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Mathematical models for determining the physicochemical properties during development of Japanese fruit plum in high tropic conditions

Modelos matemáticos para determinar las propiedades fisicoquímicas durante el desarrollo de ciruela japonesa en condiciones de trópico alto

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Plum fruit - cv. Horvin.

Photo: M. Orjuela-Angulo

ABSTRACT

Climatic conditions play a crucial role in plum fruit production, impacting harvest quality through physicochemical and physiological attributes. This study aimed to formulate a pre-harvest quality model based on the climatic conditions of the production area. In the municipality of Nuevo Colon, Boyaca, Colombia, 20 marked trees in locations A and B were measured during 2021 and 2022 (three harvests) at 10-day intervals from days 18 to 26 post-anthesis until harvest. Location A (at 2,195 m a.s.l., temperature mean of 23.36ºC, relative humidity mean of 79.93%, annual precipitation mean of 1,085.83 mm and solar radiation mean of 6.60 kW m^{-2}) and location B (at 2,567 m a.s.l., temperature mean of 15.96ºC, relative humidity mean of 91.75%, annual precipitation mean of 1,352.55 mm and solar radiation mean of 7.40 kW m^{-2}) were assessed. The results indicate that altitude, growing degree days, and precipitation significantly influence the fruit's physicochemical characteristics during its development. The multivariate analysis demonstrates that mathematical models obtained in this study, which best estimate the variables observed during fruit growth, related to the fresh weight, length, epidermis firmness and pulp firmness. The equations were derived for days after the anthesis in relation to altitude and growth degree-days. Furthermore, equations describing length and diameter variations in relation to fruit weight were established. Regression analysis showed that these models adequately estimated fruit properties during growth in both locations. These models will serve as input for determining the appropriate harvest time, in addition to providing a production projection for each cycle and managing cultivation practices.

Additional key words: days post-anthesis; pulp firmness; mathematical model; titratable acidity.

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RESUMEN

Las condiciones climáticas desempeñan un importante papel en la producción de ciruelas, impactando la calidad de la cosecha a través de atributos fisicoquímicos y fisiológicos. Este estudio tuvo como objetivo formular un modelo de calidad precosecha basado en las condiciones climáticas de la zona de producción. En el municipio de Nuevo Colón, Boyacá, Colombia, se marcaron 20 árboles en las localidades A y B tomando mediciones durante 2021 a 2022 (tres cosechas) en intervalos de 10 días, desde los días 18 a 26 post-antesis hasta la cosecha. Tanto la localidad A (2.195 msnm, 23,36°C, 79.93% humedad, 1.085,83 mm precipitación anual, 6,60 kW m^{-2} radiación solar) y B (2.567 msnm, 15,96°C, 91,75% humedad, 1.352,55 mm precipitación anual, 7,40 kW m^{-2} radiación solar) fueron evaluadas. Los resultados indican que la altura, los grados-día de crecimiento y la precipitación influyen significativamente en las características fisicoquímicas de la fruta durante el crecimiento. El análisis multivariado manifiesta que los modelos matemáticos obtenidos en este estudio, que mejor estiman las variables observadas durante el desarrollo del fruto, corresponden al peso fresco, la longitud, la firmeza de la epidermis y la firmeza de la pulpa. Se definieron ecuaciones para los días posteriores a la antesis en relación con la altitud y los grados-día de crecimiento. También se establecieron ecuaciones que describen las variaciones de longitud y diámetro en relación con el peso del fruto. El análisis de regresión mostró que estos modelos estimaron adecuadamente las propiedades del fruto durante el crecimiento en ambas localidades. Estos modelos servirán como insumo para determinar el momento adecuado de cosecha, además de proporcionar una proyección de producción para cada ciclo y gestionar las prácticas de cultivo.

Palabras clave adicionales: días post antesis; firmeza de pulpa; modelo matemático; acidez titulable.

