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Fruit growth in three ecotypes of dry-season *Spondias purpurea* L.

Crecimiento del fruto en tres ecotipos de *Spondias purpurea* de estación seca

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Abstract

Mexican plum is a tropical fruit widely consumed fresh. Although it has a high diversity, there is not enough research on fruit growth kinetics. The objective of this work was to determine a series of physical, chemical, and physiological changes during fruit growth. Trees of three ecotypes were evaluated, from fruit set to physiological maturity. Results revealed a rapid increase of fruit respiration in the three fruit ecotypes between the day 30 and 60 of the fruit growth, although respiration decreased afterwards; likewise, a similar behavior was observed with the titratable acidity. Flavor index was higher in Amarilla (12.2) than in Morada and Roja. Thus, fruit growth in these ecotypes of Mexican plum appeared to be double sigmoidal with 90 days of duration, where the titratable acidity, flavor index, polar diameter, luminosity, and chromaticity help to differentiate among them.

Keywords: Fruit; growth; respiration rate; taste index; hue.

Resumen

La fruta de ciruela mexicana es consumida principalmente en fresco. Se tiene amplia diversidad del fruto, pero se desconoce la cinética de crecimiento. El objetivo del estudio fue determinar algunos cambios físicos, químicos y fisiológicos durante el crecimiento del fruto. Se realizaron muestreos en árboles de tres ecotipos cada 15 días, entre el cuajado de fruto y madurez fisiológica. Los resultados indican que la respiración de frutos de los tres ecotipos alcanzó su máximo entre los 30 y 60 días de crecimiento del fruto, aunque posteriormente disminuye; por su parte, la acidez titulable mostró un comportamiento similar. El índice de sabor fue mayor en Amarilla (12.2) que en Morada y Roja (7-8). El crecimiento de ciruela mexicana es de aproximadamente 90 días, de tipo doble sigmoidal, donde la acidez titulable, el índice de sabor, el diámetro polar, la luminosidad y la cromaticidad ayudan a diferenciar las variedades.

Palabras clave: Fruto; crecimiento; respiración; índice de sabor; matiz.

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Introduction

Spondias purpurea L. is a fruit tree that grows in the lowland deciduous forests of tropical America, as well as in certain regions of Asia and Africa (Sollano-Mendieta *et al.*, 2021). However, Mexico is widely regarded as the center of origin of this species, with two areas of dispersal currently recognized: (1) the Pacific Region (specifically, an area west of the Balsas River that also includes the states of Jalisco, Nayarit, and Michoacán) and (2) the Gulf Region (mainly in the Yucatán Peninsula) (Fortuny-Fernández *et al.*, 2017). Commercial and family orchards tend to follow this same geographic distribution (Arce-Romero *et al.*, 2017; Avitia *et al.*, 2003). In Mexico, two ecotypes of *S. purpurea* trees are recognized: (1) dry-season *S. purpurea* L., which blooms from late December to mid-February (harvested from late March to the beginning of June), and (2) wet-season *S. purpurea* L., which flowers from February to March (harvested from September to October) (Alvarez-Vargas *et al.*, 2019; Avitia *et al.*, 2003). A large number of variants also exists within these types (>20 along the Gulf of Mexico and at least 12 in each of five different biogeographic regions in the Pacific slope) (Avitia *et al.*, 2003; Cruz & Rodríguez, 2012).

The fruit, on the other hand, is much appreciated for its sensory characteristics and chemical content (e.g., pigments, antioxidants, vitamins, and carbohydrates) (Maldonado-Astudillo *et al.*, 2014). As in all fruits, these and other factors (e.g., physical, physiological) change considerably during growth and are strongly influenced by both genetics and the environment (López-Hernández *et al.*, 2021). Nevertheless, information is still scarce regarding these topics, and what exists is largely confined to a few ecotypes. The objective of this work, then, was to evaluate the physical, chemical, and physiological changes in three ecotypes of dry-season *S. purpurea* L. (Morada, Roja, and Amarilla) during the process of fruit growth.

