ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.12, e284789, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n12e284789

ORIGINAL ARTICLE

Cultivation location and agrometeorological conditions influence pre-harvest variables of Japanese plum fruit in the Colombian tropics[1]

A localização do cultivo e as condições agrometeorológicas influenciam as variáveis pré-colheita do fruto da ameixa japonesa no trópico colombiano

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HIGHLIGHTS:

Fresh plum fruit weight presented higher values in the high zone.
Epidermis firmness demonstrated elevated values across all three harvests in the high zone.
The climate of the lower zone generated higher soluble solids in the plum fruit.

ABSTRACT: Climatic conditions influence fruit quality during the harvest period; this aspect is unknown in plums cultivated in tropical regions. This study aimed to determine the influence of cultivation climatic conditions on the quality of 'Horvin' plum fruit (from flowering to harvest) at different altitudes in the Nuevo Colón municipality (Colombia). Employing a systematic sampling approach with 20 trees per zone, one fruit was randomly selected from each tree at weekly intervals in both locations. Fruit variables, namely weight, soluble solids, titratable acidity, Hue angle, chroma, and fruit firmness, were evaluated from day 18 to 26 after the flower bud stage until harvest in low (2,195 m a.s.l.) and high zones (2,567 m a.s.l.). A direct relationship was verified between fruit weight and size at harvest and orchard location altitude. Factors such as solar radiation, precipitation, and temperature were identified as key in plum fruit quality characteristics. At a higher altitude, fruit weighed between 9 and 14 g, and the firmness of the epidermis consistently exhibited higher values in the high zone across all three harvests. Therefore, there was impact of climatic conditions, including precipitation, sunlight, and temperature, related to the cultivation location in the process of fruit development and maturation on certain fruit quality variables on the day of harvest.

Key words: *Prunus salicina* Lindl., radiation, precipitation, temperature, tree fruit

RESUMO: As condições climáticas influência na qualidade das frutas durante o período de colheita, esse aspecto é desconhecido em ameixas cultivadas em regiões tropicais. Este estudo teve como objetivo determinar a influência das condições climáticas de cultivo na qualidade dos frutos de ameixa 'Horvin' (desde a floração até a colheita) em diferentes altitudes no município de Nuevo Colón (Colômbia). Utilizando uma abordagem sistemática de amostragem com 20 árvores por locais, uma fruta foi selecionada aleatoriamente de cada árvore em intervalo semanal em ambos os locais. A avaliação abrangeu o teor de sólidos solúveis, acidez titulável, ângulo Hue e firmeza do fruto do dia 18 ao 26 após o estágio de botão floral até a colheita para zona baixa (2,195 m) e zona alta (2,567 m), respectivamente. Os resultados revelaram uma correlação direta entre o peso e o tamanho das frutas na colheita e a altitude do local de produção. Fatores como radiação solar, precipitação e temperatura foram identificados como influenciadores nas características de qualidade das frutas de ameixa. Notavelmente, na localidade de maior altitude, foram observadas frutas com pesos entre 9 e 14 g, e a firmeza da epiderme apresentou consistentemente valores mais altos na zona alta em todas as três colheitas. Portanto, houve impacto das condições climáticas relacionado ao local de cultivo no processo de desenvolvimento e maturação dos frutos, incluindo precipitação, luz solar e temperatura, em certas variáveis de qualidade relacionadas ao fruto no dia da colheita.

Palavras-chave: *Prunus salicina* Lindl., radiação, precipitação, temperatura, frutas de árvore

• Ref. 284789 – Received 20 Mar, 2024
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• Accepted 03 Jul, 2024 • Published 15 Jul, 2024
Editors: Toshik Iarley da Silva & Walter Esfrain Pereira

Introduction

Japanese plum (*Prunus salicina* Lindl.) variety 'Horvin' is a highly adaptable plant native to Asia. In Colombian rural communities, from 2012 to 2020, the national plum harvest increased by 52%, reaching 16,807 t produced on 1322 ha in 2020 (Agronet, 2021). Areas of the "Cundiboyacense highlands" have favorable conditions such as climate, soil, and precipitation for plum cultivation (Orduz-Ríos et al., 2020; Orjuela-Angulo et al., 2022a).

Fruit growth and development are an integration of multiple processes regulated through environmental factors, plant hormones, and the availability of metabolic resources (Malladi, 2020). Deciduous crops, originating and adapting to temperate zones, are susceptible to the influence of tropical climatology. Climate change, with its temperature fluctuations, poses a significant risk to plum production, impacting phenology and overall yield (Fischer, 2012; Gutiérrez-Villamil et al., 2024). Fruit development can be quantified and qualified by monitoring parameters such as weight, firmness, total soluble solids, and color, which are commonly used for this purpose. These fruit parameters can be affected by elevation and climate, as reported by Mayorga et al. (2020), Fischer et al. (2022), and Parra-Coronado et al. (2022).

