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Model of pre-harvest quality of pineapple guava fruits (*Acca sellowiana* (O. Berg) Burret) as a function of weather conditions of the crops

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ABSTRACT: Weather conditions influence the quality parameters of pineapple guava fruit during growth and development. The aim of this study was to propose a model of pre-harvest fruit quality as a function of weather conditions in the cultivation area. Twenty trees were flagged per farm in 2 localities of the Department of Cundinamarca, Colombia: Tenjo (2,580 m.a.s.l.; 12.5 °C; relative humidity between 74 and 86%; mean annual precipitation 765 mm) and San Francisco de Sales (1,800 m.a.s.l.; 20.6 °C; relative humidity between 63 and 97%; mean annual precipitation 1,493 mm). Measurements were performed every 7 days during 2 harvest periods starting on days 96 (Tenjo) and 99 (San Francisco de Sales) after anthesis and until harvest. The models were obtained using Excel® Solver, and a set of data was obtained for the 2 different cultivar periods and each study site. The results showed that altitude, growing degree days, and accumulated precipitation are the weather variables with the highest influence on the physicochemical characteristics of the fruit during growth. The models of fresh weight, total titratable acidity, and skin firmness better predict the development of fruit quality during growth and development. Equations were obtained for increases of length and diameter as a function of fruit weight and for days from anthesis as a function of growing degree days and altitude. The regression analysis parameters showed that the models adequately predicted the fruit characteristics during growth for both localities, and a cross-validation analysis showed a good statistical fit between the estimated and observed values.

Key words: total soluble solids, total titratable acidity, firmness, growing degree days.

INTRODUCTION

Pineapple guava (*Acca sellowiana* (O. Berg) Burret) is a fruit from the Myrtaceae family, which is originally from South America (Parra-Coronado and Fischer 2013). It is a perennial, long-lived species that produces 1 annual harvest in temperate and subtropical regions and can produce continually in tropical regions (Quintero 2012). Pineapple guava is considered a promising crop for the Andean region of Colombia because of its excellent ability to adapt to areas between 1,800 and 2,700 m.a.s.l.

Fruit is defined as the priority storage organ for photoassimilates (Ardila et al. 2011), and this characteristic is determined by different factors, such as phloem transport, compartmentalization, metabolism (Ho 1996), and storage organ size. Significant differences among the physicochemical characteristics of pineapple guava fruit can be observed at collection for different cultivars and even among fruit produced by the same cultivar, and these characteristics also vary according to the position of the fruit in the canopy (Martínez-Vega et al. 2008) and are strongly related to prevailing environmental conditions during fruit growth.

According to Krug (1997), growth is a function of genotype and the environment and refers to the irreversible increase in dry matter or size and changes in shape, dimension, mass, or number of structures that produce a quantitative increase in size and weight of the plant organ (Ardila et al. 2011), as well as the physicochemical characteristics of the fruit (Parra-Coronado et al. 2015a). Studies of growth are useful for determining how fruits grow as a function of time, estimating fruit size and weight at the time of harvest (Avanza et al. 2008), predicting the optimal state for harvesting, analyzing the formation and structural development of fruits over time (Mazorra et al. 2006) and recommending crop management practices (Rojas-Lara et al. 2008).

Growth and variations in physicochemical characteristics can be quantified using models defined by mathematical expressions or functions that include a set of indices. A mathematical model can synthesize and increase knowledge on a system by evaluating possible management strategies and estimating potential yield, costs and benefits of using specific commercial transactions and cultural practices, such as fertilization and irrigation (López et al. 2005).

Salisbury and Ross (2000) indicate that certain fruits show double sigmoidal growth behavior, such as raspberry, grape, blackberry, olives, and stone fruits (peach, cherry, plum, etc.). Other fruits show simple sigmoidal growth curves, such as apple, tomato, pears, orange, pineapple, melon, avocado (Salisbury and Ross 2000), kiwi (Hall et al. 2006), and pineapple guava (Rodríguez et al. 2006).

Calendar time has been used to predict growth and developmental stages of crops (Salazar-Gutiérrez et al. 2013); however, to improve the use of calendar time in making predictions, certain models that describe the effect of temperature on phenological development have been proposed (Salazar-Gutiérrez et al. 2013). According to Parra-Coronado et al. (2015b), the method most frequently used is the cumulative mean daily temperature above a base temperature (Bt); this parameter is also known as thermal or physiological time, units of heat or growing degree days (GDD) or development, which is defined as the number of degree days required until a certain developmental process or phenological phase is complete (Trudgill et al. 2005). GDD is used to estimate the growth and development of fruits, calculate the rate of appearance of different plant organs (Almanza et al. 2010), and estimate potential yield (Salazar et al. 2008).

The aim of this study was to develop a model of pre-harvest pineapple guava fruit quality as a function of weather conditions that can predict the physicochemical characteristics of the fruit during development in different production areas.

MATERIAL AND METHODS
Study areas characterization

This study was performed in 2 sites with different altitudes in the Cundinamarca Department of Colombia, and the pineapple guava crops were from clone 41 ('Quimba') established in 2006. The different crop management activities (pruning, fertilization and others) were performed similarly at both sites to eliminate the influence of crop variables on the model development. The first site is located at the Tenjo Municipality between geographic coordinates lat 04°51′23″N and long 74°06′33″W; this site has a mean altitude (H) of 2,580 m.a.s.l., mean temperature of 12.5 °C, relative humidity between 74 and 86%, and mean annual precipitation of 765 mm under a bimodal regime concentrated between the periods March – May and September – November. The second site is located at the San Francisco de Sales Municipality between geographic coordinates lat 04°57′57″N and long

74°16′27″W; this site has a mean altitude of 1,800 m.a.s.l., mean temperature of 20.6 °C, relative humidity between 63 and 97%, and mean annual precipitation of 1,493 mm under a bimodal regime concentrated between the periods February – May and September – November.

