

## Determining of thermal time and base temperature during the reproductive phase of the Japanese plum in the tropical Andes

Determinación del tiempo térmico y temperatura base durante la fase reproductiva de la ciruela japonesa en los Andes tropicales

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**Ripe Japanese plum fruit cv. Horvin.**

Photo: M. Orjuela-Angulo

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## ABSTRACT

Climate factors affect the phenological behavior of Japanese plum (*Prunus salicina* Lindl.) cultivation in tropical elevation. Thermal time is more precise than chronological time for the cultivation labor program and for the estimation of crop phenological events. The objective of this study was to determine the base temperature (Tb) and thermal time for the development of the 'Horvin' plum fruit, estimating the Tb for the reproductive phenological phase of the plum. Twenty trees, consisting of ten trees per row at two different elevations of 2,195 and 2,567 m a.s.l. (meters above sea level), in the municipality of Nuevo Colon (Colombia), were marked by locality. The appearance of each phenological stage was recorded from floral bud to harvest, estimating Tb with the minimum coefficient method of variation in function of growing degree day (GDD). The results show Tb for the phenological stages floral-anthesis with 2.84°C; anthesis-fruits set, 3.05 °C, and fruit set-harvest, 1.76°C. Therefore, this variety should be grown where there is a minimum temperature of 3.05°C during the reproductive phase. In addition, the results show that an average of 1,243.17 and 1,172.12 GDD is required to go from fruit set to fruit harvest at elevations 2,195 and 2,567 m a.s.l., respectively.

**Additional key words:** *Prunus salicina*; tropical elevation; growing degree days; phenological phases; minimum coefficient of variation.

## RESUMEN

Los factores climáticos afectan el comportamiento fenológico del cultivo de ciruelo japonés (*Prunus salicina* Lindl.) en la altitud tropical. El tiempo térmico es más preciso que el tiempo cronológico para la programación de labores culturales y para la estimación de eventos fenológicos del cultivo. El objetivo de este estudio fue determinar la temperatura base (Tb) y el tiempo térmico para el desarrollo del fruto de ciruela 'Horvin', estimando la Tb para la fase fenológica reproductiva de la ciruela. Se marcaron por localidad veinte árboles, diez árboles por surco, en dos elevaciones diferentes: 2.195 y 2.567 msnm (metros sobre el nivel del mar), en el municipio de Nuevo Colón (Boyacá, Colombia). La aparición de cada estado fenológico se registró desde el botón floral hasta la cosecha, estimando la Tb con el método de coeficiente

mínimo de variación en función de los grados día de crecimiento (GDC). Los resultados muestran las  $T_b$  para los estados fenológicos botón floral-antesis con  $2,84^{\circ}\text{C}$ ; antesis-cuajado de fruto  $3,05^{\circ}\text{C}$  y  $1,76^{\circ}\text{C}$  cuajado de fruto-cosecha. Por lo tanto, esta variedad debe cultivarse donde haya una temperatura mínima de  $3,05^{\circ}\text{C}$  durante la fase reproductiva. Además, los resultados revelan que se requiere un promedio de 1.243,17 y 1.172,12 GDC, para pasar del cuajado a la cosecha del fruto en las elevaciones 2.195 y 2.567 msnm, respectivamente.

**Palabras clave adicionales:** *Prunus salicina*; elevación tropical; grados día de crecimiento; fases fenológicas; coeficiente mínimo de variación.

## INTRODUCTION

The different levels of thermal energy affect the development of many crops in their phenological stages (Kukal and Irmak, 2018; Shivers *et al.*, 2019). Phenology registering is led through periodic and systematic observations of a variety of plant species over time. This information is used to understand trends and patterns in plant life cycles, their growth and their relationship with seasonal and climatic changes. This is because the phenological development stages depend on interactions between genetic and environmental conditions, particularly air temperature (Chaves *et al.*, 2017). Thus, phenological studies enable the evaluation of fruit crop adaptation according to determining local climatic conditions and the application of this knowledge for the improvement of crop management practices (Cepeda *et al.*, 2021; Pinzón-Sandoval *et al.*, 2021).

Calendar time is used to predict crop growth and development stages (Leguízamo-Medina *et al.*, 2022; Pinzón-Sandoval *et al.*, 2022). Moreover, some models have been proposed and adjusted. Furthermore, some models have been proposed and adjusted to use the calendar time in predicting crop development, describing the predominant effect of temperature on phenological development (Criollo-Escobar *et al.*, 2020). Several methods for determining growing degree days (GDD) or thermal time involve calculating the sum of the difference between the mean temperature and the base temperature (or temperature base,  $T_b$ ), estimated from the mean temperature of daily maximum and minimum temperatures (Cepeda *et al.*, 2021; Pinzón-Sandoval *et al.*, 2022). The GDD method is one of the most widely-recognized for describing fruit growth, as this type of model is independent of a particular date (Orjuela-Angulo *et al.*,

2022). GDD for each phenological phase is also known as thermal time, physiological time, or heat units (López *et al.*, 2014). To apply this method, a value of  $T_b$  or critical or minimum temperature required for crop development is established. It is considered that crops will not advance in their growth if the daily temperature is below that base value (Parra-Coronado *et al.*, 2015a; Woznicki *et al.*, 2019).