In Colombia, plum is cultivated in altitudes ranging from 1690 to 2900 m a.s.l. (Fischer et al., 2022; Gutiérrez-Villamil et al., 2024), average solar brightness of 1,400 hours per year, 12-hour photoperiods, temperatures between 14 and 20 °C during the day and between 6 and 8 °C at night, and rainfall between 700 and 1,600 mm per year (Gutiérrez-Villamil et al., 2024). Under these conditions, it is possible to produce plum throughout the year. Moreover, through forced production in an orchard, it is possible to obtain up to three harvests in two years. However, it is necessary to implement management that consists of the selection of varieties with low chilling requirements, chemical defoliation, proper fertilization, fruit and green pruning, and the application of chemical products that promote flower bud breaking (Gutiérrez-Villamil et al., 2024).

Orjuela-Angulo et al. (2022a) found that plum is affected by climatic factors, such as rainfall and temperature. Therefore, the hypothesis of this research was that plum fruit exhibits higher weight and better quality characteristics in the higher zone due to better temperature, radiation, and precipitation conditions. This study aimed to determine the influence of cultivation climatic conditions on the quality of 'Horvin' plum fruit (from flowering to harvest) at different altitudes in the Nuevo Colón municipality (Boyacá, Colombia).

Material and Methods

The study was conducted in two orchards located in Nuevo Colón (Boyacá, Colombia). Rootstock of a common white peach cultivar grafted with Japanese plum (*Prunus salicina* Lindl.) 'Horvin' variety were used; these trees were between 20 and 30 years old. The orchards are located in Nuevo Colón, Boyacá, as follows: low zone (Blanquita farm) situated at coordinates 5° 20' 17.56" N and 73° 27' 53.85" W, at a lower altitude of 2,195 m a.s.l.; high zone (Ana farm) positioned between coordinates 5° 21' 26.5" N and 73° 28' 10.8" W, with a higher altitude of 2567 m a.s.l. This area is characterized by a cold, humid climate B2d B1, according to the Thornthwaite classification. The relative humidity is high, reaching a maximum of 98% at higher altitudes and a minimum of 24%. The precipitation in this zone exhibits a monomodal pattern, with an annual average of 877.2 mm concentrated from April to July (Orjuela-Angulo et al., 2022b).

Climatic conditions for plum fruit development from anthesis to harvest (Figure 1) were recorded over a 2-year period (2021 to 2022) in both localities. Throughout this phase, periodic variations and climatic variables of the study locations (ambient temperature, solar radiation, relative humidity, and precipitation) were recorded. For temperature and relative humidity records in each zone, data loggers-USB were utilized and programed to collect data at 30-min intervals. To determine the precipitation in each plot, 35 mm capacity rain gauges (Opitec brand, Rocafort-Barcelona, Spain) with a height of 24.5 cm, upper diameter of 9 cm, and lower diameter of 3.3 cm, were installed in each locality, taking measurements each time a rain event occurred. Solar radiation was measured using a CHP1Inmission IEC 100-4-4pyrheliometer (Delf, Netherlands) with radiant flux from a solid angle of 5°, and a receiving surface that captures the incident radiation perpendicular to its surface. The instrument was placed in the center of the outdoor plot in the middle of the crop; the measurement was not affected since the measurements were made without any interference.

Ten trees per row and two rows per zone were selected, totaling forty trees in the study. The research trees were positioned at the center of the cultivation plot to maintain uniform climatic conditions and eliminate edge effects. Each tree (sampling unit) was numbered, and the floral buds were marked manually. The marking included date-specific numbering for each cluster present in the middle third of the canopy. The statistical design was completely randomized, with 10 repetitions per treatment; each zone (low and high) was considered as a treatment.

One fruit was randomly selected from each tree at a weekly frequency. For the determination of fruit weight, soluble solids (SS), total acidity (TA), hue angle (°h), chrome (C), and fruit firmness, sampling was carried out from day 18 and 26 post-anthesis until harvest for low and high zones, respectively, when the fruit had attained sufficient size for analysis. This procedure was repeated over two consecutive years, covering three harvests. Due to the prevailing climatic conditions during the research period, the studied crops yielded two harvests annually.

One row per zone and per harvest was considered to measure fresh weight and diameter. An OHAUS electronic balance (Ohaus, Ohio, OH) with a capacity of 2500 g (precision: 0.01 g) was used for unit weight determination. Diameters were measured using a 150 mm digital vernier caliper (Mitutoyo, Andover) with a precision of 0.05 mm.