Experimental design

Ten trees per plot and 2 plots per farm were chosen, and a total of 40 trees were used in this study. Therefore, 2 blocks of information were available per harvest per farm, which allowed additional information to be used for model validation. The trees subjected to the study were located at the center of the cultivated lot to maintain uniformity of weather conditions and eliminate edge effects. Each plant (sample unit) was numbered, and the flower buds were marked in the middle third of the canopy to monitor the growth and development of the fruit.

Sample collection

Samples were collected weekly from 10 trees on each plot, and 1 fruit was randomly picked per tree. To assess fruit growth, the samples were collected starting on day 99 after anthesis and until harvest at both sites. Sampling to determine total soluble solids (TSS), total titratable acidity (TTA), color of the skin (hue angle — °h), and fruit firmness was performed starting on day 99 for San Francisco de Sales and day 141 for Tenjo, when the fruits were sufficiently large enough for the respective analyses. This procedure was performed during 2 consecutive years (2012 to 2014) for 2 harvests per site. Meteorological data were obtained from automated iMETOS ECO D2 (Pessl Instruments GMBH, Weiz, Austria) weather stations that record daily data on temperature, precipitation, relative humidity, and total radiation.

Measured variables

The variables measured during fruit growth were as follows: individual fresh fruit weight variations (g), which was measured using a precision balance (0.0001-g approximation) and calculated with the gravimetric method; and fruit equatorial diameter and length (mm), which was measured with a manual digital caliper (0.01-mm precision). Variations in the skin and pulp firmness of the fruit were determined

with a Brookfield CT3-4500 texture analyzer (Brookfield Engineering, Middleboro, MA, USA) with a TA39 probe at ±0.5% accuracy, with 2 measurements performed per fruit. The Colombian technical standard NTC 4624 (ICONTEC 1999b) was applied when measuring TSS with an Eclipse refractometer (Bellingham Stanley, Tunbridge Well, UK) at a scale from 0 to 32 and precision of 0.2°. The TTA was determined following the Colombian technical standard NTC 4623 (ICONTEC 1999a). The maturity ratio (MR), which is defined as the ratio between the TSS and TTA, was determined. Epidermal color (°h) was measured using a Minolta CR-400 colorimeter (Konica Minolta, Ramsey, NJ, USA). All of the parameters were determined for fruits from each of the experimental plots, and the statistical analysis was entirely randomized with 5 repetitions per trial.

Estimation of thermal time

There are several methods for calculating GDD, but the most common is to obtain the mean of the daily maximum and minimum temperatures, subtract the Bt, and add the values obtained (Parra-Coronado et al. 2015b). The GDD method is the most appropriate for describing growth and development because it is independent of year and environment (Ritchie and Ne Smith 1991). According to Parra-Coronado et al. (2015b), the Bt value below which phenological development stops must be identified to use GDD. For pineapple guava, Parra-Coronado et al. (2015b) indicate that the B_t value estimated for fruit growth is 1.76 °C. The thermal time was calculated as the daily sum of the difference between the mean temperature and Bt for each stage (Parra-Coronado et al. 2015b):

$$TT = \sum_{i=1}^{n} GDD_i = \sum_{i=1}^{n} (T_i - B_t) \text{ or}$$

$$TT = \sum_{i=1}^{n} (T_i - nB_t)$$

(1)

where: TT is the thermal time (GDD) accumulated during n days of fruit growth; T_i is the average daily temperature (°C) for the i-th day.

The GDD_i values for the accumulated TTs are calculated as follows (Parra-Coronado et al. 2015b):

$$T_i = (T_{max} + T_{min})/2$$

(2)

if $T_i > B_t$, $\quad\quad$ $GDD_i = T_i - B_t$ $\quad\quad$ (3)

if $T_i < B_t$, $\quad\quad$ $GDD_i = 0$ $\quad\quad$ (4)

where: T_{max} is the maximum temperature (°C) for the i-th day; Tmin is the minimum temperature (°C) for the i-th day.

Model evaluations

Among the non-linear models used to characterize development and/or growth as a function of time, the logistic, exponential, monomolecular (Rojas-Lara et al. 2008; Ardila et al. 2011), and Michaelis-Menten (Rojas-Lara et al. 2008) models stand out. The logistic model combines exponential and monomolecular models, which are separated by an inflection point, and it is typically sigmoidal (Rojas-Lara et al. 2008). The exponential model is valid for continuous growth or reduction where conditions are always favorable (Rojas-Lara et al. 2008). The monomolecular model indicates that the rate of change in the plant's dry weight is determined by how much growth must still occur, which is the reason why growth rates show constant decreases.