For each plant phenological stage the  $T_b$  is different, as reported previously in different fruit crops (Parra-Coronado *et al.*, 2015a; Orjuela-Angulo *et al.*, 2022). Estimating the  $T_b$  in GDD is possible through several statistical methods using the least standard deviation in days, the lowest coefficient of variation, or linear regression using the methods of regression coefficient and intersection x (Parra-Coronado *et al.*, 2015a). Therefore, the base temperature statistically results in the least variance of GDD accumulation (thermal or physiological time), which means a measure of accumulated heat over a specified time (Salazar-Gutiérrez *et al.*, 2013; Parra-Coronado *et al.*, 2015a; Akbar, 2019). The accumulation of daily mean temperature is a widely used procedure in agriculture. This method is based on quantifying the amount of degree days needed to end a phenological phase (Pinzón-Sandoval *et al.*, 2021; Leguizamo-Medina *et al.*, 2022). It is important to determine the temperature requirement for each crop, and thus predict the changes in the phenological stage.

The accuracies of thermal time models allow the date of different development stages to be predicted (Salazar-Gutiérrez *et al.*, 2013). These predictions are partially dependent on the precision of the  $T_b$ , indicating the need to determine the critical temperature at each phenological stage (Díaz, 2020). Once the  $T_b$  has been identified, the moment when the stages cease their metabolic processes will be known (Orjuela-Angulo *et al.*, 2022). Various models exist for predicting climates and crops, which interact in various ways with crop phenology and in turn the physiological thermal time of each plant (Cepeda *et al.*, 2021; Pinzón-Sandoval *et al.*, 2022).

Degree days are a measure that combines time and temperature in the development of any living organism; as the temperature increases, the cycles of these living beings generally decrease (Leguizamo-Medina *et al.*, 2022; Orjuela-Angulo *et al.*, 2022). Thermal time is expressed as the number of heat units required to complete plant development (Leguizamo-Medina *et al.*, 2022; Orjuela-Angulo *et al.*, 2022). In agriculture, degree days have been shown to be a useful and reliable tool for determining the ripening date of fruits. This method is based on monitoring and

accumulating thermal units over time, allowing for a more accurate prediction of the time when fruits will reach their optimal ripening (Parra-Coronado *et al.*, 2015a). The degree day model, based on the accumulation of thermal units higher than base temperature threshold, is a simple and valuable tool for predicting the vegetative and reproductive development of plants (Salazar *et al.*, 2008; Parra-Coronado *et al.*, 2015a). However, this model also has certain limitations associated with the impact of extremely high or low temperatures on crop growth (Woznicki *et al.*, 2019).

The accumulation of GDD has been calculated in several fruit trees such as 'Hass' avocado (Ramírez-Gil *et al.*, 2023), peach (Pinzón-Sandoval *et al.*, 2021; 2022), apple (Cepeda *et al.*, 2021), European plum (Shivers *et al.*, 2019), lulo (Criollo-Escobar *et al.*, 2020), cape gooseberry (Salazar *et al.*, 2008; Syropoulou *et al.*, 2022), banana passion fruit (Mayorga *et al.*, 2020), and feijoa (Parra-Coronado *et al.*, 2015a). Most of these are fruit trees grown in high tropics.

The Japanese plum (*Prunus salicina* Lindl.) is considered the most promising crop in the Boyaca department, which is located in the eastern mountain range of Colombia, at elevations between 1,800 and 2,800 m a.s.l. (Fischer *et al.*, 2022; Gutiérrez-Villamil *et al.*, 2024). It is therefore considered fundamental for new production models (Serrano *et al.*, 2021). This Japanese plum is a deciduous species, requiring fewer chill hours to break its winter dormancy than European plum (*Prunus domestica* L.), making it better adapted to high tropical zones (Campos, 2013; Gutiérrez-Villamil *et al.*, 2024). In Colombia, 80% of Japanese plum crops are of the Horvin variety, which is marketed nationwide in cities such as Cali, Popayan, and Bogota, among others (González-Romero *et al.*, 2018). This crop has been established as an alternative for sustainable economy, by farmers who are mostly small and medium producers (Campos, 2013; Gutiérrez-Villamil *et al.*, 2024). A Tb of 2.9°C was reported for the period between fruit set and harvest in *P. salicina* (Orjuela-Angulo *et al.*, 2022). However, the Tb for the other fruit phenological stages, which would serve as a technical tool for better crop management by allowing the accumulation of GDD in Andean zones to be identified accurately, is still unknown. Considering to the above, the objective of this study was to determine the base temperature and thermal time for phenological stages between floral bud and fruit harvest of 'Horvin' plum under high tropical Colombian conditions.

## MATERIAL AND METHODS

### Study areas, plant material and growing conditions

The study was conducted in two localities in the municipality of Nuevo Colon, Boyaca department (Colombia), in locality A (Blanca farm, 5°20'17.56" N and 73°27'53.85" W), at a lower elevation of 2,195 m a.s.l., and locality B (Ana farm, 5°21'26.5" N and 73°28'10.8" W), at a higher elevation of 2,567 m a.s.l. These two farms had rootstock of 'Durazno blanco común', grafted with scions of Japanese plum, Horvin variety (*Prunus salicina* Lindl.) with an age between 20 and 30 years. In the study, 10 trees were selected from each row, with 2 rows per farm (locality), totaling 40 trees.





The study area is characterized by a cold, humid climate with "Thornthwaite classification" B2d B1 and mean temperature of 15.6 to 23.4°C for the two localities. Precipitation in this area has a monomodal behavior, with average annual precipitation values of 877.2 mm.