For the physicochemical characterization of variables such as TA, firmness, color, and SS, four repetitions were conducted

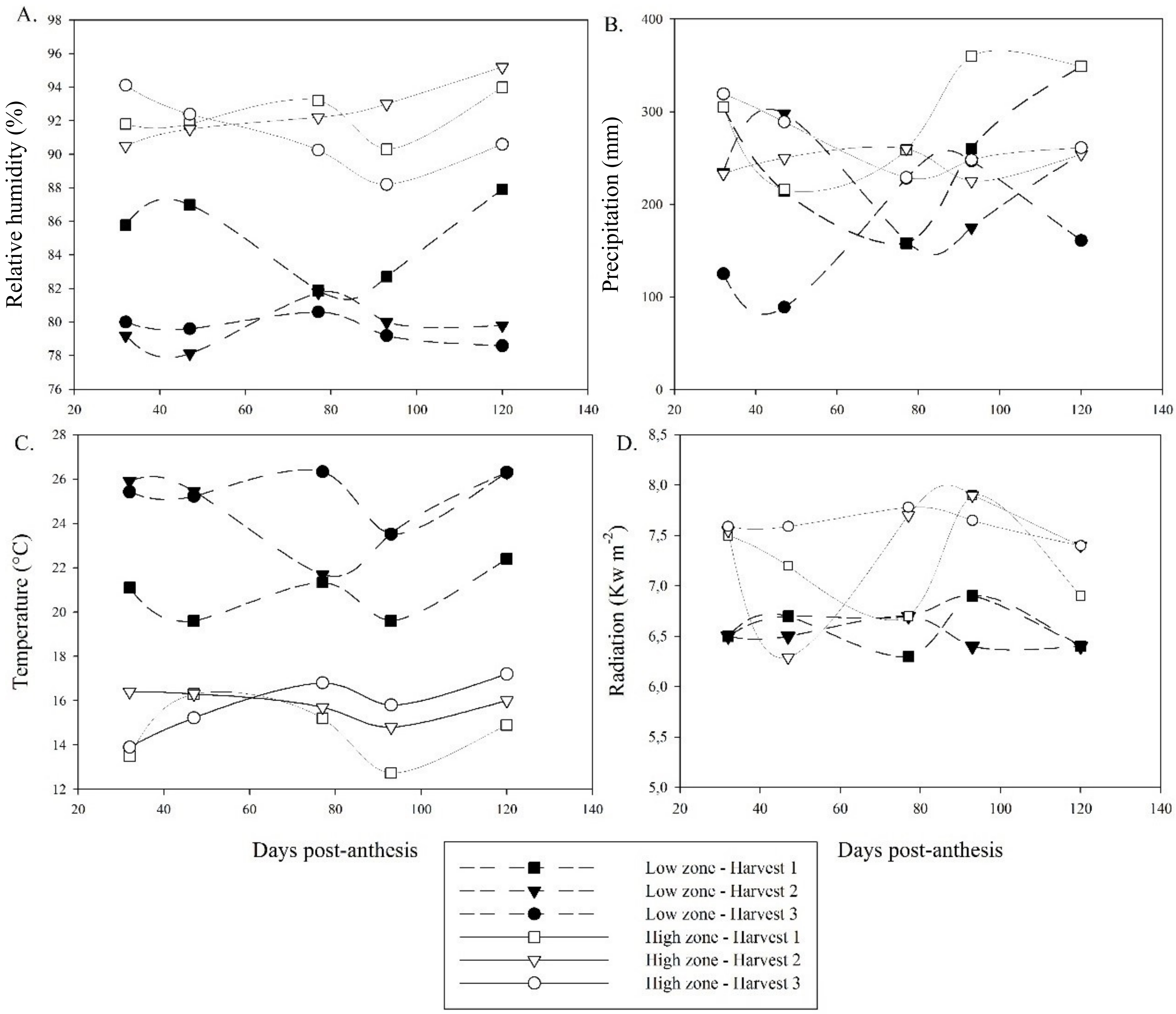


Figure 1. Relative humidity of the air (A), precipitation (B), air temperature (C), and radiation (D) for plum fruit development in low (2195 m a.s.l.) and high zones (2567 m a.s.l.) and three harvest cycles under the Colombian tropics

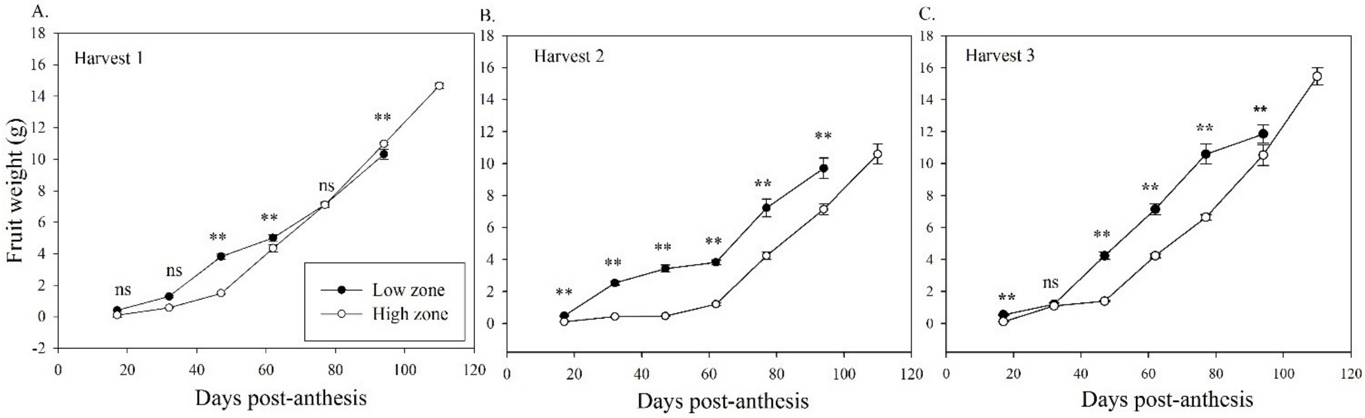
per assay at pre-harvest intervals of every 15 days. A HANNA HI 96801 refractometer (Hanna brand, Woonsocket, RI, USA) with a measurement range of up to 85% (°Brix) was used for SS determination. TA was determined using a METROHM Ti touch-916 titrator (Metrohm, Zofingen, Switzerland) following the method described by Gutiérrez-Villamil et al. (2023). The firmness of the epidermis and pulp (with the epidermis was removed) were measured using a LLOYD LS1 texture analyzer (Ametek-LLOYD, Berwyn, PA, USA), with a tip of 3 mm in diameter, coupled to NexyGen PlusTM software. A Minolta CR-400 colorimeter (Konica Minolta, Ramsey, NJ, USA) was used to determine the hue (°h) and chroma of the fruit epidermis by measuring 10 fruits per sample. The maturity ratio (MR) was determined based on the SS/TA ratio, according to González et al. (2021).