To analyze fruit growth based only on the GDD value, the average data for each location were used and non-linear polynomial, exponential and sigmoidal models were initially used to determine variations in the fruit weight. Based on the best-fit equations for both locations, a single model was determined for the variables measured during growth. Based on the weather conditions recorded for each site, variables with higher coefficients of determination (R^2) and lower standard errors were selected. Considering that R^2 values indicate the percentage of variation of the dependent variable (Y) that is explained by the independent variables (Xi), R^2 values between 0.50 and 0.65 indicate that more than 50% of the variance in Y is explained by the variance in Xi. For the effect of weather conditions considered by the model, R^2 values greater than 0.5 indicate that a particular effect begins to be noticeable. R^2 values between 0.66 and 0.81 indicate an adequate predictive performance; R^2 values between 0.82 and 0.90 show good predictive performance; and R^2 values greater than 0.91 are considered excellent (Williams 2003).

Unique growth models were obtained for the length and diameter of fruits as a function of weight and for calendar days elapsed after anthesis as a function of GDD and H. The Excel® Solver tool was used to develop the models by including data from 2 different periods for each cultivar and location (1 plot per harvest). The data input for the models of each of the variables included the Bt value for fruit growth and daily meteorological records, with which thermal time (GDD), accumulated precipitation (P), mean relative humidity (RH), and total accumulated radiation (Rad) were obtained for each period studied.

The Excel® Solver was used to estimate the parameters in the unique models of the evaluated variables during fruit development. "Solver is an iterative non-linear procedure that performs the first estimation with the initial values assigned to the parameters in the equation, and those values are increased or decreased until the lowest value of the sum of the square of the deviations is obtained" (Parra-Coronado et al. 2015b).

The IBM-SPSS v.20 statistical package (Chicago, IL, USA) was used to perform a factor analysis by principal components, and a Varimax rotation was applied to display those variables that have a greater effect on the models. A statistical descriptive analysis was also performed. As complementary verification, a sensitivity analysis was performed with the Excel® Solver tool, which was used to adjust the models by adding weather variables to observe their influence over the R^2 value.

Each model was evaluated with data that were not used to produce the model. To show the goodness of fit of the model, a cross validation was performed between the observed and simulated values. The R^2 values, index of concordance (d; Equation 5) and root mean squared error (RMSE; Equation 6) were calculated to determine the performance of each of the models (Parra-Coronado et al. 2015b).

$$d = 1 - [(\textstyle\sum_{i=1}^{n} (P_i - O_i)^2)/(\textstyle\sum_{i=1}^{n} (P'_i + O'_i)^2)],$$
$$0 \le d \le 1 \quad\quad (5)$$

where: n is the number of observations; P_i is the predicted value for the i-th date; O_i is the value observed for the i-th date. The general mean of the observed values is Ō.

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

RESULTS AND DISCUSSION
Equations for longitude, diameter, and post-anthesis days

Unique growth equations were obtained for longitude and diameter as a function of fruit weight (Equations 7 and 8) and

for days elapsed from anthesis as a function of GDD and H (Equation 9). All of them showed a good statistical fit (R^2).

$$L = 19.70 \times W^{0.30} \quad (7)$$
$$R^2 = 0.94; \text{ Standard error} = 3.44$$

$$D = 9.67 \times W^{0.36} \quad (8)$$
$$R^2 = 0.98; \text{ Standard error} = 1.77$$

$$DaysPostAnt = (4.50E - 6 \times GDD + \\ + 2.40E - 4) \times (H^{1.26}) \quad (9)$$
$$R^2 = 0.99; \text{ Standard error} = 0.72$$

where: L is the fruit length (mm); D is the fruit diameter (mm); W is the fruit weight (g); DaysPostAnt is the time elapsed from anthesis (days).

Figure 1 shows a cross-validation evaluation of the models through comparisons of predicted and observed values for longitude and diameter during fruit growth as well as predicted and observed values for post-anthesis days. The cross-validation and regression analyses showed that the models adequately predicted longitude and diameter as a function of pineapple guava fruit weight and days post-anthesis as a function of GDD and H. Good statistical concordance was observed, the intercept was not significantly different than 0, and the slope was statistically equivalent to 1. These are expected estimates for a good statistical fit between estimated (Y) and observed (X) values. The high R^2, concordance index, and RMSE values reflect a good fit for models belonging to the production area.

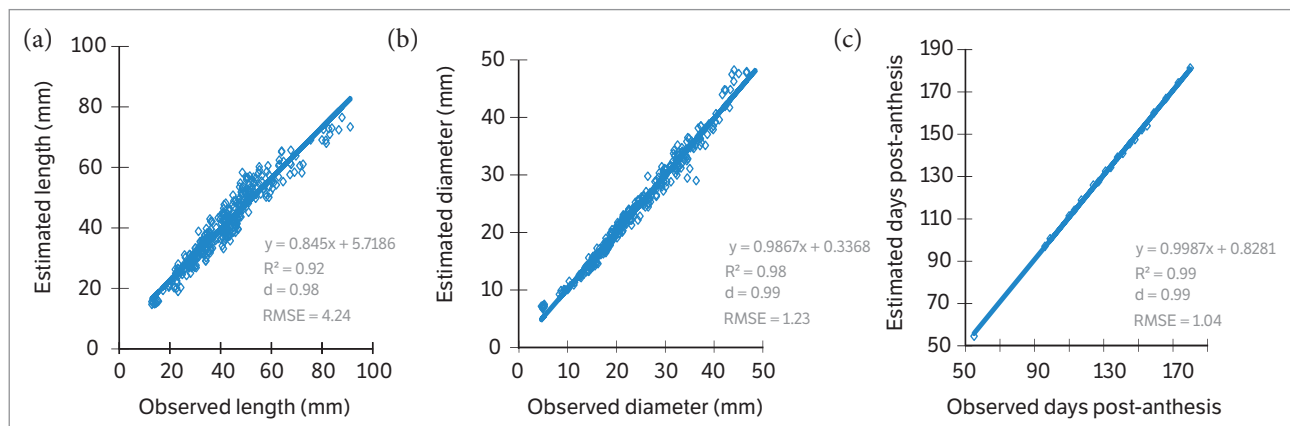Therefore, the models represented by Equations 7 and 8 may be used to determine the length and diameter of the fruit, and the model represented by Equation 9 may be used to estimate days elapsed since anthesis as function of H and TT in any of the areas that produce pineapple guava with altitudes between 1,800 and 2,580 m.a.s.l.