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INTRODUCTION

Japanese plum (*Prunus salicina* Lindl.) 'Horvin' is a main variety cultivated in Colombia, in altitudes between 1,690 to 2,900 m a.s.l. (Fischer *et al*., 2012; Gutiérrez-Villamil *et al*., 2024). Plums are a deciduous crop that, in high tropical areas, with proper management, can yield up to three harvests in 2 years, and even staggered harvests throughout the year (Orjuela-Angulo *et al*., 2024a, 2024b; Gutiérrez-Villamil *et al*., 2024). The plum is highly valued for its nutraceutical properties, notably its high fiber and sorbitol content, which support digestion. Additionally, it is known for its antioxidant pigments and antiseptic effects due to anthocyanins (Rozo-Romero *et al*., 2015). According to the Agronet (MinAgricultura, 2025), between 2007 and 2023, the area planted with plums increased from 1,181 ha to 2,016 ha, with a slight decrease in the last three years. During this period, production has ranged from 12.7 to 14.9 t ha^{-1}.

Plum fruit shows important changes during the phenological stages of fruit development. So, the 'Horvin' plum fruit shows a decrease in respiratory intensity, titratable acidity, and firmness, and an increase in size and weight, soluble solids, and the maturity index as a function of growth time. These parameters reliably determine the optimal harvest time for plums, as well as the fundamental characteristics for the design of packaging and post-harvest storage and handling systems (Parra-Coronado *et al*., 2007). In high tropic climatic conditions, lower altitudes and climatic factors-namely temperature, precipitation, relative humidity, and solar radiation positively influence soluble solids content and firmness of plum fruits, while higher altitudes are associated with increases in the weight, size of the fruits and time to harvest (Orjuela-Angulo *et al*., 2024a).

Mathematical modeling involves fitting empirical data into mathematical formulas with a trend, attempting to determine a relevant prediction while minimizing error to the greatest extent possible, making it nearly negligible (Nde *et al*., 2024). Some models, such as stochastic ones, require a deeper mathematical understanding. It is known that models address situations, as certain responses obtained depend on the collected information and the desired level of precision (Cobuloglu and Büyüktahtakın, 2015). Simulation models refer to a set of equations representing variables with the aim of generating specific responses to real situations, allowing for the simulation of different alternatives (Rafique *et al*., 2024). According to Parra-Coronado *et al*. (2017), models accurately predicted the fruit characteristics during pineapple guava (feijoa) fruit development based on climatic factors. In plum fruit cultivated in tropical conditions these aspects are unknown. This information can be important to improve the crop system and to choose optimum areas for plum cultivation (Gómez-Ramos *et al*., 2024).

The objective of this study was to determine different pre-harvest models of plum fruits, depending on climatic conditions, to estimate some physicochemical characteristics during their development, in two locations in the Colombian high tropics.

MATERIALS AND METHODS

Study areas and vegetal material

The study was conducted in two locations (farms), situated in different areas within the municipality of Nuevo Colon (Boyaca, Colombia), as follows: Blanquita farm (location A) located at 5°20'17.56'' N and 73°27'53.85'' W, at an altitude of 2,195 m a.s.l.; Ana farm (location B), located between coordinates 5°21'26.5'' N and 73°28'10.8'' W, at an altitude of 2,567 m a.s.l. The precipitation in this area exhibits monomodal behavior, with average annual precipitation of 877.2 mm concentrated in the months from April to July (Orjuela-Ángulo *et al.*, 2022). These sites are characterized by being small parcels of land (smallholdings or "minifundios"), with a size less than 2 ha, for the boht study areas.

The plant material was Japanese plum (*Prunus salicina* Lindl.) 'Horvin' grafted on peach rootstock (cv. Blanco comun), these trees were planted approximately 25 years ago, similar for the two locations. Both locations underwent identical management practices, including pruning, irrigation, and fertilization, with the purpose of eliminating the influence of these practices on cultivation.

Two rows were selected for each location, and 10 trees were marked in each row, for a total of 20 trees per location and 40 trees in the present study. The selected trees in each location were taken from the central areas of the plots to avoid edge effects arising from uneven climatic conditions. Each tree from which samples were collected was marked to ensure their preservation. Markings of floral buds were made on the selected trees in the middle third of the canopy to study fruits growth throughout this research. Ten fruits were taken for each measurement performed in the laboratory.

Measurements of the physical and biochemical attributes of fruit quality

Sampling was conducted over three harvests for each location from 2021 to 2022. Sampling occurred every 10 d starting on the 18^{th} d (location A) and the 26^{th} d (location B) post-anthesis until harvest, which fruit growth, total soluble solids content (TSS), total titratable acidity (TTA), epidermal color expressed as hue angle (°h), and fruit firmness were determined.