The statistical software IBM-SPSS v.20 (SPSS Inc., Chicago, IL, USA) was employed for analysis of variance and the Student t test ($p \leq 0.05$) to compare the means of the low and high zones. The mean and standard error were also calculated.

Results and Discussion

In the three harvests, the fruit from the low zone reached harvest faster and, in general, presented more weight until they were harvested; however, the fruit from the high zone took longer on the tree and, in the end, had greater weight, especially in harvests 1 and 3. This fruit was also characterized by presenting less weight in phase I of growth, but had a large increase in weight in the rapid growth phase or phase II (Figure 2).

The differences can be explained by the altitude of the studied localities and, consequently, the climatic conditions (Fischer et al., 2022). The results obtained in this research indicate that fruit produced at higher temperatures (22°C in a low zone) achieve their growth more quickly, requiring fewer calendar days to harvest. This is consistent with the findings of other studies (Mayorga et al., 2020; Ramírez-Jiménez et al., 2021). However, at higher temperatures, the plum fruit weight was lower (Figure 2), which could be because the higher temperature in the lower zone decreased the rate of



**Significant at p ≤ 0.01; [ns] no significant, according to the Student t test at each sampling point

Figure 2. Fresh weight of plum fruit from low (2195 m a.s.l.) and high zones (2567 m a.s.l.) in the Colombian tropics. A. Fruit weight for Harvest 1. B. Fruit weight for Harvest 1. C. Fruit weight for Harvest 1. Vertical bars in each mean correspond to the standard error (n=10)

photosynthesis and the content of structural carbohydrates, as reported for tomatoes (Pimenta et al., 2022).

Furthermore, harvests with the highest accumulated precipitation (corresponding to the high zone), average radiation, and relative humidity of the air (Figure 1A) produced fruit of greater weight (Figure 2). This is in accordance with findings by Parra-Coronado et al. (2007), who found that the same plum cultivar could tolerate 1500–2500 mm and obtained optimal fruit development and good harvest quality. However, a low water supply can cause a decrease in the fresh weight of the fruit, as found in different varieties of *P. salicina* (Hamdani et al., 2023).

On day 19 post-anthesis in harvest 1, the firmness of epidermis was 34 N, on average, for the low zone, while the high zone recorded a value of 30 N. The observed behavior decreased for both localities, with a more noticeable decline in final fruit development (Figure 3A–C). Regarding altitude, fruit produced at higher altitudes exhibited higher firmness than those produced at lower altitudes.