Materials and methods

The *S. purpurea* L. trees used (40-year-old) are in an orchard located in the Municipality of Tepalcingo, Morelos, Mexico (18° 39' 42'' LN; 98 ° 55' 28'' LO; 1160 m. a. s. l.). The climate in this region is warm and sub-humid, with an average temperature of 22.5 °C and an annual precipitation of 840 mm (Díaz *et al.*, 2008; García, 2004).

The ecotypes Roja, Morada, and Amarilla were chosen based on their favorable adaptation to the region of study. Three trees were selected from each ecotype, and from these a total of ten branches were marked –five from November to December 2020 (during reproductive bud development) and other five from January to February 2021 (during floral development and anthesis). Fruits were then harvested from these branches in groups of 6-20. This occurred every 15 days from February to April 2021 (i.e., spanning the period from fruit set to physiological maturity, when growth ceases and the color changes). Subsequently, the samples were protected (i.e., placed inside plastic bags and within insulated crates containing dry ice as a refrigerant) and transported by vehicle to the Laboratory of Agricultural Production of the Universidad Autónoma del Estado de Morelos (UAEM), Faculty of Agricultural and Livestock Sciences.

Fruit weight (CQ100LW digital scale, Ohaus Corp., Parsippany, USA), dimensions (1235C55 digital caliper, Thomas Scientific, Swedesboro, USA), and color (SP64 portable spectrophotometer, X-Rite Inc., Grand Rapids, USA) were determined upon arrival. In the latter's case, luminosity (L*), chromaticity (C*), and hue (h) were measured in triplicate for each fruit (Negueruela, 2012).

Respiration, on the other hand, was determined chromatographically (GC-TCD) using a static method (Saltveit, 2016). Briefly, 2–5 fruits were placed inside an airtight, glass container for 3 h, after which a 1 m0′ sample of headspace air was extracted and injected into an Agilent 7890A system (Agilent Technologies, Sta. Clara, USA). Injector, oven, and detector temperatures were 150 °C, 80 °C, and 170 °C, respectively (N_2 carrier gas; 2 ml min^{-1} flow rate). CO_2 standards (460 µL L^{-1}; Grupo Infra-Gases Especiales, CDMX, Mexico) were always used for these quantifications, and the results were expressed as ml CO_2 kg^{-1} h^{-1}.

Liquid samples were used to measure the content of total soluble solids (TSS). For this, 1 g of fruit tissue was homogenized in 12 ml of dH_2O (Ultra Turrax T-25, IKA Labortechnik, Staufen, Germany), filtered and centrifuged (4000 g for 10 min), and three drops of the filtrate were placed on top of a digital refractometer (PAL-1, Atago Co., Ltd., Tokyo, Japan). The results were given as percentage of TSS. Titratable acidity (TA) was determined by the method described in the Association of Official Analytical Chemist (AOAC, 1990) and the results expressed as percentages of citric acid. Then, from these data, the taste index (TI) was then calculated using the formula TI = TSS/TA (Erkan & Dogan, 2019).

All graphs and statistical tests (analyses of variance, comparisons of means using Tukey's HSD test [$\alpha \leq 0.05$]) were created and performed using the software Sigma Plot V. 14 (Systat Software Inc., San Jose, CA, USA).

Results

Fruit dimensions and weight increased continuously, except between day 30 and 60, when growth decreased slightly (Figures 1e-f and 2a). In Amarilla, polar diameter was smaller on day 45 and 90 (15 mm and 24 mm) compared to both Morada (20 mm and 28 mm) and Roja (19 mm and 26 mm); otherwise, there were not real differences between them (Figures 1a-1c). Lightness (L*) and chromaticity (C*) changed steadily until day 30 (i.e., decreasing and increasing respectively) (Figures 1d and 1e); afterwards, they remained more or less constant. However, L* and C* were both higher in Amarilla (50 and 29) compared to either Morada (40 and 18) or Roja (41 and 22). Hue, on the other hand, was very similar in all three, except in Roja on day 30 (h = 80 *vs.* 100 in the rest) (Figure 1f).