The growth variables determined for the harvest included the determination of the fresh weight of the fruits and their respective dimensions (polar and equatorial diameters). For the determination of unit weight, an OHAUS electronic balance with a precision of 0.01 g was used (OHAUS Corporation, Parsippany, NJ, USA). The titratable acidity (TTA) was determined using a METROHM Ti Touch-916 titrator (Metrohm AG, Herisau, Switzerland). An HANNA HI 96801 refractometer with a measurement range up to 85% (°Brix) was used for total soluble solids (TSS) determination (HANNA Instruments, Woonsocket, Rhode Island, USA). Firmness was assessed using a LLOYD LS1 texture analyzer (Lloyd Instruments, West Sussex, UK) and, where applicable, a medium puncture durometer. For the color variable, a Minolta CR-400 colorimeter (Konica Minolta, Ramsey, NJ, USA) was employed. The maturity ratio (RM) was determined based on the ratio between TSS/TTA. The above variables were determined according to the methodology proposed by Parra-Coronado and Hernández-Hernández (2008). The experimental design was completely randomized, with five repetitions per trial.

Meteorological data and estimation of growth degree-days

Periodic records of climatic variables in the study areas (ambient temperature, solar radiation, relative humidity, precipitation) were collected. For temperature and relative humidity records, USB dataloggers were utilized (Uni-Trend Technology, Dongguan City, China), allowing the programming of data collection frequency (every half-hour), followed by subsequent data retrieval. In order to validate the information above, the Agrometeorological Station (cat) Nuevo Colon, located at coordinates 73°27'23.4" W and 5°21'13.7" N (IDEAM code 35075010), was available. Rain gauges were installed in each location to determine precipitation, with measurements taken each time a rainfall event occurred. Solar radiation in each location was measured using a pyrheliometer (Sku-Lppyrhe16, Senseca, Caselle di Selvazzano, Italy; spectral response 200 to 4,000 nm, Range: 0 to 2,000 W m^{-2}), which has a receptive surface capturing solar rays' incident perpendicularly on its surface.

Thermal time (TT) was calculated following the methodology used by Orjuela-Angulo *et al*. (2022), where thermal time was calculated based on the difference between the daily mean temperature and the base temperature, as expressed below (Eq. 1):

$$TT = \sum_{i=1}^{n} GDC_i = \sum_{i=1}^{n} GDD_i \rightarrow TT = \sum_{i=1}^{n} (Ti - nTb) \quad (1)$$

Where *TT* is the accumulated thermal time (°Cd) during the *n* days of fruit growth until harvest: *Ti* is the daily mean temperature (°C) for day *i*, and *Tb* is the base temperature (°C), which was 1.78°C for the present study. The growth degree days (GDD) for the accumulation of *TT* are calculated using the following considerations (Eq. 2, 3 and 4):

$$Ti = \frac{Tmax + Tmin}{2} \quad (2)$$

$$If\ Ti > Tb, GDC_i = Ti - Tb \quad (3)$$

$$If\ Ti < Tb, GDC = 0 \quad (4)$$

Where *T* max is the maximum temperature (°C) for day *i*, and *T* min is the minimum temperature (°C) for day *i* (Orjuela-Angulo *et al*., 2022).

Experimental design and statistical analysis

The experimental design was completely randomized, with five repetitions per trial. To identify differences between the means of the variables analyzed between locations, the *t*-student test was performed, for the same variable and harvest period. All analyses were performed with the statistical software SPSS v.20 (Chicago, IL), through which the principal component analysis (PCA) was conducted. For carrying out these analyses, the data were previously standardized, with mean 0 and variance 1. According to Manly (1997), this PCA reduces dimensionality and reveals the different basic components, which are called principal components (PC). Each PC is obtained from new components, as a linear combination of the initial variables. The first PC is associated with the largest eigenvalue, which contains the maximum value of the total variance. The second PC is the next linear combination, uncorrelated with the first PC, which represents the maximum residual variance, and so on, until the variance is entirely accounted for. It is advantageous for a little number of PC to explain a large proportion of the total variance; that is, the data set can be defined in a reduced dimensional space. Through this technique, the aim is to identify principal factors in a set of information while simultaneously observing the distances between the categories of the original variables. Subsequently, quadratic, exponential, and hierarchical linear regression models are developed (Pinzón-Sandoval *et al*., 2021). The purpose of this analysis is to identify which variables have the greatest impact on obtaining the suggested models.