Mathematical models of thermal time for fruit weight

Table 1 shows the equivalence between days after anthesis (DAA) and thermal time (GDD) of pineapple guava fruits for the studied sites. Fruit growth requires 1,972 GDD (180 DAA) until harvest in Tenjo, whereas it

Table 1. Equivalence between days after anthesis and growing degree days of pineapple guava fruits for the studied sites.

Tenjo Altitude: 2,580 m.a.s.l.		San Francisco de Sales Altitude: 1,800 m.a.s.l.	
Days after anthesis	Growing degree days	Days after anthesis	Growing degree days
96	1,028	99	1,731
110	1,173	113	1,969
117	1,265	127	2,209
124	1,353	134	2,328
131	1,434	141	2,447
138	1,512	148	2,563
145	1,587	155	2,677
152	1,661		
159	1,739		
166	1,816		
173	1,896		
180	1,972		

Figure 1. Cross validation of the physical characteristics of pineapple guava fruits and post-anthesis days. (a) Validation of the model for longitude as a function of fresh weight; (b) Validation of the model for diameter as a function of fresh weight; (c) Validation of the model for days post-anthesis as a function of thermal time (GDD) and altitude (H) of the cultivation area.

requires 2,677 GDD (155 DAA) in San Francisco de Sales. This finding indicates that, for higher altitudes, a higher number of calendar days are required for growth until harvest. However, fewer GDD will be required because this value depends directly on the temperatures recorded at each location.

Fruit weight as a function of GDD was adjusted to different types of growth curves for fruits produced in both locations. Fruit growth, which is represented by the fresh weight of the fruits, showed a good fit for non-linear polynomial (quadratic and cubic), exponential (simple with three parameters and Stirling Model) and sigmoidal logistic models, which is consistent with what Fischer (2003), Rodríguez et al. (2006), and Fischer et al. (2012) reported. The growth curve indicated three stages after anthesis: the first is a slow growth stage that lasts for approximately 80 DAA in both locations; the second is a faster growth stage from 80 to 127 DAA (2,209 GDD) for San Francisco de Sales and 80 to 145 DAA (1,587 GDD) for Tenjo; and the third is a rapid growth stage at both sites from 127 and 145 DAA until harvest for San Francisco de Sales and Tenjo, respectively. This behavior is similar to what was found by Rodríguez et al. (2006) for pineapple guava cv. 'Quimba' and Esemann-Quadros et al. (2008), who studied the development, anatomy and morphology of pineapple guava fruits.

Rodríguez et al. (2006) show that fruits from clones 41 ('Quimba') and 8-4 cultivated in the La Vega Municipality (Cundinamarca) under similar weather conditions to those in San Francisco de Sales exhibited a simple sigmoidal growth curve, although a cubic polynomial model best explained the fruit growth. These authors observed that the growth curve for fruit showed three stages after anthesis: slow growth stage up to 70 DAA; moderate growth stage from 70 to 126 DAA; and rapid growth stage from 126 until 154 DAA, which was characterized by a significant increase in fruit volume for both clones and is consistent with the results of Esemann-Quadros et al. (2008). Fischer (2003) indicated that pineapple guava fruit normally show a simple sigmoidal growth curve shape; however, depending on the cultivar and agroecological conditions, the fruit could also exhibit a double sigmoidal curve that shows slow growth during the first 40 days and spans from 120 to 150 DAA to physiological maturity.

Several authors have used different models to describe the growth of different fruits. Hall et al. (2006) found that the growth curve for kiwi fruits fit a sigmoidal growth pattern; Avanza et al. (2008) found that that the growth curve for 'Valencia late' sweet orange fit the fifth parameterization of the logistic model; Almanza et al. (2010) found that the growth curve for grapes fit a logistic model; Ardila et al. (2011) found that the growth curve for three hybrid species of tomato fit a logistic sigmoidal model; and Pereira Silva et al. (2013) found that the growth curve for ten genotypes of peach fit a double sigmoidal pattern. All of these models showed high R^2 values, which indicate their high predictive power.

Multivariate analysis

A multivariate analysis (Table 2) was performed using all of the data from both locations, which were also used to produce the mathematical models. The results indicated that the weather variables that had a higher impact on the models, including H, P, GDD, and average RH, corresponded to the second principal component (PC2) and explained 30.3% of the variance. Rad was not important for model development. Correlations between the influential variables indicated that at higher H, there is lower P, GDD and RH, and this result is consistent with reports by Fischer et al. (2012), who suggested that at higher altitude (from 1,500 m.a.s.l. and above), there is lower P and RH.