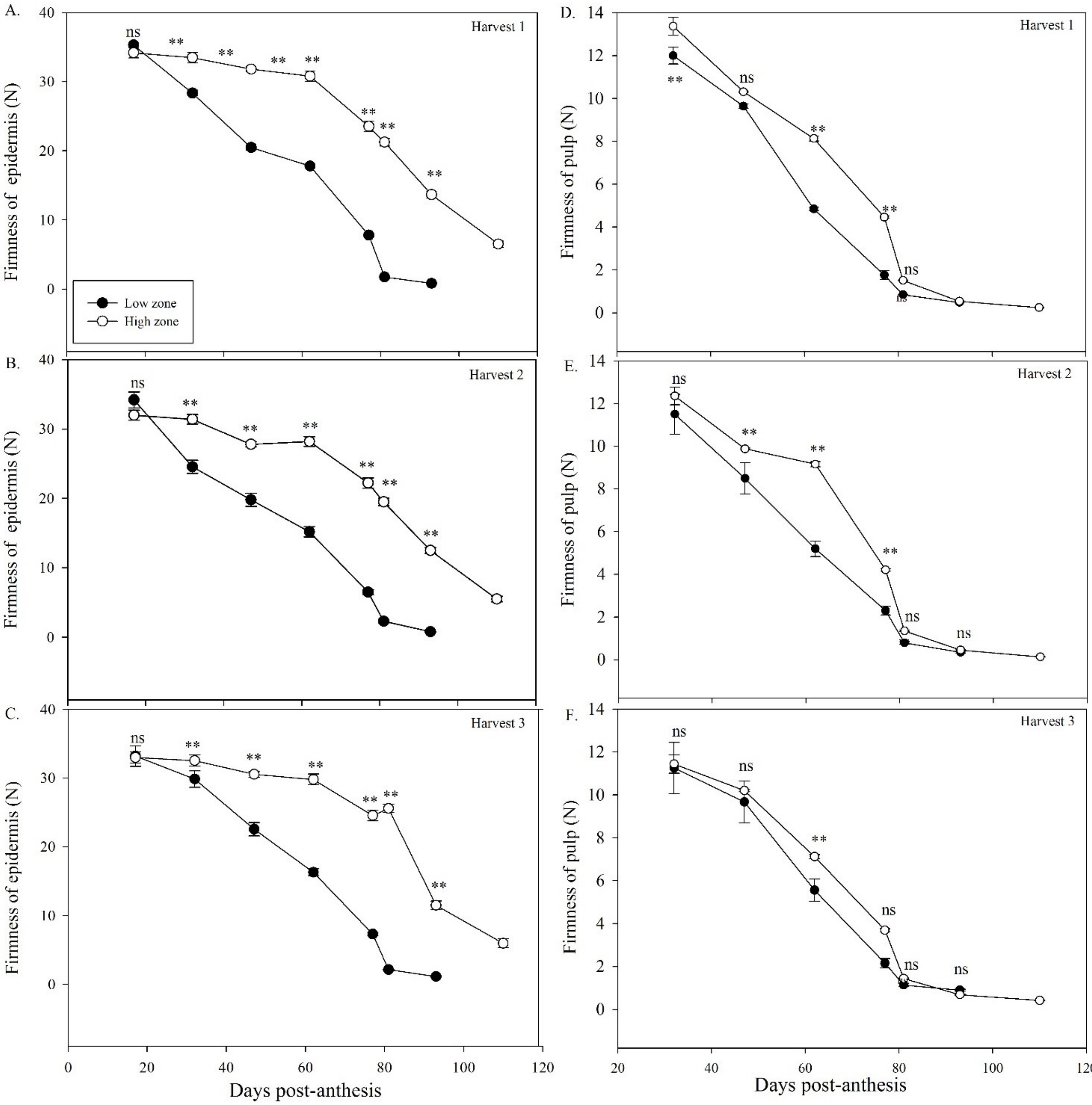
Pulp firmness exhibited higher values for all three harvests and showed a consistent trend across both orchards. On day 25 of harvest 1, the pulp firmness was measured at 12 N for the low zone, while the high zone records a value of 13.5 N. The observed behavior decreased for both studied localities, similar to the data found for harvest 2, where values of 12.3 N for the low zone and 12.4 N for the high zone were obtained. In the final fruit development stage of each harvest, a more noticeable decrease was observed compared to the initial days (0.3 and 0.4 N) for the low and high zones, respectively. For the third harvest, values between localities were similar, with 12 N for the low zone and 12.2 N for the high zone on day 19 after anthesis. On day 92, a value of 0.7 N was obtained for the low zone, while on day 120, a value of 0.5 N was recorded for the high zone (Figure 3).

The temperature for harvest 2 in the low zone was 24.6 °C, and the high zone had a lower temperature at 15.9 °C. This trend was maintained for harvests 1 and 3. Regarding precipitation, for the first harvest in the low zone, it was 1285.01 mm, while the high zone recorded a value of 1,489.3 mm. In relation to the climatic conditions for both low and high zones, temperature and precipitation are fundamental factors for epidermal firmness development in plums, as they interact with certain modifications occurring in the primary cell wall (Martínez-González et al., 2017). The highest temperature found in the low zone (Figure 1A) can generate a higher rate in the ripening process, resulting in greater enzyme activity; this can explain the lower firmness of fruit cultivated in this zone. This response can also be attributed to precipitation, as fruit in the low zone is grown under lower precipitation (Figure 1A), which could lead to lower turgor pressure in the fruit and reduced firmness. According to Orjuela-Angulo (2022a), the 'Horvin' plum presented a correlation between firmness and precipitation, pH, Ca, and B. Ca is closely related to firmness as it comprises part of the fruit cell wall, an important factor when considering fertilization to obtain better quality (Jaime-Guerrero et al., 2024).

The °h value decreased continuously in fruit from the two zones and in the three harvests. It was characteristic that °h was greater in the high zone at the beginning of fruit development, with values greater than 120°; then, there was a rapid decrease until harvest with values close to 20°. This value was lower ($p < 0.05$) than in the low zone, indicating that the fruit tends to be more red in the high zone (Figure 4).