The study was conducted in two phases. For first phase, the base temperature ( $T_b$ ) was calculated and, in the second part, the duration in growing degree days (GDD) was estimated in order to predict the periods of floral bud-anthesis, anthesis-fruit set, and fruit set-harvest. The study includes the recording of the floral bud date and daily meteorological data such as relative humidity, temperature, including maximum and minimum temperatures (°C), precipitation, and solar radiation for each locality. The data was collected over three harvest cycles.

For temperature and relative humidity records in each locality UNI-T brand USB data loggers, accuracy  $\pm 0.5^\circ\text{C}$  (UT330B IP67, Osaka, Japan), with a data collection frequency set to every 20 min were used. To determine the precipitation in each plot, 35 mm capacity rain gauges from Opitec brand (Rocafort-Barcelona, Spain) with 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 CHP1 Inmisión IEC 100-4-4 pyrhe-liometer (Delft, Netherlands) with radiant flux from a solid angle of  $5^\circ$ , and a receiving surface that captures the radiation incident perpendicular to its surface.

The phenological stages are presented in table 1 and the dates of the phenological stages are described in table 2. In this study, the date of the fruit set was reported at 17 d after observing the floral cluster.

**Table 1. Phenological stages of 'Horvin' plum evaluated in this study.**

Floral bud		Anthesis	
			
Fruit set		Riped fruit	
			

**Table 2. Registration dates for the phenological stage of floral bud-anthesis, anthesis-fruit set, fruit set-harvest for the 'Horvin' plum, during three harvest cycles.**

Phenological stage	Harvest	Locality A (2,195 m a.s.l.)	Locality B (2,567 m a.s.l.)
Flower bud marking	1	Jun 20, 2021	August 6, 2021
	2	March 27, 2022	March 12, 2022
	3	August 20, 2022	August 24, 2022
Flower emergence	1	July 18, 2021	August 26, 2021
	2	April 7, 2022	April 4, 2022
	3	September 13, 2022	September 26, 2022
Fruit set	1	August 3, 2021	September 15, 2021
	2	April 22, 2022	April 25, 2022
	3	September 29, 2022	October 17, 2022
Harvest	1	September 25, 2021	November 29, 2021
	2	Jun 25, 2022	Jun 30, 2022

	3	November 24, 2022	December 11, 2022
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Similarly, cultivation practices were recorded in each location, in order to observe whether they are assumed or not, as input variables, which will influence the output or response variables. Crop management, including fertilization, pruning, pest and disease control and other procedures, was carried out according to established practices in the region.

### **Estimation of base temperature (T<sub>b</sub>)**

The T<sub>b</sub> for each of the following plum fruit phenological stages was estimated: from floral bud-anthesis, anthesis-fruit set, and fruit set-harvest. The sum of the temperatures recorded in each studied location was made for each phenological stage from floral bud. Then, the coefficient of variation (CV) of the calculated heat units (GDD) was minimized, based on a temperature range between 0 and 12°C, for each of the different stages considered in this study, according to the proposal by Parra-Coronado *et al.* (2015b).

The determination of the optimal temperature for the T<sub>b</sub> of each stage is based on identifying the temperature at which the lowest coefficient of variation is achieved, using a second-degree regression model (Orjuela-Angulo *et al.*, 2022). The Solver tool for Excel<sup>®</sup> was used for the estimation of T<sub>b</sub>. Solver is an iterative nonlinear procedure. The process begins by using a set of initial values for the parameters of the equation. Then, using the Solver tool, these values are gradually adjusted, either increasing or decreasing them, with the aim of finding the minimum value of the deviations. The deviation refers to the difference between the values obtained from the equation and the actual or expected values (Parra-Coronado *et al.*, 2015a).

### **Estimation of thermal time (GDD)**

One degree day is accumulated when the average daily temperature is 1 degree higher T<sub>b</sub>, for a period of 24 h (Parra-Coronado *et al.*, 2016). For this study, it was necessary to know the date of bud appearance in each location and harvest.

Thermal time was calculated based on the difference between T<sub>b</sub> and the average temperature, and the daily sum was then deduced (Eq. 1).



$$TT = \sum_{i=1}^n GDD_i = \sum_{i=1}^n (T_i - T_b) \rightarrow TT = \sum_{i=1}^n (T_i - nT_b) \quad (1)$$

Where  $TT$  is the accumulated thermal time ( $^{\circ}\text{C d}$ ) over  $n$  days until the appearance of the state, from fruit set to harvest:  $T_i$  is the daily average temperature ( $^{\circ}\text{C}$ ) for day  $i$  and  $T_b$  is the base temperature ( $^{\circ}\text{C}$ ). The  $GDD$ , for the accumulation of  $TT$ , are calculated using the following considerations (Eq. 2, 3 and 4):

$$T_i = \frac{T_{max} + T_{min}}{2} \quad (2)$$

$$\text{Si } T_i > T_b, \quad GDD_i = T_i - T_b \quad (3)$$

$$\text{Si } T_i < T_b, \quad GDD_i = 0 \quad (4)$$

Where  $T_{max}$  is the maximum temperature ( $^{\circ}\text{C}$ ) for day  $i$  and  $T_{min}$  is the minimum temperature ( $^{\circ}\text{C}$ ) for day  $i$  (Orjuela-Angulo *et al.*, 2022).