Respiration was relatively high at the time of fruit set in all three ecotypes evaluated (36.2 ml CO_2 kg^{-1} h^{-1}, 16.1 ml CO_2 kg^{-1} h^{-1}, and 15.0 ml CO_2 kg^{-1} h^{-1} in Morada, Roja, and Amarilla, respectively); nevertheless, values decreased sharply almost immediately thereafter (to 5.4 ml CO_2 kg^{-1} h^{-1} on day 15 in Amarilla, 2.5 ml CO_2 kg^{-1} h^{-1} on day 30 in Roja, and 4.2 ml CO_2 kg^{-1} h^{-1} on day 30 in Morada) (Figure 2a). Respiration increased again for a brief period of time (to 17.5 ml CO_2 kg^{-1} h^{-1} on day 30 in Amarilla, 9.3 ml CO_2 kg^{-1} h^{-1} on day 45 in Roja, and 9.3 ml CO_2 kg^{-1} h^{-1} on day 60 in Morada) before decreasing steadily to values between 1.5 ml CO_2 kg^{-1} h^{-1} and 3.7 ml CO_2 kg^{-1} h^{-1} on day 90 (i.e., at physiological maturity) (Figure 2a).

In terms of TSS, there were no real differences among the three ecotypes (the only discrepancies occurred with time). Initial values, which were again relatively high (14.4%, 11.4%, and 10.7% in Roja, Morada, and Amarilla, respectively), decreased continuously during growth (final TSS of 6.0% in Amarilla, 6.2% in Morada, and 7.3% in Roja) (Figure 2b). In all cases, a plateau was reached between day 30 and 45. On the other hand, titratable acidity (TA) in Roja, Morada, and Amarilla (originally 2.0%, 1.53%, and 1.12%, respectively, at the time of fruit set) first increased (to values of 2.4%, 2.13%, and 2.72% on day 45, 60, and 30) and then gradually declined (final values of 1.0%, 0.73%, and 0.46%, respectively) (Figure 2c). In this case, Roja had the highest TA on average (1.9%). Conversely, the taste index (TI or TSS/TA ratio) declined first (6.7-9.5 to approximately 4) before increasing steadily from day 60 onwards (reaching 12.9 in Amarilla, 7.0 in Roja, and 8.1 in Morada) (Figure 2d).