Regarding the chroma, in the first sampling it was higher in the low zone and decreased continuously until harvest. In the high zone, there was also a tendency to decrease depending on fruit ripening, but the values were higher than in the low zone, indicating greater intensity of the red color in fruit from the high zone. This behavior was consistent in the 3 harvests (Figure 4).

In the high zone, there were lower temperatures and higher radiation; these climatic factors are associated with the pigmentation of the fruit cultivated at high altitudes (Fischer et al., 2024). A high altitude can be an important condition for improving fruit color because it increases the pigment content, and fruit grown at a high altitude accumulates more anthocyanins and other phytochemical compounds to protect it from high radiation, especially UV (Fischer et al., 2024), as found in grape (Oliveira et al., 2019) and peach fruit (Karagiannis et al., 2016). Therefore, high zone plums have a more saturated red color that can have advantages for marketing and consumer health.

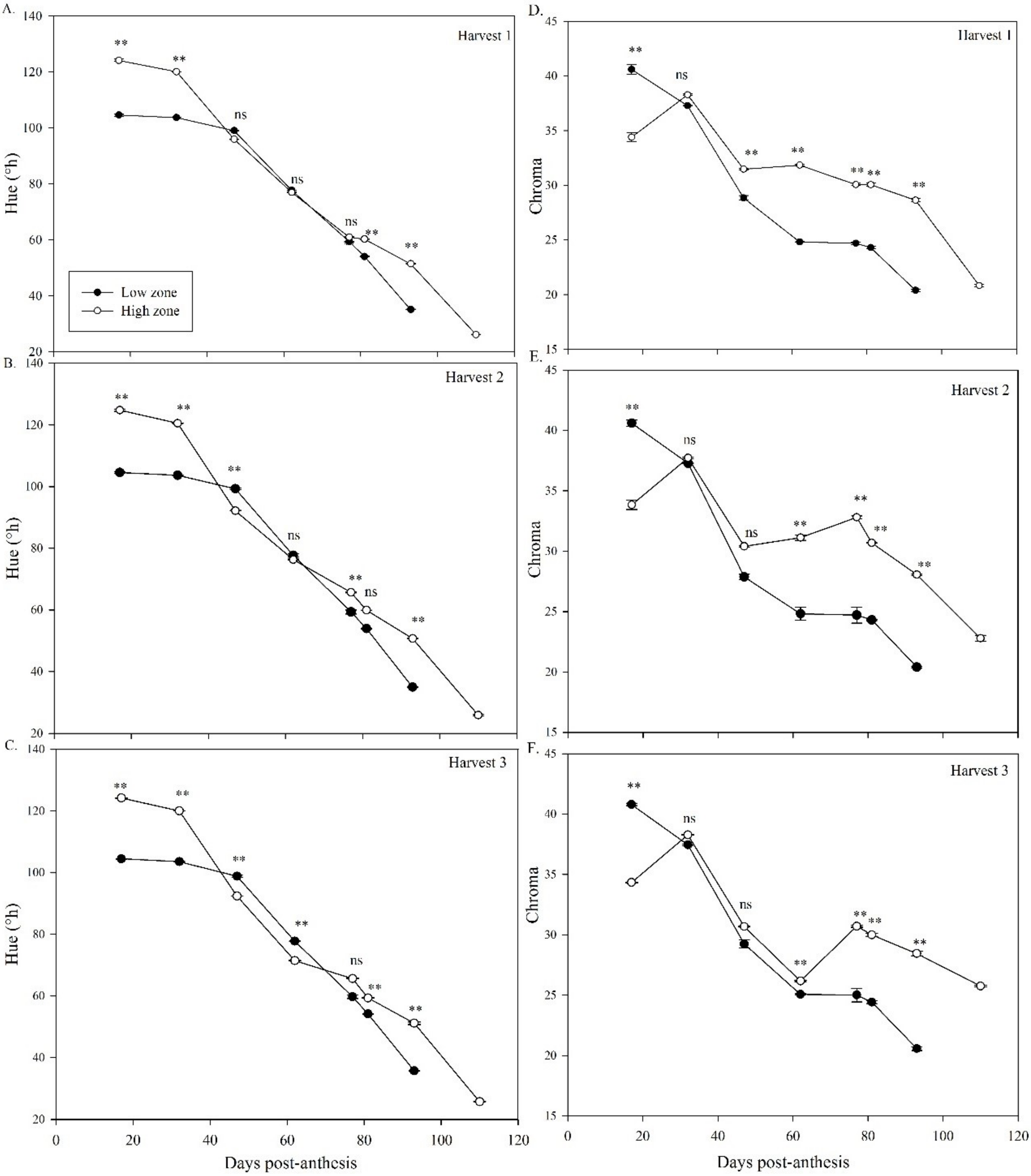


** Significant at p ≤ 0.01, ns no significant, according to the Student t test at each sampling point

Figure 3. Firmness of the epidermis and pulp for plum fruits in the low (2195 m a.s.l.) and high zones (2567 m a.s.l.) in the Colombian tropics. A. Firmness of epidermis for Harvest 1. B. Firmness of epidermis for Harvest 2. C. Firmness of epidermis for Harvest 3. D. Firmness of pulp for Harvest 1. E. Firmness of pulp for Harvest 2. F. Firmness of pulp for Harvest 3. Vertical bars on each mean correspond to the standard error (n=10)