Table 2. Coefficients of the first 3 principal components considering all data from Tenjo and San Francisco de Sales.

Variable	PC1	PC2	PC3	Communality
Days post-anthesis	**0.750**	0.416	−0.388	0.886
H (m.a.s.l.)	0.175	**0.885**	−0.297	0.902
GDD (°C)	0.401	**−0.783**	0.073	0.780
Rad ∑[W/m²]	0.484	0.244	−0.686	0.765
P (∑mm)	0.135	**−0.868**	−0.013	0.772
RH average (%)	0.050	**−0.802**	0.160	0.671
Weight (g)	**0.852**	0.076	0.056	0.735
TSS (°Brix)	0.227	0.317	**−0.775**	0.753
TTA (%)	**0.805**	−0.121	−0.336	0.776
Hue angle (°h)	−0.033	−0.032	**0.820**	0.674
Skin firmness (N)	**−0.874**	0.258	0.075	0.836
Pulp firmness (N)	**−0.796**	0.260	0.215	0.747
Eigenvalue	4.589	3.642	1.066	
Variance (%)	38.242	30.349	8.886	
Cumulative variance (%)	38.242	68.591	77.476	

Values > 0.7 (absolute value) are highlighted. PC1, PC2, and PC3 = Principal components 1, 2 and 3, respectively; H = Height; GDD = Growing degree days; Rad = Total accumulated radiation; P = Accumulated precipitation; RH = Relative humidity; TSS = Total soluble solids; TTA = Total titratable acidity.

Fruit variables with the highest impact on the models are TTA, weight and skin and pulp firmness, and they correspond to the first principal component (PC1) and explain 38.2% of the variance. The TSS and hue angle, which correspond to the third principal component (PC3), were also influential and explained 8.9% of the variance. The variables with less influence on the model development (with lower communality) were RH, hue angle, and TSS, which are in PC3 and have low communality values.

The coefficients of PC1 indicate that weight, TTA and TSS increase with time, which is consistent with what was reported by Rodríguez et al. (2006), who observed an increase in both TTA and TSS during the last stage of development of clones 41 and 8-4 of pineapple guava fruits. These coefficients also show that pulp and skin firmness and hue angle decrease during fruit growth, which is consistent with the results of several authors (Parra-Coronado et al. 2006; Amarante et al. 2008; Velho et al. 2011). Parra-Coronado et al. (2006) found that firmness decreases with pear growth; Velho et al. (2011) claimed that in some pineapple guava cultivars, °h decreases as the green color is lost; and Amarante et al. (2008) concluded that for several pineapple guava cultivars, visible color changes (°h) do not occur because of fruit genetics, with only variations in the shade of green showed. As the fruit grows, firmness decreases as a result of enzymes acting on pectin substances, which are converted into water-soluble pectic acids and other substances and cause softening of the fruit as it ripens (Parra-Coronado et al. 2006).

Mathematical models for fruit quality variables as a function of weather conditions

The best fit mathematical models of TT for fruit weight were modified for each of the physicochemical variables of fruits (weight, firmness, TSS, TTA, and °h) by introducing the most important weather variables (GDD, H, P, and RH) according to the multivariate analysis. Exponential and polynomial equations were evaluated with average values, with the best fit selected and RH excluded because it is directly related to P and has no effect on R^2. The Excel® Solver tool was later used on the datasets for the two studied locations to obtain the mathematical models for each of the fruit physicochemical characteristics as a function of the main weather variables (GDD, H, and P), in Equations 10 to 15. The variables for Equations 10 to 15 are defined as follows: W is the fruit weight (g); TTA is the total titratable acidity

(% citric acid); TSS is the total soluble solids (°Brix); SkiFir is the skin firmness (N); PulpFir is the pulp firmness (N); Hue is the fruit skin color (hue angle, °h); P is the accumulated precipitation (mm) recorded in the study area.

Equation for fruit weight

$$W = e^{(4.19E - 3 \times (GDD - 6060.00) + 0.30 \times H^{0.56} - 36.71 \times p^{-0.46})} \tag{10}$$

$R^2 = 0.89$; Standard error = 6.55

Equation for total titratable acidity

$$TTA = (-6.29E - 4 \times GDD - 1.51E - 3 \times H + \\ + 8.50E - 5 \times P)^2 + (-4.40E - 3 \times GDD - \\ - 0.01 \times H + 1.32E - 3 \times P) + 15.62 \tag{11}$$

$R^2 = 0.73$; Standard error = 0.17

Equation for total soluble solids

$$TSS = (2.10E - 4 \times GDD + 0.02 \times H - 5.64E - \\ - 4 \times P)^2 + (-0.01 \times GDD - 1.01 \times H + \\ + 0.03 \times P) + 1{,}082.56 \tag{12}$$

$R^2 = 0.53$; Standard error = 0.99

Equation for skin firmness (SkiFir)

$$SkiFir = (-1.02E - 3 \times GDD + 0.02 \times H - 4.84E - \\ - 4 \times P)^2 + (4.17E - 3 \times GDD - \\ - 1.30 \times H + 0.02 \times P) + 1{,}408.00 \tag{13}$$

$R^2 = 0.64$; Standard error = 4.35

Equation for pulp firmness (PulpFir)

$$PulpFir = (-7.73E - 4 \times GDD + 0.01 \times H + \\ + 5.42E - 4 \times P)^2 + (0.02 \times GDD - \\ - 0.85 \times H - 0.03 \times P) + 938.85 \tag{14}$$

$R^2 = 0.59$; Standard error = 3.38

Equation for skin color

$$hue = (-4.33E - 4 \times GDD + 4.79E - 3 \times H + \\ + 3.40E - 3 \times P)^2 + (6.20E - 3 \times GDD - \\ - 0.12 \times H - 0.07 \times P) + 261.70 \tag{15}$$

$R^2 = 0.27$; Standard error = 1.38

Fruit weight was adjusted to a modified exponential model,

whereas the remaining fruit traits (TTA, TSS, firmness, and °h) were adjusted to second-order modified polynomial models.