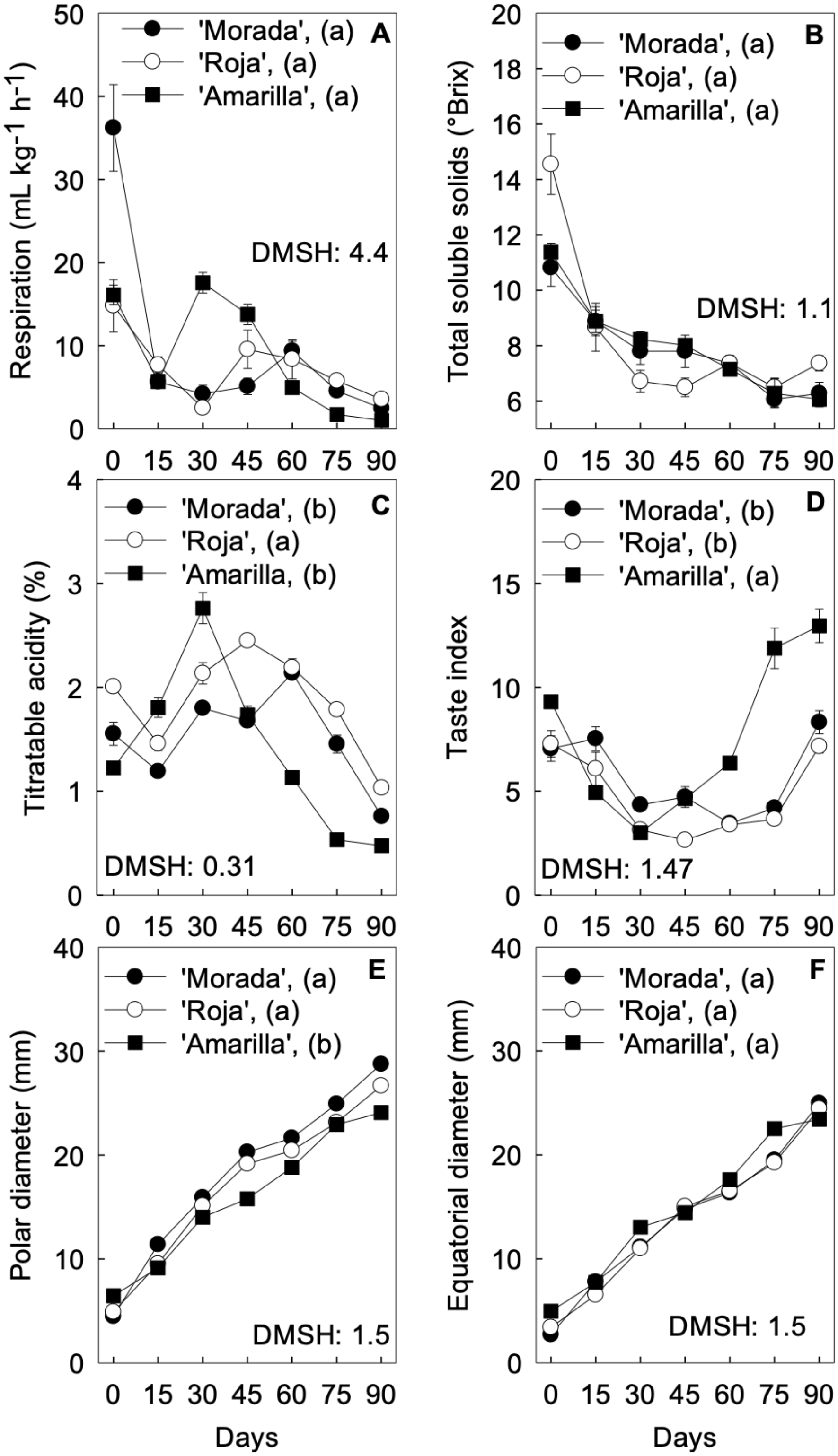

Figure 1. Changes in the physical and chromatic parameters of *S. purpurea* L. (ecotypes Morada, Roja, and Amarilla) from fruit set to physiological maturity. Each point represents the average of 6-10 measurements ± SE.
Source: Author's own elaboration.