A model was determined for each of the variables measured during fruit development, based on the climatic conditions encountered at each location during the three harvests. Polynomial, exponential, and sigmoidal equations were tested for this research. For the adjustment and selection of each model, the following statistical criteria were used: coefficient of determination (R^2) and the lowest root-mean-square error (RMSE).

Considering that R^2 indicates what proportion of the variability of the dependent variable is explained by the independent variables in a regression model, some impact begins to manifest with R^2 values greater than 0.3. Therefore, if R^2 is greater than 0.7, it can be considered that there is a strong correlation between the variables analyzed. However, when R^2 is between 0.3 and 0.7, there is some degree of correlation between both variables, but a more detailed analysis is required to determine the strength of the correlation (Gao *et al*., 2023). According to Parra-Coronado *et al*. (2017), an R^2 value between 0.66 and 0.81 indicates adequate predictive performance, a value of R^2 between 0.82 and 0.90 reveals good prediction, and models with an R^2 value greater than 0.91 are considered excellent.

Following the procedure shown by Parra-Coronado *et al*. (2017), to assess the goodness of the selected models, data not considered from variables for model construction (observed values) were used for cross-validation between observed and simulated values. For this purpose, one of the three randomly chosen harvests studied in each location was selected. The coefficient of determination (R^2), the concordance index (Eq. 5), and the root mean square error (RMSE, Eq. 6) were calculated to observe the trend of the overall model.

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(|P_i'| + |O_i'|\right)^2}\right], 0 \leq d \leq \quad (5)$$

Where n is the number of observations, P_i is the predicted value for the i-th date, O_i is the observed value for the i-th date, P_i' is the mean of the predicted values ($P_i - \overline{O}$), O_i' is the mean of the observed values ($O_i - \overline{O}$), ($\overline{O}$) is the overall mean of the observed values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (6)$$

Where n is the number of observations, Pi is the predicted value for the i-th date, and Oi is the observed value for the i-th date (Orjuela-Angulo *et al*., 2022).

RESULTS AND DISCUSSION

The mean values show a significant difference, with higher TSS values observed for locality B, diameter, maturity ratio, hue angle, epidermal firmness, and pulp firmness parameters (Tab. 1). It is important to note that the values of fruit quality parameters at the time of harvest may be influenced by the climatic conditions during crop growth. According to Parra-Coronado *et al*. (2017) each cultivar and harvest may be uniquely affected by climatic changes throughout its development, which, in turn, directly impacts fruit quality at the time of harvesting. Climatic conditions such as temperature, humidity, solar radiation, and precipitation play a decisive role in the process of fruit growth and ripening. For instance, a warmer season or more hours of sunlight can expedite fruit development and ripening, positively affecting sugar concentration and sensory quality, such as taste and color Parra-Coronado *et al*. (2017).

Mathematical models in thermal time for fruit length and diameter

Equations 7 and 8 represent the fruit length and diameter in relation to weight, and equation 9 represents a relationship for days post anthesis as a function of GDD, H, and HR.

$$Da = 27.919e^{0.05}\ R^2 = 0.85\ \textit{Typical error} = 4.33 \quad (7)$$

$$Db_c = 35.41e^{-0.11W}\ R^2 = 0.91\ \textit{Typical error} = 2.49 \quad (8)$$

$$DPA = 0.16H - (87.57GDD) + (20.66RH^{0.01})\ R^2 = 0.71\ \textit{Typical error} = 1.25 \quad (9)$$

Where Db_c for fruit polar diameter (mm), D_a for fruit equatorial diameter (mm), W for fruit weight (g), RH for relative humidity (%), H for altitude (m a.s.l.), and GDD for growing degree days (°C). These variables contribute to equations that describe the relationships between fruit dimensions, weight, and the elapsed time since anthesis, with the fitting of these equations ranging between 0.80 and 0.95.

In table 2, the relationship between days post-anthesis (DPA) and thermal time (GDD) for plum fruit is evident. In the case of location A, plum fruit development requires 1,470 GDD and 67 DPA to reach

Table 1. Mean values of the physical and chemical characteristics in the plum fruit at three harvest time for study localities (A and B).

