

RELATIONSHIP BETWEEN DIFFERENT PHYSICAL PROPERTIES OF TOMATO FRUITS AND WATER LOSS DURING POSTHARVEST

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Abstract. Water loss contributes to acceleration of postharvest senescence of tomato (*Solanum lycopersicum* L.). Ten cultivars representing two fruit types were studied. Fruit were stored at 25°C and 75% relative humidity. Physical characteristics were examined to determine relationships between physical properties and water loss rate in tomato fruit. Water loss rate increased almost linearly with storage time and was different for each cultivar. When the vapour pressure deficit was increased the fruit water loss rate was affected among cultivars. Water loss rate was positively correlated with initial fruit water content. An increase in the surface area to volume of fruit may explain the differences in water loss that was observed between cultivars. The cuticle thickness did not influence the differences in the fruit water loss during storage. However, it was observed the existence of a positive correlation between Surface Area of the Peduncle Scar to Fruit Surface Area ratio and water loss of the tomato fruit.

Key words: *Solanum lycopersicum* L., cultivars, transpiration fruit, physical properties

INTRODUCTION

Fruit quality and postharvest shelf-life durability of tomato are greatly influenced by genetic characteristics [Dorais et al. 2001], flesh firmness being the main attribute affecting the visual appearance [Hertog et al. 2004]. Since flesh firmness strongly depends on fruit water content [Karlova et al. 2014] harvested fruit remain fresh only as long as they retain water. Transpiration becomes the main process determining commercial and physiological deterioration of fruits and vegetables. It induces wilting, shriveling, and loss of firmness, crispness and succulence [Ben-Yehoshua and Rodov 2003], reducing the potential storage life of most horticultural products [Nascimento Nunes 2008].

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Surface characteristics of the fruit mainly determine gaseous diffusivity and the rate of transpiration, the latter representing 92–97% of the weight loss of tomato fruits [Shirazi and Cameron 1993] as well as in other vegetables [Díaz-Pérez et al. 2007]. In this regard, there is been recent interest in edible films for foods, including tomato [Tanada-Palmu et al. 2000].

The water loss partially depends on the interaction between external factors such as temperature and humidity and the water content of the same product [Kader 2002]. Physical fruit properties, including the fruit size, water content at harvest content, surface area, surface area : volume ratio (SA : V), may affect water loss in horticultural crops [Wills et al. 1989]. Furthermore, the presence of superficial damage or the properties of the epidermis can strongly influence the water loss [Robinson et al. 1975]. Fruit cuticle is an important contributing factor to tomato fruit shelf life and storability [Kosma et al. 2010]. In this way, the epidermal cells of tomato fruit are coated with cutinized layers that are an efficient physical barrier which can regulate fruit water loss [Vogg et al. 2004]. Cuticle thickness of tomato fruit increases with fruit maturity diminishing water permeability of ripe fruits in comparison with mature green fruits [Luque et al. 1995]. A model was proposed in which the cuticle affects the softening of intact tomato fruit both directly, in providing a physical support, and indirectly, in regulating water status [Saladié et al. 2007]. However, cuticle thickness of different tomato cultivars and their relationship with water loss is not well known.

Furthermore, despite the importance of water loss in determining the shelf life of tomato fruit, the physical properties of the fruit that affect fruit transpiration and the basis of the variability between cultivars has not been sufficiently studied.

The aim of this work was to determine the relationships between some physical properties of tomato fruit genotypes and their relative rates of water loss.

MATERIAL AND METHODS

Plant material. The study was conducted in Esperanza, Santa Fe, Argentine during spring 2012 and fall 2013. Tomato (*Solanum lycopersicum* L.) plants were grown according to the recommendations of the FCA-Horticultural Extension I.N.T.A. in a Typic Argiudoll soil with a silty loam texture, pH about 6.7, and complementary drip irrigation.