SS increased as the fruit developed in both zones and in all harvests. For tree harvest cycles, SS was higher ($p < 0.01$) in the low zone, with values above 14 °Brix at harvest (Figure 5). A lower altitude accentuates a higher SS content, a characteristic appreciated by consumers because the fruit is sweeter. This can be attributed to higher temperatures accelerating the conversion of starch to sugar and respiratory metabolism (Parra-Coronado et al., 2022). In kiwi, a higher SS has also been found at lower altitudes (Zenginbal & Ozcan, 2018), but in feijoa, the opposite result has been observed (Parra-Coronado et al., 2022).

A more pronounced effect was observed for the high zone in the parameters of weight, diameter, chrome, and firmness of the epidermis and pulp (Table 1). The highest fresh weight, diameter, and length were recorded in the high zone in three harvests, corresponding to the highest precipitation and relative humidity, as well as the highest accumulated solar radiation records during the fruit growth period (Figure 1). Therefore, higher radiation can induce greater photosynthesis in the fruit and in the leaves near the fruit. When any of these factors are lacking or reduced, the yield tends to be low (Fischer et al., 2024). Mayorga et al.

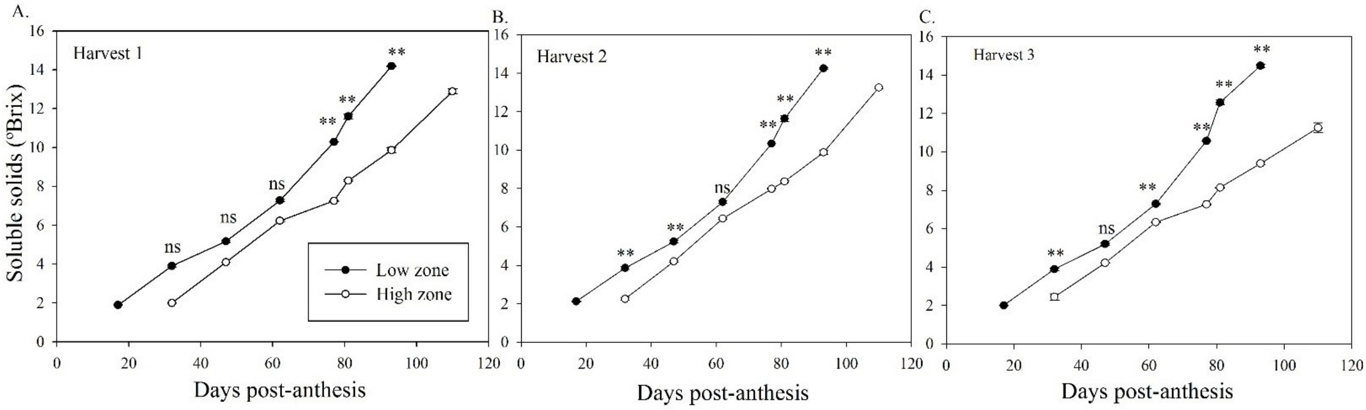


** Significant at p ≤ 0.01, ns no significant, according to the Student t test at each sampling point

Figure 4. Behavior of the hue and Chroma for plum fruit in the low (2195 m a.s.l.) and high zones (2567 m a.s.l.) in the Colombian tropics. A. Hue for Harvest 1. B. Hue for Harvest 2. C. Hue for Harvest 3. D. Chroma for Harvest 1. E. Chroma for Harvest 2. F. Chroma for Harvest 3. Vertical bars in each mean correspond to the standard error (n=10)

(2020) also found fruit with a greater weight and diameter at higher altitude zones.

In addition, the average data obtained in the tree harvest for weight and length were 6.29 g and 20.5 mm, respectively, for the low zone and 10.0 g and 23.6 mm, respectively, for the high zone. These variables had a close relationship with light utilization. A decrease in light utilization significantly affects fruit set and quality during tree growth. It was also observed that the harvests with the highest accumulated precipitation (corresponding to the high zone) and higher average relative humidity (Figure 1) produced heavier fruits. Parra-Coronado et al. (2007) found that plum cultivars tolerated 1500–2500 mm precipitation to ensure good fruit development and harvest quality. In fruit species, 1000–2000 mm of annual precipitation



** Significant at p ≤ 0.01, ns no significant, according to the Student t test at each sampling point

Figure 5. Behavior of the soluble solids (SS) for plum fruit grown in low (2195 m a.s.l.) and high zones (2567 m a.s.l.) in the Colombian tropics. A. Soluble solids for Harvest 1. B. Soluble solids for Harvest 2. C. Soluble solids for Harvest 3. Vertical bars in each mean correspond to the standard error (n=4)