Parameter	Harvest 1		Harvest 2		Harvest 3	
	Locality A	Locality B	Locality A	Locality B	Locality A	Locality B
Fresh weight (g)	5.65 b	7.31 a	5.76 b	11.06 a	7.31 b	11.65 a
Length (mm)	20.04 a	18.82 b	20.04 b	23.11 a	21.45 a	26.76 b
Diameter (mm)	19.36 a	17.9 b	19.36 b	28.75 a	20.75 b	25.38 a
TSS (ºBrix)	7.75 a	7.04 b	7.78 a	7.11 b	7.80 a	7.23 b
Ripening relation (%)	35.23 a	28.56 b	40.22 a	31.25 b	38.2 a	29.58 b
Hue angle (ºh)	340.19 b	324.12 a	340.22 a	318.77 b	340.74 a	318.23 b
Skin firmness (N)	25.67 a	22.91b	22.41 a	20.81 b	24.88 a	22.67 b
Pulp firmness (N)	6.41 a	5.22 b	6.12 a	5.07 b	6.26 a	4.99 b

Means followed by different letters for the same parameter indicate significant differences between locations for the same harvest time, according to the t-Student test ($P \leq 0.05$).

harvest, whereas for location B, it necessitates 1,835 DCD and 93 DPA. This indicates that, for fruit development, the higher-altitude location requires a greater number of calendar days as well as a higher quantity of GDD. GDD describes physiological processes influenced by temperature (Lescano Vega, 2016). Various studies demonstrate that GDD differs for each crop to be established (Parra-Coronado *et al*., 2015). GDD is employed to calculate growth and development in plants, serving as a physiological time parameter used to determine certain phenological periods involving the appearance of new organelles and, consequently, projecting cultivar production (Urbina, 2015). According to the inherent characteristics of plants, when temperature, one of the predominant factors in growth and development, increases, processes accelerate. As a result, at lower altitudes, the accumulated growth days are fewer (Parra-Coronado *et al*., 2015).

Table 2. Equivalence between days post anthesis (DPA) and growing degree days (GDD) of the plum fruit for the study locations (A and B).

Locality A (2,195 m a.s.l.)		Locality B (2,567 m a.s.l.)	
DPA (day)	GDD (°C)	DPA (day)	GDD (°C)
18	584.15	26	366.95
23	673.75	31	453.85
28	770.80	36	545.55
33	864.05	41	642.75
38	949.40	46	730.88
43	1,054.05	51	944.25
48	1,157.75	56	1,045.55
53	1,262.45	61	1,134.8
58	1,369.50	66	1,220.55
67	1,470.05	71	1,309.50
		76	1,409.80
		81	1,531.55
		86	1,627.95
		93	1,835.35

Each of the variables was adjusted according to the different proposed models. For the case of DPA as a function of GDD, altitude, and relative humidity, it shows a good fit (Eq. 9) for linear models, in contrast to quadratic, simple exponential, and sigmoidal logistic models. This aligns with findings reported by Parra-Coronado *et al*. (2016). According to the growth models obtained (Eq. 7, 8 and 9), it can be observed that they are not linear but show three stages. The first stage is growing but not directly linear, a second stage with a brief linear pause where the pit is formed, and a third stage where total growth occurs.

Based on the above description, for location A, GDD for these three stages behave as follows: the first stage from DPA 18 to 33 with 864 GDD, the second stage from 33 to 48 DPA with 1,157 GDD, and total growth in 67 DPA with 1,470 GDD. Location B behaves very similarly for the three stages: the first stage from 26 to 41 DPA with 642 GDD, the second stage from 41 to 66 DPA with 1,220 GDD, and total growth in 93 DPA with 1,835 GDD. This behavior is reported by Pinzón *et al*. (2014) for peach fruits. Fischer *et al*. (2012) observed that fruits indeed undergo three stages of development and growth, with the last phase characterized by a more pronounced increase in fruit volume, a phenomenon observed in both study locations (Tab. 1).