Ten tomato cultivars representing two tomato types (pear and globe) were studied to determine the physical fruit factors that best correlated with the rate of fruit water loss. Eight cultivars of globe type were utilized: ‘LAW 1030’ (De Ruiter), ‘LAW 1002’ (De Ruiter), ‘Superman’ (Peto Seed), ‘Colt 45’ (Royal Sluis), ‘C5586’ (BHN), ‘C5605’ (BHN), ‘LAW 1030’, ‘Alambra’ (Tezier); and two pear type: ‘Colibri’ (Clause) and ‘Cano’ (Asgrow) (fig. 1).

One hundred twenty fruits of each variety, covering a wide range of sizes depending on cultivars (150–200 g), were randomly chosen and taken to the laboratory within 15 min after harvesting. The ripening stage of harvesting was between pink and light red (approximately 60% of the surface with red color) [Salveit 1991] (fig. 1).

Equatorial (E) and polar (P) diameter were measured with electronic caliper Schwyz® with a precision of 0.01 mm. The E value were the average of two perpendicular measurements and P represents the dimension of the proximal end (scar stem end) to distal (end of the fruit). The weight (W₀) and weight loss was determined by an electronic balance (Ohaus EB3). The weight loss due to respiration was considered negligible compared to that of transpiration [Shirazi and Cameron 1993]. The Surface Area (SA) of fruit skin (cm²) was estimated by the empirical equation:

$$SA = \pi \times 4 (E / 2) \times (P / 2)$$

Fruit volume (V) was determined by immersing each fruit in a known volume of water and measuring the water displacement. SA : V ratio was then calculated. The Surface Area of the Peduncle Scar, PS (cm²) was calculated considering the stem scar area as a circle, depending on the diameter ($PS = 0.7854 \times SD^2$), being SD the stem scar diameter, measured with an electronic caliper taking two mutually perpendicular readings.

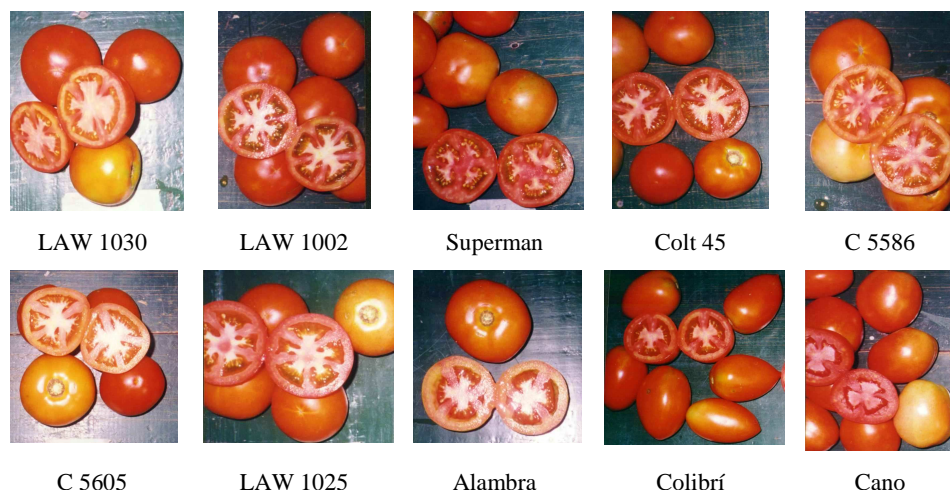


Fig. 1. Fruits of different tomato cultivars and ripening stages between pink and light red at the beginning of the experiment (day 0)

For measuring the cuticle thickness pieces of epidermal tissue were cut with a freezing microtome (Leitz Wetzlar Sledge Microtome 1207, Germany), and later were stained with Sudan IV stain. Digital images were obtained by a digital camera Olympus® (V-PMTVC, Tokyo, Japan), which was coupled to an Olympus optical microscope CX31® and analyzed by image analysis software Image-Pro Plus® 4.0 (Cybernetics®, Carlshad, USA) with a magnification of 100×.