According to the criteria set by Williams (2003) for R^2, the fruit weight model shows good predictive performance, and the models for TTA and skin firmness show an adequate predictive performance. The models for pulp firmness and TSS indicate that more than 50% of their variance is explained by the effect of weather conditions, but they do not show adequate predictive performance. The model for skin color did not show a good fit, indicating low dependence of the weather conditions and low predictive ability. Using these models, it is possible to estimate weight, TTA and skin firmness in pineapple guava fruits of clone 41 ('Quimba') during development in cultivation studied areas.

Figures 2 and 3 present cross validation evaluations of the models through comparisons of the predicted and observed values during fruit growth (considering data not used in the production of the model). The cross validation

and regression analyses showed that the models for weight, TTA and skin and pulp firmness adequately estimated the growth parameters as a function of the weather variables in the cultivation areas. A good statistical concordance was found. The R^2, concordance index, and RMSE values also reflected the good fit of these models for production areas. The models for TSS and °h do not adequately estimate growth parameters, which is consistent with the results from the multivariate analysis.

The mathematical model for fresh fruit weight (Equation 10) is a good tool for estimating the potential yield according to location. For this, the fruits number is determined from a crop sampling, counting the number of fruits in some trees and its planting density in the area. To date, equations were not available to determine the physiochemical characteristics of pineapple guava fruits in terms of the weather conditions of the cultivation area; therefore, the results obtained in this study will be useful.
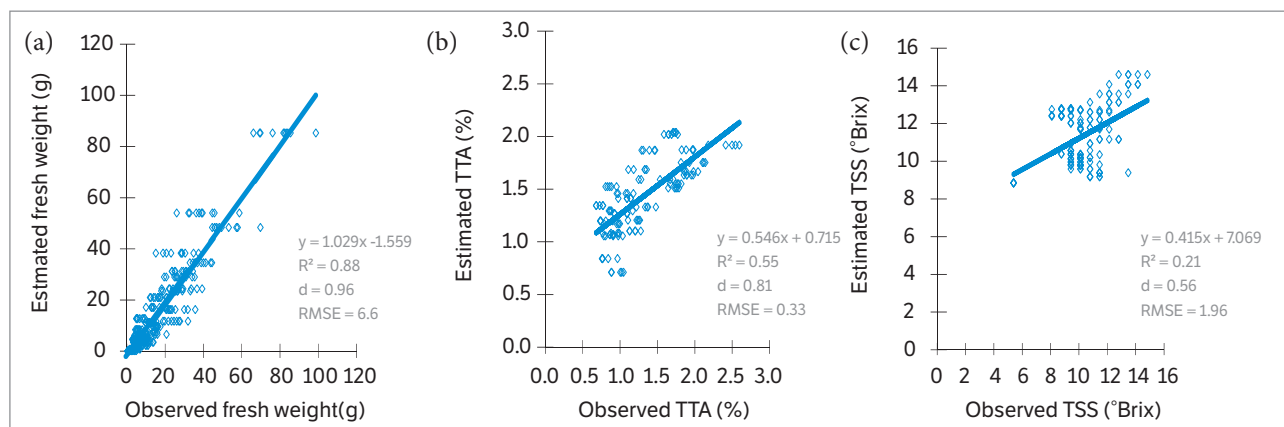
Figure 2. Cross validation of the physiochemical characteristics of pineapple guava fruits. (a) Validation of the fresh weight model; (b) Validation of the total titratable acidity (TTA) model; (c) Validation of the total soluble solids (TSS) model.
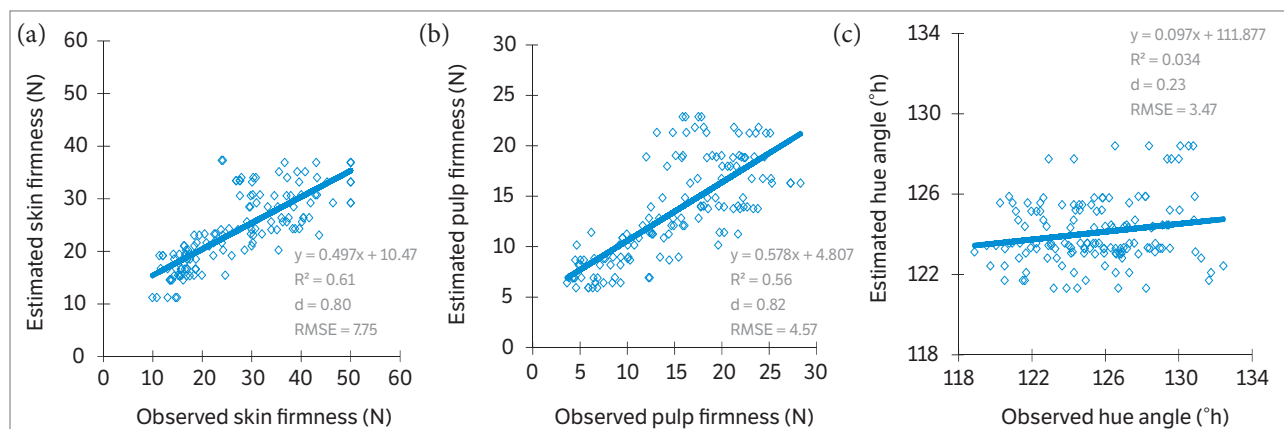
Figure 3. Cross validation of the physiochemical characteristics of pineapple guava fruits. (a) Validation of the skin firmness model; (b) Validation of the pulp firmness model; (c) Validation of the color model (hue angle).