Table 1. Average values of physicochemical characteristics in plum fruit at the time of harvest for the low (2195 m a.s.l.) and high zones (2567 m a.s.l.) in the Colombian tropics

Variable	Harvest 1		Harvest 2		Harvest 3	
	Low zone	High zone	Low zone	High zone	Low zone	High zone
Fresh weight (g)	5.7 ± 0.8 b	7.3 ± 1.6 a	5.8 ± 1.4 b	11.1 ± 1.5 a	7.3 ± 1.6 b	11.6 ± 3.0 a
Length (mm)	20.0 ± 1.6 a	18.8 ± 1.4 b	20.0 ± 1.6 b	23.1 ± 3.0 a	21.5 ± 1.6 b	26.7 ± 2.1 a
Diameter (mm)	19.4 ± 2.0 a	17.9 ± 1.4 b	19.4 ± 2.0 b	28.8 ± 1.8 a	20.8 ± 1.7 b	25.4 ± 1.9 a
SS (°Brix)	7.8 ± 0.1 a	7.0 ± 1.1 b	7.8 ± 1.0 a	7.1 ± 1.1 b	7.8 ± 0.1 a	7.2 ± 0.2 b
Maturity ratio	35.2 ± 12.1 a	28.6 ± 13.3 b	40.2 ± 1.2 a	31.3 ± 2.9 b	38.2 ± 4.1 a	29.6 ± 2.6 b
Hue (°h)	35.4 ± 1.3 a	26.1 ± 2.5 b	35.0 ± 2.6 a	25.9 ± 1.2 b	35.7 ± 2.4 a	25.8 ± 1.3 b
Chroma	20.39 ± 0.9 b	20.8 ± 1.5 a	20.4 ± 0.6 b	22.8 ± 2.5 a	20.6 ± 0.5 b	28.4 ± 0.1 a
Epidermis firmness (N)	22.9 ± 3.5 b	25.7 ± 1.1 a	20.8 ± 1.7 b	22.4 ± 2.0 a	22.7 ± 8.6 b	24.8 ± 6.2 a
Pulp firmness (N)	6.4 ± 0.8 a	5.2 ± 0.4 b	6.1 ± 0.8 a	5.1 ± 2.0 b	6.3 ± 1.8 a	5.0 ± 9.5 b

Average (n=10) ± SE - Averages followed by different letters within the same variable for each harvest indicate significant differences, according to the Student t test (p ≤ 0.05)

is required for growth, as the crucial phases in water demand are fruit set and filling. An adequate water supply ensures a high content of carbohydrates and acids in the fruit, as water is the main component of almost all cells, maintaining turgidity and serving as the reaction substrate for all biochemical processes (Fischer et al., 2012).

Regarding SS, statistical differences (p ≤ 0.05) are evident in the three harvests with higher values in the low zone; these results are consistent with the maturity ratio (Table 1). In the low zone, the temperature was higher. In tomato fruit, high temperature leads to a lower soluble sugar concentration (Pimenta et al., 2022), perhaps due to the lower carbohydrate reserves that fruit has as a result of higher temperatures. The range of hue variation indicates a significant and progressive shift from green to red hues. This chromatic transition is particularly appreciated in certain fruit, such as plums, because it determines harvest time, quality, and consumption preference. In the high zone, the lower °h and higher chroma in fruit indicated a more red color, associated with higher radiation in this zone (Figure 1). It also appears that lower temperatures (Figure 1) prior to harvest stimulate chlorophyll degradation and anthocyanin synthesis.

For the firmness of the epidermis and pulp, statistical differences (p ≤ 0.05) were observed between zones. The highest firmness values for both the epidermis and pulp were obtained at higher altitudes, indicating that climate has an important effect on Japanese plum quality, mainly the low temperature that diminishes the ripening process. These results are consistent with reports by Fischer et al. (2012), who linked climatic variables in certain cultivars with the distinctive characteristics at harvest.

Conclusions

1. Lower altitudes and climatic factors—namely temperature, precipitation, relative humidity, and solar radiation—positively influence the SS content and firmness of plum fruit. In contrast, higher altitudes were associated with increases in fruit weight and size.

2. The altitude significantly affected the maturation time of plums, with those cultivated at higher elevations requiring longer periods to reach harvest maturity. This effect was observed in each specific result regarding harvest characteristics.

3. Fruit grown at lower altitudes, where temperatures were higher, developed more rapidly. In contrast, fruit cultivated at higher altitudes required a longer maturation period.

Contribution of authors: M. Orjuela-Angulo designed the research, acquired and analyzed the data, and wrote the manuscript. H. E. Balaguera-López contributed to data analysis and interpretation, supervised the work, and wrote the manuscript. J. H. Camacho-Tamayo participated in the experimental design and manuscript supervision and correction.

Supplementary documents: There are no supplementary sources.

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

Financing statement: There was no funding for this research.

Acknowledgments: The authors thank Yaneth Alberto Rojas and Sandra Mendoza, support staff of the Laboratory of "Calidad y poscosecha de productos agrícolas" of the Universidad Nacional de Colombia, Bogotá.

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