Principal components analysis of the fruit parameters

Following the principal component analysis (Tab. 3), it indicates that the most influential variables for model development belong to the group of the first component (CP1). These variables include weight, epidermal firmness (Firepi), pulp firmness (Firpul), total soluble solids (TSS), days post-anthesis, altitude (H), radiation (Rad), precipitation (P), and average relative humidity (HR). In the second component (CP2), influential variables include fruit diameter (Db_c) and growing degree days (GDD). For the third component (CP3), it was found that the most influential variables are diameter (Da) and hue angle (°h). Although Total Titratable Acidity (TTA) is not present as an influential variable in the first three principal components, it will be considered for the development of mathematical models as it is deemed an important variable in the quality of plum fruits. Additionally, it presents a communal value exceeding 0.70.

For the first principal component (PC1), which explains 59.54% of the accumulated variance, the climatic variables with the greatest influence in the first principal component (CP1) are altitude, precipitation, relative humidity, and radiation. The dependent variables that have the greater contribution on this component are SST, fruit weight, epidermal firmness, and pulp firmness. The variables with the greatest

Table 3. Integrated multivariate analysis of Japanese plum fruit characteristics and agroenvironmental factors in Boyaca (Colombia), represented by the first three principal components.

Variable	CP1	CP2	CP3	Communalities
Weigth (g)	**0.90**	0.15	0.22	**0.89**
Equatorial diameter (mm)	0.19	-0.38	**0.85**	**0.90**
Polar diameter (mm)	0.47	**-0.71**	0.32	**0.82**
Hue angle (°h)	0.10	0.13	**0.93**	**0.89**
Epidermal firmness (N)	**0.78**	0.20	0.07	0.53
Pulp firmness (N)	**-0.82**	-0.30	-0.09	**0.81**
Total soluble solids (°Brix)	**0.96**	0.06	0.04	**0.93**
Total titratable acidity (%)	0.60	-0.51	-0.25	**0.72**
Post-anthesis days	**0.98**	0.16	0.08	**0.71**
Altitude (m a.s.l.)	**0.98**	0.16	0.08	**0.98**
Growing degree days (°C)	0.30	**0.83**	-0.03	**0.98**
Radiation (ΣW m^{-2})	**0.97**	0.22	0.07	**0.97**
Precipitation (Σmm)	**0.98**	0.16	0.08	**0.79**
Relative humidity average (%)	**0.98**	0.14	0.08	**0.98**
Eigen value	8.34	1.91	1.84	
Variance (%)	59.54	13.61	13.15	
Cumulative variance (%)	59.54	73.15	86.31	

CP1, CP2, CP3: principal components 1, 2, and 3 respectively. Values > 0.7 (absolute value) appear bold.

contribution, both climatic and fruit, are closely related to each other, with the firmness of the pulp showing an inverse correlation with the other variables analyzed. For the second principal component (CP2), contributing 13.61% of the variance, the independent variable with the greatest impact is GDD, while the dependent variable that has the most influence on this component is Fruit Diameter (Db_c, mm).

For the third principal component (CP3), contributing 13.15% of the variance, the dependent variables with the greatest impact are length and hue (°h). This aligns with Podestá (2002), who considers that the color and weight of plum fruits (the color generally changes from pale red to bright red, and the weight tends to increase) change in the last week of their physiological maturity stage (Molina-Ochoa *et al*., 2015). Additionally, one of the principal components with greater weight was relative humidity. Regarding the climatic conditions used for modeling from this climatic variable, it is necessary to affirm that the altitude, along with relative humidity and precipitation, are fundamental factors for pulp development in plum fruits.

According to Parra-Coronado *et al*. (2007), in a study conducted on plum variety Horvin in the same municipality (Nuevo Colon-Boyaca), some climatic conditions can influence the growth and development of fruit production, such as altitude, precipitation, and relative humidity, which is similar to this research. According to Africano-Pérez *et al*. (2016), during the growth of peaches (*Prunus persica* L.), an interesting transformation process occurs in their appearance and composition. As they progress in their development, these fruits undergo changes in color, texture, and nutrient content. In the early stages of growth, peaches show a green epidermis due to the presence of chlorophyll, which are the pigments responsible for the green color in plants. However, as they mature, chlorophyll begins to degrade, and pigments such as anthocyanins and carotenoids lead to the reddish and yellowish hues characteristic of ripe peaches, which aligns with the results obtained in this research. An indicator of physiological maturity is color, which determines the precise moment for harvest.

According to Africano-Pérez *et al*. (2016), color changes indicate when to harvest to avoid losses due to overripening. Another important variable of physiological maturity is firmness, which, according to Fischer *et al*. (2012), decreases as fruits develop due to the reaction of some enzymes present in the fruit tissues, consistent with the findings in this research.