CONCLUSION

The results obtained in this study show that the weather variables altitude, growing degree days, and precipitation have the greatest influence on the physicochemical characteristics of pineapple guava fruits during their growth and development.

The mathematical models that better predict the evolution of fruit quality of pineapple guava fruits during growth and development as a function of the weather variables are those for weight, TTA, and skin firmness. The models for TSS and pulp firmness did not show adequate predictive performance, although they indicated that more than 50% of the variance of these variables is explained by the effect of weather conditions. The skin color model showed low predictive ability, indicating that this parameter is not dependent of the weather conditions.

The parameters of the regression analysis showed that the growth models obtained for longitude and diameter as a function of weight satisfactorily predicted the growth of pineapple guava fruit for the two locations and produced a high R^2 value. The model for DAA as a function of GDD and H also presented satisfactory predictive power, and a good statistical fit was found between the estimated and observed values. To date, no models of this type have been available to help determine physical properties as a function of the related variables. Therefore, the models resulting from this study are of great utility because they can be used to determine the physical properties of fruits in any of the areas of pineapple guava cultivation located between 1,800 and 2,580 m.a.s.l.

Further evaluations of the mathematical models in different cultivation areas are recommended, and the influence of other factors on fruit growth should be considered because of the wide range of pineapple guava varieties, variability in weather conditions, and type of soil and management practices that may occur in cultivation areas.

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REFERENCES

Almanza, P., Quijano-Rico, M., Fischer, G., Chávez, B. and Balaguera-López, H. E. (2010). Physicochemical characterization during growth and development of grapevine (*Vitis vinifera* L.) fruits under high tropical conditions. Agronomia Colombiana, 28, 173-180.

Amarante, C. V. T., Steffens, C. A., Ducroquet, J. P. H. J. and Sasso, A. (2008). Qualidade de goiaba-serrana em resposta à temperatura de armazenamento e ao tratamento com 1-metilciclopropeno. Pesquisa Agropecuária Brasileira, 43, 1683-1689. http://dx.doi.org/10.1590/S0100-204X2008001200007.

Ardila, G., Fischer, G. and Balaguera-López, H. E. (2011). Caracterización del crecimiento del fruto y producción de tres híbridos de tomate (*Solanum lycopersicum* L.) en tiempo fisiológico bajo invernadero. Revista Colombiana de Ciencias Hortícolas, 5, 44-56. http://dx.doi.org/10.17584/rcch.2011v5i1.1252.

Avanza, M. M., Bramardi, S. J. and Mazza, S. M. (2008). Statistical models to describe the fruit growth pattern in sweet orange 'Valencia late'. Spanish Journal of Agricultural Research, 6, 577-585. http://dx.doi.org/10.5424/sjar/2008064-352.

Esemann-Quadros, K., Mota, A. P., Barbante, G., Guerra, M. P., Ducroquet, J. P. H. J. and Pescador, R. (2008). Estudo anatômico do crescimento do fruto em *Acca sellowiana* Berg. Revista Brasileira de Fruticultura, 30, 296-302. http://dx.doi.org/10.1590/S0100-29452008000200005.

Fischer, G. (2003). Ecofisiología, crecimiento y desarrollo de la feijoa. In: G. Fischer, D. Miranda, G. Cayón and M. Mazorra (Eds.), Cultivo, poscosecha y exportación de la Feijoa (*Acca sellowiana* Berg) (p. 9-26). Bogotá: Produmedios.

Fischer, G., Ramírez, F. and Almanza-Merchán, P. J. (2012). Inducción floral, floración y desarrollo del fruto. In: G. Fischer (Ed.), Manual para el cultivo de frutales en el trópico (p. 120-140). Bogotá: Produmedios.

Hall, A. J., Richardson, A. C. and Snelgar, W. P. (2006). Modelling fruit development in 'Hayward' kiwifruit. Acta Horticulturae, 707, 41-47. http://dx.doi.org/10.17660/ActaHortic.2006.707.4.

Ho, L. C. (1996). The mechanism of assimilate partitioning and carbohydrate compartmentation in fruit in relation to the quality and yield of tomato. Journal of Experimental Botany, 47, 1239-1243. http://dx.doi.org 10.1093/jxb/47.Special_Issue.1239.

Instituto Colombiano de Normas Técnicas y Certificación (1999a). Norma técnica colombiana NTC 4623. Productos de frutas y verduras. Determinación de la acidez titulable. Bogotá: ICONTEC.

Instituto Colombiano de Normas Técnicas y Certificación (1999b). Norma técnica colombiana NTC 4624. Jugos de frutas y hortalizas. Determinación del contenido de sólidos solubles. Método refractométrico. Bogotá: ICONTEC.

