship between fruit firmness and Ca content in several blueberry cultivars.

Scarce literature describes relationships between DM content and nutrients in fruits of various fruit species; however, the positive relationship between DM content and soluble solids in stone fruits is known, given that the latter are part of the DM content (Escribano et al., 2017; Scalisi and O'Connell, 2021). In this regard, positive correlations have been described in pear (Dias et al., 2024) and cherry fruits (Palacios-Peralta et al., 2023) between the content of soluble solids and K concentration, such as what was obtained for 'Santina' and 'Lapins' in this study, probably explained by their sugar mobilizing function (Marschner, 2012).

The negative correlation obtained between DM content and Ca concentration in 'Regina' is noticeable, given that in other species such as apple trees a positive relationship has been described between fruit quality, with DM content (Palmer et al., 2010) and with increases in Ca concentration (Casero et al., 2004). However, in the three cultivars of sweet cherry fruits evaluated, there was no positive correlation between DM content and Ca concentration, therefore an increase in the Ca concentration in cherry fruits does not allow us to infer an increase in their DM content.

In relation to the mineral nutrient concentrations in fruits of the three cherry cultivars, there is a not consistent correlation. A study carried out by Ates et al. (2021) indicated positive K-Cu, and negative K-Ca and K-Mg correlations, differing from our results. In blueberries 'Blue crop' and 'Draper' with foliar applications of Ca and B at different doses, there was no correlation between Ca and B concentrations in fruits at harvest (Arrington and DeVetter, 2017). An old study of agronomic response to the application of increasing Ca doses in the absence of B application carried out in pineapple (*Ananas comosus* (L.) Merr.) by Hernández-Medina and Lugo-López (1958), indicated that the increase in Ca doses reduced fruit yield and green weight of plants, which could indicate a possible antagonistic effect between both nutrients.

CONCLUSIONS

The three sweet cherry cultivars evaluated in this study presented differences in fruit quality attributes and mineral nutrient concentration. The highest firmness of fruits was obtained in 'Regina', while the lowest value was obtained in 'Santina'. 'Lapins' presented the highest size and weight of fruits. The differences in mineral nutrient concentration in fruits of these three cultivars make it impossible to generate a reference nutrient standard for cherry fruits, and if so- it should be specified by cultivar. The correlations of mineral nutrients in fruits were not very consistent between the three cultivars and, in general, N-P and K-B correlation was found in the three cultivars. In turn, the firmness of fruits of the three cultivars presented a positive correlation with N concentration, and in two of the cultivars there was a correlation with the concentration of P. The DM content did not present a correlation with firmness, size or weight of fruits in the three sweet cherry cultivars evaluated; therefore, it is not a predictor of these quality attributes. Finally, there was a high positive correlation between fruit size and weight.

Author contributions

Conceptualization: J.H., J.D. Methodology: J.H., J.D. Software: J.H. Validation: J.H. Formal analysis: J.H. Investigation: J.H., J.D. Resources: J.H., J.D. Data curation: J.H. Writing-original draft: J.H. Writing-review & editing: J.H. Visualization: J.H. Supervision: J.H. Project administration: J.H., J.D. Funding acquisition: J.D. All co-authors reviewed the final version and approved the manuscript before submission.

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