### Processing and data analysis

The GDD model was conceived by applying the necessary dataset for the identification of floral bud, anthesis, fruit set, and harvest. With the estimated  $T_b$ , the thermal time from floral bud to harvest was obtained for each location (farm), and these times were averaged for the considered phase.

The mean thermal time obtained from two different study areas was used to evaluate the proposed model, allowing a representative value of the accumulated temperature during the study period to be obtained. Subsequently, this mean thermal time value was determined based on a series of equations and parameters to simulate the behavior of certain phenomena or variables, in order to evaluate the accuracy and reliability of the model by comparing the simulated values with the observed values in both study areas. The linear model exhibited greater adjust than the other models evaluated, logistic, exponential, and logarithmic (data not shown).

This cross-validation is a double-sample, leave-one-out method that uses all input points to first estimate the parameters of one interpolation model and then the others. This type of validation allows us to visualize the goodness of fit of the data in the proposed model. The coefficient of determination ( $R^2$ ), the agreement index (Eq. 5), and the growth curves simulated with the adjusted mathematical method correctly described the behavior of GDD and its TT. In this way, for the different thermal time measurements from bud to flower (for the three harvests) it was 465.32, while for the stage from flower to fruit set it was 322.76, and from fruit set to harvest it was 1207.91. In this way, the evaluated thermal time variable is confirmed as an adequate criterion for determining thermal time throughout the phenological stage of the crop with good GDD performance for the establishment of the cultivar under observed and estimated conditions (Orjuela-Angulo *et al.*, 2022; León-Burgos *et al.*, 2022).

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

Where ( $n$ ) is the number of observations, ( $P_i$ ) the predicted value for the  $i$ -th date, and ( $O_i$ ) the observed value for the  $i$ -th date,  $P_i' = P_i - \bar{O}$  and  $O_i' = O_i - \bar{O}$ , where the overall mean of the observed values is  $\bar{O}$  (Parra-Coronado *et al.*, 2015a).

## RESULTS

### Climatic conditions and floral buds

Regarding the climatic conditions during the three cycles of phenological stages in the two farms and elevations, notable differences were observed (Tab. 3). In locality A (2,195 m a.s.l.), the average for the three cycles was as follows: mean temperature 23.36°C; radiation 6.6 kW m<sup>-2</sup>; average relative humidity (RH) 79.9%; and total accumulated precipitation 1,085.9 mm. For locality B (2,567 m a.s.l.), the values were 15.96°C; 7.4 kW m<sup>-2</sup>; 91.7%; and 1,352.6 mm, respectively. Therefore, locality A had a higher temperature, but lower values of radiation, HR, and accumulated precipitation.

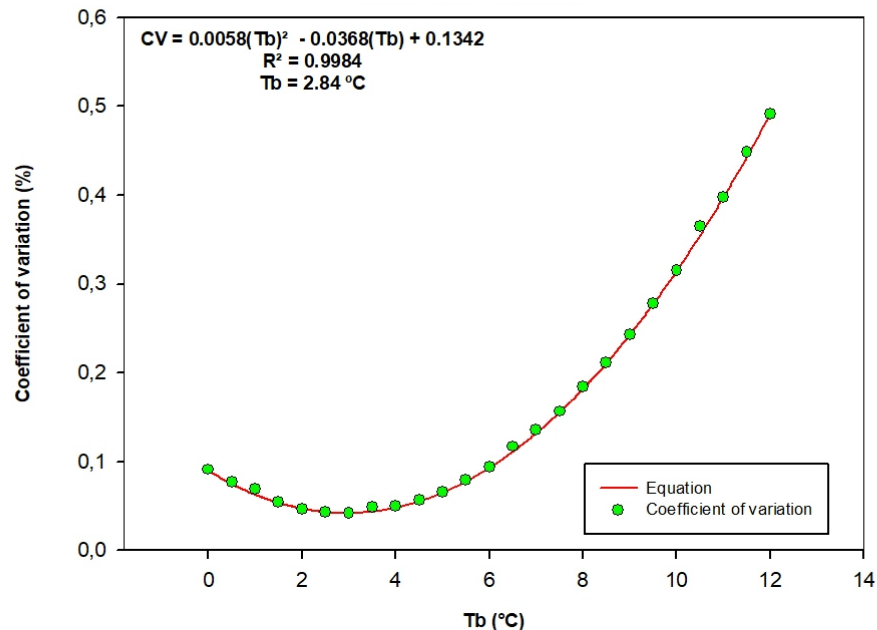
Floral bud amount differs between the two locations (Tab. 3). In location B, at 2,567 m a.s.l., there is a lower amount of floral bud (2,726) and therefore a lower number of fertilized units (246) for the three harvests, while in location A, at 2,195 m a.s.l., the amount of floral bud for the three harvests was 3,070, with 282 fertilized units.