Krug, H. (1997). Environmental influences on development growth and yield. In: H. C. Wien (Ed.), The physiology of vegetable crops (p. 101-180). London: Cabi Publishing.

López, I. L., Ramírez, A. and Rojano, A. (2005). Modelos matemáticos de hortalizas en invernadero: Trascendiendo la contemplación de la dinámica de cultivos. Revista Chapingo Serie Horticultura, 11, 257-267.

Martínez-Vega, R. R., Fischer, G., Herrera, A., Chaves, B. and Quintero, O.C. (2008). Características físico–químicas de frutos de feijoa influenciadas por la posición en el canopi. Revista Colombiana de Ciencias Hortícolas, 2, 21-32. http://dx.doi.org/10.17584/rcch.2008v2i1.1170.

Mazorra, M. F., Quintana, A. P., Miranda, D., Fischer, G. and Chaparro, V. M. (2006). Aspectos anatómicos de la formación y crecimiento del fruto de uchuva *Physalis peruviana* (Solanaceae). Acta Biológica Colombiana, 11, 69-81.

Parra-Coronado, A. and Fischer, G. (2013). Maduración y comportamiento poscosecha de la feijoa (*Acca sellowiana* (O. Berg) Burret). Una revisión. Revista Colombiana de Ciencias Hortícolas, 7, 98-110. http://dx.doi.org/10.17584/rcch.2013v7i1.2039.

Parra-Coronado, A., Fischer, G. and Camacho-Tamayo, J.H. (2015a). Development and quality of pineapple guava fruit in two locations with different altitudes in Cundinamarca, Colombia. Bragantia, 74, 359-366. http://dx.doi.org/10.1590/1678-4499.0459.

Parra-Coronado, A., Fischer, G. and Chaves-Cordoba, B. (2015b). Tiempo térmico para estados fenológicos reproductivos de la feijoa (*Acca sellowiana* (O. Berg) Burret). Acta Biológica Colombiana, 20, 167-177. http://dx.doi.org/10.15446/abc.v20n1.43390.

Parra-Coronado, A., Hernández-Hernández, J. E. and Camacho-Tamayo, J. H. (2006). Estudio de algunas propiedades físicas y fisiológicas precosecha de la pera variedad Triunfo de Viena.

Revista Brasileira de Fruticultura, 28, 55-59. http://dx.doi.org/10.1590/S0100-29452006000100017.

Pereira Silva, D. F., Da Costa e Silva, J. O., Pires Matias, R. G., Rodrigues Ribeiro, M. and Horst Bruckner, C. (2013). Curva de crescimento e padrão respiratorio de frutos de genótipos de pessegueiro em região de clima subtropical. Revista Brasileira de Fruticultura, 35, 642-649. http://dx.doi.org/10.1590/S0100-29452013000200037.

Quintero, O. C. (2012). Feijoa (*Acca sellowiana* Berg). In: G. Fischer (Ed.). Manual para el cultivo de frutales en el trópico (p. 443-473). Bogotá: Produmedios.

Ritchie, J. T. and Ne Smith, D. S. (1991). Temperature and crop development. In: R. J. Hanks and J. T. Ritchie (Eds.), Modelling plant and soil systems (p. 5-29). Madison: American Society of Agronomy.

Rodríguez, M., Arjona, H. E. and Campos, H. A. (2006). Caracterización fisicoquímica del crecimiento y desarrollo de los frutos de feijoa (Acca sellowiana Berg) en los clones 41 (Quimba) y 8-4. Agronomía Colombiana, 24, 54-61.

Rojas-Lara, P. C., Pérez-Grajales, M., Colinas-León, M. T. B., Sahagún-Castellanos, J. and Avitia-García, E. (2008). Modelos matemáticos para estimar el crecimiento del fruto de chile manzano (*Capsicum pubescens* R y P). Revista Chapingo Serie Hortícola, 14, 289-294.

Salazar, M. R., Jones, J. W., Chaves, B. and Cooman, A. (2008). A model for the potential production and dry matter distribution of cape gooseberry (*Physalis peruviana* L.). Scientia Horticulturae, 115, 142–148. http://dx.doi.org/10.1016/j.scienta.2007.08.015.

Salazar-Gutiérrez, M. R., Johnson, J., Chaves-Cordoba, B. and Hoogenboom, G. (2013). Relationship of base temperature to development of winter wheat. International Journal of Plant Production, 7, 741-762.

Salisbury, F. B. and Ross, C. W. (2000). Fisiología de las plantas 3: desarrollo de las plantas y fisiología ambiental. (p. 527-564). Madrid: Thompson Editores Spain, Paraninfo S.A.

Trudgill, D. L., Honek, A., Li, D. and Van Straalen, N. M. (2005). Thermal time – Concepts and utility. Annals of Applied Biology, 146, 1-14. http://dx.doi.org/10.1111/j.1744-7348.2005.04088.x.

Velho, A. C., Amarante, C. V. T., Argenta, L. C. and Steffens, C. A. (2011). Influência da temperatura de armazenamento na qualidade pós-colheita de goiabas serranas. Revista Brasileira de Fruticultura, 33, 14-20. http://dx.doi.org/10.1590/S0100-29452011005000016.

Williams, P. (2003). Near-infrared technology: getting the best out of light. Nanaimo: PDK Projects.