Considering only altitude (Tab. 4), it is observed that for the first principal component (CP1), which contributes 50.86% of the variance, the preharvest quality variables with the highest impact are weight, SST, and Firpulp (decreasing), considering only °H as the climatic variable. For the second principal component (CP2), contributing 19.28% of the variance, the preharvest quality variable with the highest impact is Da and hue angle (°hue). For the third principal component (CP3), contributing 15.16% of the variance, the dependent variable with the highest impact is TTA. The analysis shows high communalities, indicating that the extracted components represent the quality variables well. The results align with the observation that the weight of plum fruits at harvest was higher for those produced at a higher altitude (locality B), where the accumulated solar radiation is greater (7.6 kW m^{-2}), which is consistent with the findings of Parra-Coronado *et al*. (2015) for pineapple guava fruits grown at different altitudes.

Cepeda *et al*. (2021) show similar trends in Anna apple fruits, indicating that fruits produced at higher altitudes had lower GDD values, with 455.39 and 589.32 GDD and 45 and 60 DDA, which aligns with the current research. It was also observed that one of the principal components with the highest coefficients, 0.99, is the accumulated precipitation (corresponding to locality B), and higher average relative humidity (Tab. 1), which produced fruits with greater length and diameter. This aligns with Parra-Coronado *et al*. (2007), who state that a plum cultivar requires annual precipitation between 1,000 and 2,000 mm and is tolerant within the range of 1,500 to 2,500 mm to ensure good fruit development and quality at harvest.

Mathematical models for plum fruit quality variables based on climatic conditions

The models were obtained considering the variables with the greatest impact, according to the results of the multivariate analysis. For this research, variables such as weight (W), epidermis firmness (Firepi), pulp firmness (Firpul), TSS, TTA, hue angle (hue), as well as climatic variables GDD, H, P, RH were considered.

To select the best-fitting model, equations of exponential, hierarchical linear, and polynomial types were evaluated. The second-degree polynomial model was chosen because it best fits the dependent and independent variables.

Equation for fruit weight (W)

The proposed mathematical models for fruit weight based on thermal time showed a good fit, with a high R^2 value and low typical error.

$$W = 0.058e^{(0.01H) + (10.78GDD) + (0.056P) + (0.058RH) + (0.29)}$$

$$R^2{=}0.85 \; \textit{Typical error} = 2.2$$

Equation for fruit equatorial fruti (Da)

$$Da = (H + 0.00000267GDD + 0.00000056P + 0.00075RH)^2 + (H\text{-}0.0135GDD + 0.0018P + 0.0058HR) + 76.23$$

$$R^2 = 0.63 \; \textit{Typical error} = 1.45$$

Equation for fruit polar diameter (Db_c)

$$Db_c = (-0.00000026H + 0.0000089GDD - 0.0000396P + 0.001RH)^2 + (H - 0.033\mathrm{GDC} + 0.00018P + 0.0013RH) + 146.5$$

$$0.75 \; \textit{Typical error} = 1.56$$

Equation for epidermis color (hue)

$$hue = (-0.000051H + 0.00019GDD + 0.0000763P + 0.003RH)^2 + (0.039H - 0.092GDD + \mathrm{P}{+}0.001RH) + 1822.02$$

$$R^2 = 0.60 \; \textit{Typical error} = 2.57$$

Equation for total titratable acidity (TTA)

$$TTA = (0.00000022\,H + 0.00000106GDD + P{+}\,0.00001RH)^2 + (H + GDD\text{-}0.00000133P + 0.003RH) + 0.715$$

$$R^2 {=}0.60 \; \textit{Typical error} = 2.57$$

Equation for epidermis firmness (FirEpi)

$$Firepi = (H + 0.000031GDD + 0.00000011P + 0.00015RH)^2{+}(0.003H{+}0.00446GDD + 0.004P + 0.00005RH) + 15.87$$

$$R^2 = 0.71 \; \textit{Typical error} = 1.20$$

Equation for pulp firmness (FirPul)

$$Firpul = (0.00012H + 0.00003GDD + 0.000035P + 0.00075RH)^2 + (H + GDC + 0.0000012P + 0.0019RH) + 5.69$$