**Table 3. Temperature, solar radiation, relative humidity, and precipitation for the stage from floral bud to harvest, floral bud amount, and number of fertilized units for each locality.**

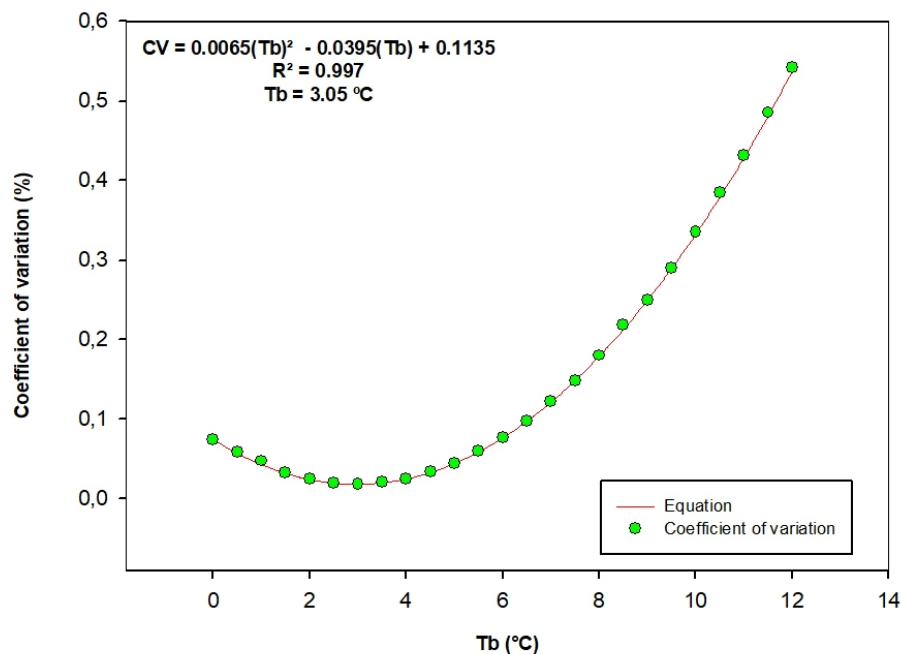
Locality	Harvest	Mean temperature (°C)	Solar radiation (kW m <sup>-2</sup> )	Relative humidity (%)	Precipitation accumulated (mm)	Amount of floral buds	No. fertilized units
Locality A (Blanca farm, 2,195 m a.s.l.)	1	20.14	6.6	86.6	1,285.2	880-1100	80
	2	24.57	6.7	79.8	1,122.2	895-1126	92
	3	25.36	6.5	73.4	850.2	920-1220	110
Locality B (Ana farm, 2,567 m a.s.l.)	1	15.61	7.2	91.6	1,489.3	850-950	91
	2	15.92	7.4	92.5	1,222.9	870-950	84
	3	16.36	7.6	91.1	1,345.5	905-928	71

### Estimation of base temperature (T<sub>b</sub>)

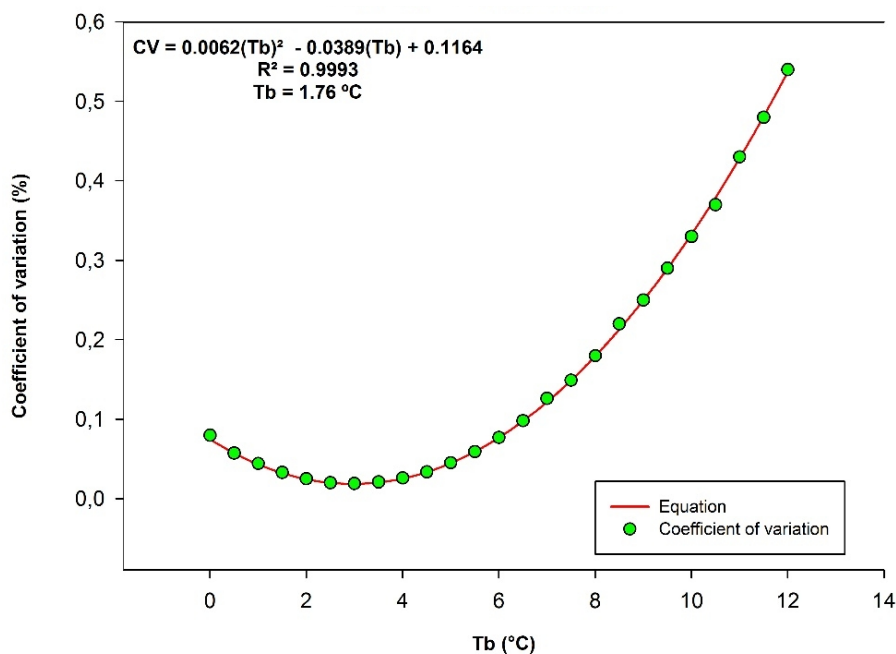
Since T<sub>b</sub> is essential for fruit development, some statistical methods have been performed to obtain it in a simpler way. The values that had an appropriate fit were those found by the coefficient of variation method, which were 2.84°C with  $R^2=0.99$  for phenological stages of floral bud to anthesis (Fig. 1). This was followed for anthesis to fruit set with 3.05°C and  $R^2=0.99$  (Fig. 2), and finally 1.76°C adjusted to  $R^2=0.99$  for fruit set until fruit harvest (Fig.3).