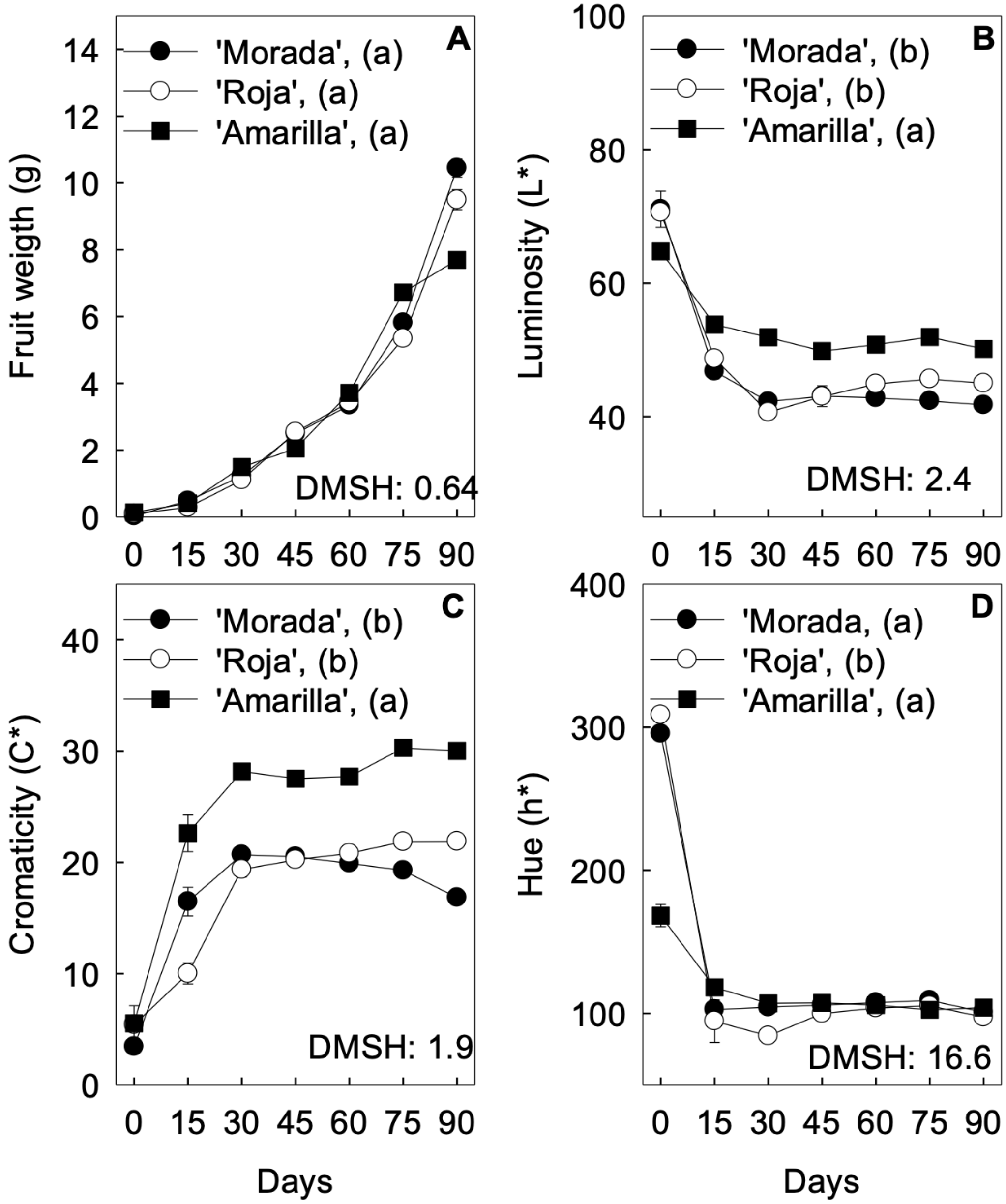

Figure 2. Changes in the physiological and chemical parameters of *S. purpurea* L. (ecotypes Morada, Roja, and Amarilla) from fruit set to physiological maturity. Each point represents the average of 6-10 measurements ± SE.
Source: Author's own elaboration.

Discussion

Trends in fruit weight and dimensions (Figures 1e-f and 2a) strongly suggest the presence of a double sigmoidal growth pattern similar to that of wet-season *S. purpurea* L. (Alvarez-Vargas *et al.*, 2019). This contrasts with other studies describing fruit growth as either linear (when fresh or dry weight are used) or quadratic (when the equatorial diameter is plotted) (Pereira *et al.*, 2003). On the other hand, the growth period (i.e., 90 days from flowering to anthesis) was intermediate in length compared to those reported by Pereira *et al.* (2003) and Salazar & Becerra (1994) (124 and 70 days, respectively; in the latter case, the ecotype Amarilla from Nayarit was also used). Interestingly, the longest period ever recorded (240 days) corresponds to a wet-season fruit of temperate climate (Alvarez-Vargas *et al.*, 2019). The differences in the size and days to ripe of tree fruits is associated to the carbohydrate economy and temperature (DeJon, 2022), but in *Spondias purpurea* this is a task for research in the future.