$$R^2 = 0.75 \; \textit{Typical error} = 0.88$$

Equation for total soluble solids (TSS)

$$STT = (H + 0.000056GDD - 0.001P + 0.0012RH)^2 + (-0.007H + GDD + 0.0010P + 0.000081RH) + 84.91$$

$$R^2 = 0.86 \ \textit{Typical error} = 1.21$$

Where W: fruit weight (g), TTA: total titratable acidity (% citric acid), TSS: total soluble solids (°Brix), Firepi: epidermis firmness (N), Firpul: pulp firmness (N), hue: fruit epidermis color; hue angle (°h), H: Altitude of the production area (m a.s.l.), GDD: growing degree days (°C), GDD: Average relative humidity (%), HR: Cumulative precipitation (mm) recorded in the area.

The fruit weight was fitted to a modified exponential model, while the other fruit characteristics (TTA, TSS, firmness, and hue) were fitted to second-order hierarchical quadratic models.

In table 4, the values of the model evaluation through cross-validation are presented by comparing the weight, length, diameter, color, TTA, TSS, Firepi, Firpul, predicted and observed lengths and diameters during fruit growth. The cross-validation evaluation and regression analysis parameters show that the models with the best prediction based on climatic conditions (altitude, GDD, precipitation, and relative humidity) correspond to the weight of the fruits, pulp firmness, and STT content, with R^2 values exceeding 0.7. Regarding statistical agreement, the intercept is not significantly different from zero, these estimates reflect good goodness between the estimated (Y) and observed, additionally, the fit shows that in some central tendency models, the regression root mean square error (RMSE) was acceptable, which is consistent with the research of Parra-Coronado *et al*. (2017), where for pineapple guava cultivation in the proposed selection models for fruit quality, variables such as altitude, GDD, precipitation, among others, are involved, showing a successful goodness of fit in the proposed models.

Variables that do not have an impact are discarded because including all considered variables would result in a cumbersome model when calculating the dependent variable. In consideration, a mathematical model that combines them could be established; therefore, the most impactful variables determined in the multiple components analysis are considered.

CONCLUSION

The mathematical models obtained will enable predictions related to the evolution of plum fruit quality during the growth and development stage. These predictions serve as input to determine the opportune moment for fruit harvesting, providing

Table 4. Integrated multivariate analysis of Japanese plum fruit characteristics considering altitude as the climatic variable in Boyaca (Colombia), represented by the first three principal components.

Variable	CP1	CP2	CP3	Communalities
Post-anthesis days	**0.99**	0.02	0.01	**0.97**
Altitude (m a.s.l.)	**0.99**	0.02	0.01	**0.98**
Weight (g)	**0.92**	0.12	0.04	**0.87**
Equatorial diameter (mm)	0.21	**0.91**	0.07	**0.87**
Polar diameter (mm)	0.56	0.55	0.41	**0.78**
Total titratable acidity (°Brix)	**0.92**	0.04	0.27	**0.92**
Total titratable acidity (%)	0.49	-0.05	**0.82**	**0.91**
Hue angle (°*h*)	0.20	**0.85**	-0.29	**0.85**
Epidermal firmness (N)	0.72	-0.05	-0.25	0.58
Pulp firmness (N)	**-0.87**	0.05	0.16	**0.79**
Eigen value	5.09	1.93	1.52	
Variance (%)	50.86	19.28	15.16	
Cumulative eigenvalue (%)	50.86	70.14	85.30	

* CP1, CP2, CP3: principal components 1, 2, and 3 respectively. Values > 0.7 (absolute value) appear bold.

an approximate value for the potential yield in each cycle. Additionally, they facilitate timely implementation of cultural practices such as pruning, irrigation, etc.

The results from this research demonstrate that relative humidity (RH), growing degree days (GDD), altitude (H), and precipitation (P) are the climatic variables that have the most significant impact on the physicochemical characteristics of plum fruit throughout its development.

The model based on altitude, GDD, precipitation, and relative humidity shows a good fit for variables such as total soluble solids (TSS), pulp firmness (firpul), epidermis firmness (firepi), length, diameter, and weight.

Cross-validation parameters reveal that models for weight, TSS, and pulp firmness, considering climatic variables such as altitude, GDD, precipitation, and relative humidity for plum fruit development prediction, exhibit a high coefficient of determination, indicating that the points closely align with the regression line.

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