Measurement of water loss. Fruit were placed in individual PET containers (polyethylene terephthalate), 1 fruit per container, and kept in controlled-temperature room at 25°C (mean vapor pressure difference, VPD \approx 0.95 kPa = 9.5 mbar) and air velocity

$< 0.1 \text{ m s}^{-1}$. Fruit water loss was measured daily gravimetrically on individual fruit over 14 days. The water loss percentage (WL) was determined as a daily accumulated weight loss W_i with respect to the initial fruit weight (W_o): $WL (\%) = [(W_o - W_i) / W_o] \times 100$. The Initial Water loss was measured on the first day of postharvest (IWL) using the same equation above.

The initial water content (IWC) was determined randomly in 10 fruit per cultivar, at the beginning of the experiment. Fresh weight of each fruit was obtained (W_o), and then was dried in an oven for 5 days at 60°C to obtain the individual fruit dry weight. Fruits were weighed again after 24 h, and if no weight change occurred, dried weight was recorded (W_d), resulting IWC (%): $IWC = (W_o - W_d) / W_o \times 100$.

The Diffusion Rate (fruit transpiration rate), DR ($\text{mg cm}^{-2} \text{ mbar}^{-1} \text{ h}^{-1}$) was calculated from the changes in fruit weight over time (daily expressed as 24 hours from the previous day) and expressed by dividing the weight loss (mg h^{-1}) with respect to its superficial area (cm^2) and air vapour pressure deficit (VPD, mbar). VPD was calculated every hour by the difference between the saturated (e_{sat}) and current air vapour pressure (e_c), considering the actual mean temperature (T_a): $VPD_{(T_a)} = e_{sat} - e_c$.

The Transpiration Coefficient (TC) ($\text{mg kg}^{-1} \text{ mbar}^{-1} \text{ h}^{-1}$) was calculated as DR but expressed over the fresh weight of the fruit instead of its surface area.

Regression and statistical analysis. The experiment was repeated three times and to determine the effect of cultivar on WL, IWC, DR and TC, a completely randomized experimental design was used with fifteen replications per cultivar and twenty fruits for experimental units. Regression analyses were used to determine the relationship between the physical properties of the fruits and its water loss. Statgraphics® (Statistical Graphics Corp®, USA) was used for statistical analyses and regressions ($P \leq 0.05$). For the results of cuticle thickness the value of $P \leq 0.01$ was considered significant.

RESULTS AND DISCUSSION

Fruit WL was increased almost linearly during the 14 days of evaluation with differences between cultivars. 'LAW 1002' had the highest value of weight change, reaching 12.8% of WL water loss at the end of the experiment, which was 2.66-fold higher compared with 'C5586', the cultivar that showed the lowest transpiration (fig. 2). During postharvest storage of tomatoes these differences are very important, since the product is considered of no commercial value after losing 7% of their fresh weight [Ben-Yehoshua and Rodov 2003], showing symptoms of shrivelling and deterioration. This value represent the maximum permissible loss. Por example, other authors found that this value was of 2 to 3% [Nunes and Emond 2007]. This differences in weight loss before visual deterioration of tomato are most likely related to cultivar variations, such as for example size of the fruit. Generally, smaller fruits have a higher surface area to volume ratio. Although this threshold value was subjectively determined it is an indicator of the importance of transpiration in determining the shelf life of tomato fruit. Shriveling symptoms were already visible on the sixth day of storage for LAW 1002 fruit but at the end of the experiment (14 d) only two varieties, 'C5586' and 'Colibri', not reached the threshold value of shrivelling (fig. 2).