Overall, epicarp color in Roja and Morada was darker and less pure than in Amarilla (L* and C* in Figures 1d and 1e). Nevertheless, hue values in Roja deviated significantly from those in the other two ecotypes over the course of development (approximately 15 d–45 d) (Figure 1f). This made it difficult to distinguish the fruits solely based on chromatic values –a task that became possible only during ripening, when each ecotype acquired its characteristic color (purple in Morada, red in Roja, and yellow in Amarilla). The color of epidermis in *Spondias purpurea* is attributed to pigments as carotenoids, anthocyanins, and chlorophylls (Sollano-Mendieta *et al.*, 2021). The accumulation of these pigments is strongly regulated by the development and genotype, also the environmental conditions and soil characteristics (pH, CE, nutrients content) affect the behaviour during the growth of fruit, as it has been demonstrated in blueberry (Spinardi *et al.*, 2019). However, in *Spondias purpurea*, this hypothesis has not been proven.

In terms of respiratory activity, all three followed the trend expected during fruit development (Figure 2a), that is, an increase at the beginning (when cell division is active and the number of cells per unit of mass or volume is large), followed by a decline as cells grow (and the number of cells per unit of mass or volume becomes diluted), followed by another increase near the end (though with values not quite as high as before) (Saltveit, 2016). In this context, the respiratory peaks on day 30 (Amarilla), 45 (Roja), and 60 (Morada) were likely the result of endocarp development –a process that requires both a large quantity of dry matter as well as a high metabolic rate. These events also coincided with the plateaus obtained in the growth curves of each fruit (Figures 1a, b, and c).

Total soluble solids (TSS) were similarly high at the beginning of development (Figure 2b). However, in this case, they decreased continuously until reaching 50% of their initial values. Typically, the content of soluble organic compounds (e.g., sucrose, reducing sugars, organic acids, and sugar alcohols) varies depending on the species and stage of development (Yahia *et al.*, 2019). Some are, for instance, translocated from the leaves through the phloem, while others are synthesized *in situ* (Yahia *et al.*, 2019). The reduction seen here though is likely the result of: (1) normal tissue metabolism during fruit development (i.e., the active consumption of growth substrates) and (2) a "dilution effect" due to accelerated growth. As with respiration, the plateaus observed on day 30–45 coincided with a hardening of the endocarp (which requires large quantities of substrates) as well as with a slowdown in mesocarp growth.

Titratable acidity (TA) likewise increased during the first half of development, only to decrease steadily from day 30 onwards. Again, this is expected, as the content of organic acids in fruits tends to be low at first and then increases with development, reaching a peak mid-season before falling with maturity (Vallarino & Osorio, 2019). In this context, rising acidity is simply the result of an increase in the synthesis of such compounds *in situ*, partly from the inter-conversion of imported carbon (mostly sucrose) and partly from the fixation of CO_2 in the dark (Atkinson *et al.*, 2017). In grapes (*Vitis vinifera*), however, similar declines in acidity are probably due to: (1) a decrease in the synthesis of organic acids, (2) the formation of potassium salts, (3) an increase in the permeability of cell membranes (causing organic acids to be metabolized faster), and (4) a "dilution effect" due to the rapid growth of fruit during development (Lavee & Nir, 1986).

The taste index (TI or TSS/TA ratio), on the other hand, decreased during the first half of development, largely due to an increase in TA (Figure 2d). This trend then reversed during the second half due to lower values of acidity and higher TI (day 60–90). The latter is important as higher TI become relevant during physiological maturity, when the taste of fruit begins to change, especially during ripening, when taste develops fully and palatability is very important (Ladaniya, 2008).

Conclusions

The dry-season *Spondias purpurea* L. ecotypes Roja, Morada, and Amarilla presented a double sigmoidal growth pattern typical of stone fruits. This growth occurred relatively fast (90 d from flowering to physiological maturity) and was reflected by parameters such as respiratory activity. Polar diameter, luminosity (L*), chromaticity (C*), and the taste index (TI) differed among all three and can therefore be used to distinguish Amarilla from Morada and Roja (especially when their fruit is still green and immature). Conversely, fruit weight, equatorial diameter, respiratory activity, and total soluble solids (TSS) did not vary significantly among the three, making them poor varietal identifiers.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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