**Figure 1. Base temperature (Tb), estimated by the coefficient of variation, from the flower bud to the appearance of the flower in 'Horvin' plum, cultivated in tropical conditions. Where the base temperature is a function of the coefficient of variation, which is a dependent variable, where  $n$ -corresponds to the base temperatures obtained from least squares for each phenological stage.**



**Figure 2. Base temperature (Tb), estimated by coefficient of variation, from flower to fruit set for 'Horvin' plum, cultivated in tropical conditions. Where the base temperature is a function of the coefficient of variation, which is a dependent variable, where  $n$ -corresponds to the base temperatures obtained from least squares for each phenological stage.**



**Figure 3. Base temperature (Tb), estimated by coefficient of variation, from fruit set to ripe fruit for 'Horvin' plum, cultivated in tropical conditions. Where the base temperature is a function of the coefficient of variation, which is a dependent variable, where  $n$ -corresponds to the base temperatures obtained from least squares for each phenological stage.**

### Estimation of thermal time (GDD)

Japanese plum cultivation varies according to the thermal time and the number of days needed to reach each of the phenological stages. Values of GDD for the stages from floral bud to harvest, for the two study locations are presented in table 4. The lowest accumulation of GDD was from anthesis to fruit set, followed by floral bud to anthesis, while the highest accumulation of GDD was observed from fruit set to harvest with 1,243.17 and 1,172.12 GDD for Locality A and B, respectively.

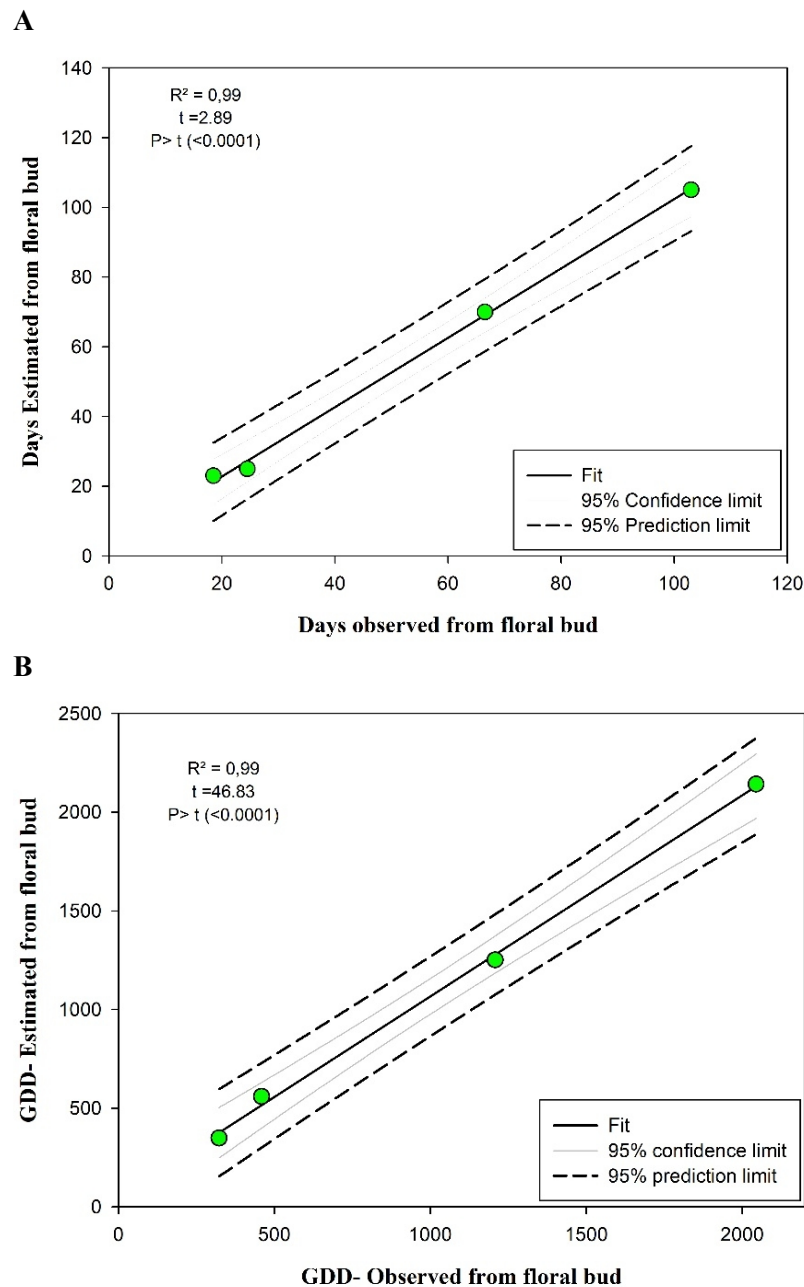
According the phenological stages, Japanese plum cultivation requires 465.31 GDD from floral bud to anthesis, 322.75 GDD from anthesis to fruit set, and 1,207.64 GDD from fruit set to harvest. This indicates that the time required to go from floral bud to harvest in calendar days varies from 94.1 for location A, in contrast to locality B where it is 110.3 d, meaning the farm at 2,567 m a.s.l., needed about 16 more days to complete its reproductive phase (Tab. 4).

**Table 4. Thermal time (GDD) and calendar time (d) for the phenological stages of 'Horvin' plum fruit in study localities A (2,195 ma.s.l.) and B (2,567 ma.s.l.).**

Development stage	Tb (°C)	Thermal time (GDD)		Calendar time (d)	
		Locality A	Locality B	Locality A	Locality B
From floral bud to anthesis	2.84	459.09±130.22	471.54±91.14	21.0±7.25	20.3±0.47
From anthesis to fruit set	3.05	306.82±42.90	338.69±32.20	15.33±0.47	20.33±0.48
From fruit set to harvest	1.76	1243.17±199.92	1172.12±41.43	57.66±4.92	69.6±3.39

The number of days required from floral bud to anthesis varies from 21 d (locality A) to 20.3 d (locality B); for anthesis until fruit set, it varies from 15.3 d (locality A) to 20.3 d (locality B); and from fruit set to harvest, it ranged from 57.7 d (locality A) to 69.6 d (locality B), data presented in table 4.

The validation of the models using the cross-validation method between predicted and observed days (Fig. 4A) shows that the model accurately predicts the number of days to reach each phenological stage when the estimated Tb value was determined for each stage. It was observed that the intercept and the slope are close to 1, which indicates a good fit between the estimated (y) and observed (x) values, as well as a high  $R^2$ . For the validation of the models, the cross-validation method between observed and estimated GDD was used (Fig.4B). The analyses show that the model accurately predicts the GDD required to reach each phenological stage. It was also observed that the intercept is not significantly different, and the slope is equal to 1. These results show a good fit between the estimated (y) and observed (x) values, as well as a high coefficient of determination.



**Figure 4. Cross-validation using specific  $T_b$  values and comparison of estimated and observed days from floral bud to harvest (A), and comparison of estimated and observed GDD (B) for 'Horvin' plum, cultivated in tropical highland conditions.**

## DISCUSSION

The environmental conditions varied in the evaluated locations (Tab. 3), despite being at the same thermal level. These climate variations influenced the number of days required from floral bud until harvest in Japanese plum (Tab. 4), as previously reported by Trbic *et al.* (2022).

Variables such as temperature, precipitation, solar radiation, and evapotranspiration also affect data collection for Tb calculation (Parra-Coronado *et al.*, 2015a). Likewise, the climatic conditions influence, among other factors, the duration of phenological phases of the cultivar, fruit ripening, harvest times, and overall crop growth (Ramírez-Jiménez *et al.*, 2021). This has been related to the temperature and relative humidity control in the fruit development and growth rate (Zhang *et al.*, 2022), as reported for *P. salicina* by Orjuela-Angulo *et al.* (2024).

The 'Horvin' plums developed from floral bud to harvest in 94 d at 2,195 m a.s.l. farm, while at the higher and colder location, at 2,567 m a.s.l., it took 110 d. This longer duration in fruit development with increasing elevation in the Cundiboyacense region of Colombia was also found by Fischer *et al.* (2007) in cape gooseberry at 2,300 and 2,690 m a.s.l. (66 and 75 d), and Parra-Coronado *et al.* (2015a) in feijoa at 1,800 and 2,580 m a.s.l. (168 and 209 d, respectively). These results corroborate that at higher elevations, development is prolonged, mainly due to lower temperatures that slow down metabolism (Fischer *et al.*, 2024; 2022). This behavior of prolonging phenological phases at higher sites was also observed in the period from anthesis to fruit set, which required 20.3 d at 2,195 m a.s.l., compared to only 15.3 d at 2,567 m a.s.l.

According to the average temperatures recorded in the two locations (Tab. 3), the higher the elevation, the lower the temperature, a trend that has been shown to occur in mountainous regions (Fischer *et al.*, 2024; 2022; Parra-Coronado *et al.*, 2022). It has been found that temperature falls by between 0.6 and 0.7°C per 100 m increase in elevation (Benavides *et al.*, 2017), which agrees with the records in this study (Tab. 3). In contrast to temperature, solar radiation increases with increasing elevation in the study area, including ultraviolet radiation, because the atmospheric layer is thinner in higher areas and therefore filters less solar rays (Benavides *et al.*, 2017). This can bring advantages in fruit coloration, an important aspect in the commercialization of 'Horvin' plum (Fischer *et al.*, 2022).

On the other hand, while precipitation increased by 266.7 mm at 2,567 m a.s.l. compared to 2,195 m a.s.l., which is in opposite to Benavides *et al.* (2017), who suggest that precipitation shows an inverse relationship with solar radiation. This finding is probably due to the very particular microclimate in the area of the Nuevo Colon municipality where the study was carried out, where there is only one (prolonged) rainy season per year, compared to the rest of the areas of the Boyaca and Cundinamarca departments, where two rainy seasons per year prevail. In this



regard, Manz *et al.* (2016) indicate that precipitation patterns in the Andes are not sufficiently recorded due to their high spatial-temporal variability and the deficient network of rain gauges.

Since the production of floral buds for each location occurred in similar proportions, environmental conditions with a predominance of dry days increased the number of fertilized individuals in the floral clusters. This is similar to the findings of Orduz-Ríos *et al.* (2020), who state that the production of Japanese plum flowers is affected by the temperature and wind speed in the cultivation areas. Additionally, it was observed in location B (2,567 m a.s.l.) that, when ambient temperatures were below  $T_b$ , particularly when frosts occurred in January and February, some of the floral and newly set fruit organs suffered sudden detachments. The reason for the dropping of these organs due to frosts is that the surfaces of the tender and outer tissues of the flowers and newly set fruits cool below the temperature of the surrounding air as a result of heat exchange, which causes damage to the intracellular compartments and cell membranes (Voronkov *et al.*, 2019). This situation occurs especially on clear nights in high tropical areas. To avoid this form of damage in tree production, the fruit grower should schedule management practices so that the plants do not present these susceptible states during the coldest months of the year in high tropics.

The accumulation of thermal time for the first two phenological stages during the reproductive phase of 'Horvin' plum at 2,195 m a.s.l. is lower than for the location at 2,567 m a.s.l., while for fruit development from floral bud or fruit set, this relationship is inverse. This result indicates that the temperature accumulation during fruit development at the lower elevation is higher than at the higher elevation. This behavior agrees with what was reported by Pérez de Camacaro *et al.* (2017), where by fruits such as strawberries are affected by the environmental conditions in which they develop.

The lower accumulation of thermal time of the crop at 2,567 m a.s.l., mainly caused by the lower temperature at this elevation, led to the prolongation of fruit development by 12 d from its fruit set and by 16 d from the floral bud, compared to the lower elevation. This characterization is presented in table 4 where the calendar time was greater for location B, but inversely proportional to the accumulation of thermal time. This behavior is similar to that indicated by Salazar-Gutiérrez *et al.* (2013).

In many other studies to determine the  $T_b$  in thermal time estimation, a single temperature of  $10^{\circ}\text{C}$  has been used; however, in studies similar to the present one at tropical elevations, a different  $T_b$  was found for each of the reproductive phenological states (Mayorga *et al.*, 2020), which was almost always lower than  $10^{\circ}\text{C}$  (the 'standard  $T_b$ '). Thus, for the estimation of the  $T_b$  in the different stages of 'Horvin' plum development, the value is not constant but is found in a range between  $1.76$  and  $2.84^{\circ}\text{C}$ . To go from floral bud to anthesis, the  $T_b$  was  $2.84^{\circ}\text{C}$ , while to go from anthesis to fruit set it was  $3.05^{\circ}\text{C}$ , and from fruit set to harvest, only  $1.76^{\circ}\text{C}$  was required. These results complement the reports of Orjuela-Angulo *et al.* (2022), who only estimated a single value of  $2.9^{\circ}\text{C}$ . In this regard, Pinzón-Sandoval *et al.* (2022) indicate that knowing the climatic conditions of the cultivation site, plus the  $T_b$  at each stage of plant development, allows for better adaptation and application of good agricultural practices and, therefore, optimal crop management.

The lower  $T_b$  for the development of 'Horvin' plum fruit of  $1.76^{\circ}\text{C}$  could be due to the fact that the growing fruits are already better acclimated to the low temperatures of an orchard at altitude (Salazar *et al.*, 2008; Parra-Coronado *et al.*, 2015a), and present structures that are not as susceptible to cold compared to flowers or floral buds (Nicolás-Almansa *et al.*, 2023). For the growth of cape gooseberry fruit, Salazar *et al.* (2008) calculated a  $T_b$  of  $1.9^{\circ}\text{C}$ , while Mayorga *et al.* (2020) found a  $T_b$  of only  $0.01^{\circ}\text{C}$  for banana passion fruit, this fruit plant tolerates mild frosts.

As the results show, the calculation of the  $T_b$  is significant for each of the phenological states, allowing the generation of growth and development models and their related simulation, and the application of a single  $T_b$  value is not recommended (Orjuela-Angulo *et al.*, 2022; Parra-Coronado *et al.*, 2015a).

It is important to specify that in the two locations, there were no major temperature variations between the days of observation, but changes occurred from one elevation to another, which agrees with the records of Orjuela-Angulo *et al.* (2022) for Japanese plum, in four locations in the same area. This variability of the two study locations includes the calculation of thermal time (compared to calendar time alone), which can explain the differences in fruit maturity when observations made in different seasons are compared (Almanza-Merchán and Balaguera-López, 2009).

The 'Horvin' cultivar differs in the GDD required to reach each of the phenological states, where it was observed that, for the stage from floral bud to harvest for the location at 2,195 m a.s.l., the required thermal time was 2,054.78°C, while for the farm at 2,567 m a.s.l., it was 2,033.62°C (Tab. 4). Similar results were obtained by different authors who determined the GDD in different environments, for each phenological stage in different cultivars. Parra-Coronado *et al.* (2015a) determined the GDD for each of the phenological stages in the Quimba feijoa cultivar, finding that 196 GDD were required from floral bud to anthesis, 116 GDD from anthesis to fruit set, and 2,651 GDD from fruit set to fruit harvest. For 'Sampion' and 'Ligol' apples, 2,550 and 2,600 GDD, respectively, are required to reach harvest from full bloom, using a Tb of 0°C (Lysiak, 2012). Stenzel *et al.* (2006) considered a Tb of 12.8°C, finding that the thermal sum for the growth and ripening of 'Folha Murcha' orange fruit in Londrina and Paranavaí (Brazil) is in the range of 4,462 to 5,090 GDD. Finally, the parameters of the regression analysis and cross-validation show that the proposed models can predict the exact days of phase change (Pérez-Planells *et al.*, 2015).

## CONCLUSIONS

The results suggest that thermal time and base temperature requirements depend on the elevation where the Japanese plum cv. Horvin cultivation is established under Andean tropical conditions. The Tb values determined vary depending on the phenological stage of 'Horvin' plum fruit. They were found to be 2.84°C from floral bud to anthesis, 3.05°C for the anthesis until fruit set, and 1.76°C from fruit set to harvest. Therefore, this variety should be grown where there is a minimum temperature of 3.05°C during the reproductive phase.

The studied locations differ in the number of days required for plum fruit development. For location A, the duration was 57.7 d from fruit set to harvest, and for location B, it was 69.6 d. Regarding GDD values, these were found to be 1,243.17 for locality A and 1,172.12 for locality B. These results for Tb and thermal time are therefore very important tool for selecting suitable areas for cultivation and making decisions in the crop management practices of 'Horvin' plum under tropical conditions.

**Conflict of interests:** The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the

presented results.

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