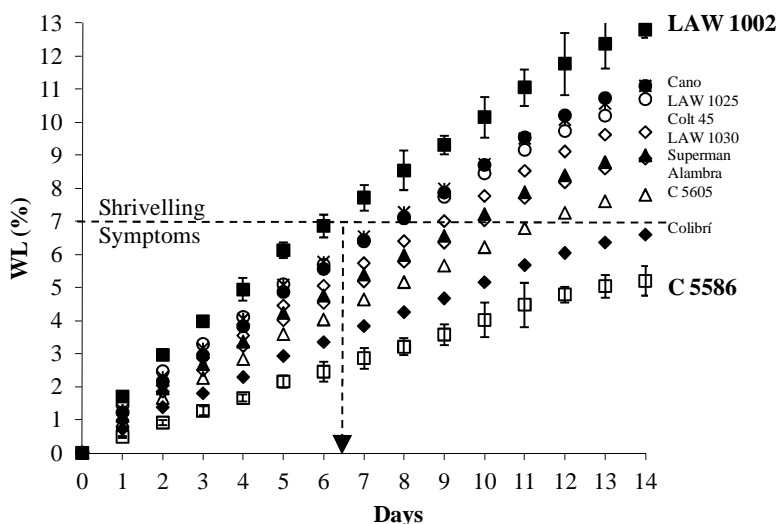


Fig. 2. Evolution of water loss during 14 days of storage for fruits of ten cultivars of tomato. Water loss (WL) was expressed relative to initial fresh weight; the mean vapour pressure deficit and mean temperature during storage were 9.5 mbar and 25°C, respectively. Vertical bars represent standard deviation (SE) only for 'LAW 1002' and 'C5586' cultivars. The dotted lines corresponds to the maximum limit of acceptability before the quality of the fruit became unacceptable

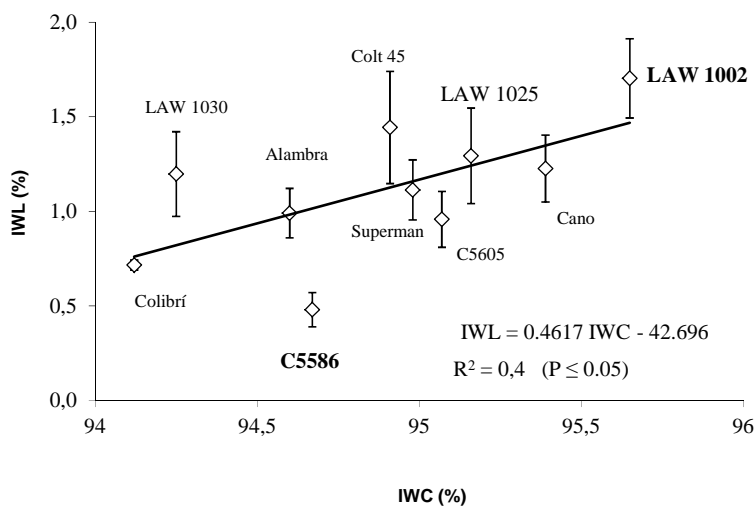


Fig. 3. Relationship between the initial fruit water content (IWC) and the water loss during the first day of storage or initial water loss (IWL). Vertical bars represent standard deviation (SE)

A positive linear relationship between the initial fruit water content (IWC) and the loss of water during the first day of storage, or initial water loss (IWL), was observed ($R^2 = 0.4$) (fig. 3). Here again the difference between fruits of the cultivars 'LAW 1002' and 'C5586' were significant and in turn possibly caused by differences in the initial water content of the fruit (fig. 3). A strong positive correlation between initial water content and water loss rate also was observed in pepper fruit [Lownds et al. 1994].

These results can be explained by the free energy of water expressed as water potential. Water loss (WL) is generally proportional to the water potential difference between inside (Ψ_i) and outside (Ψ_o) the fruit as a driving force to water movement, while the physical resistance to water loss which provides the epidermal tissue of the fruits is synthesized by the proportionality factor (L_w) [Nobel 2009]. Thus, the water loss (WL) can be represented as: $WL = L_w (\psi_o - \psi_i)$.

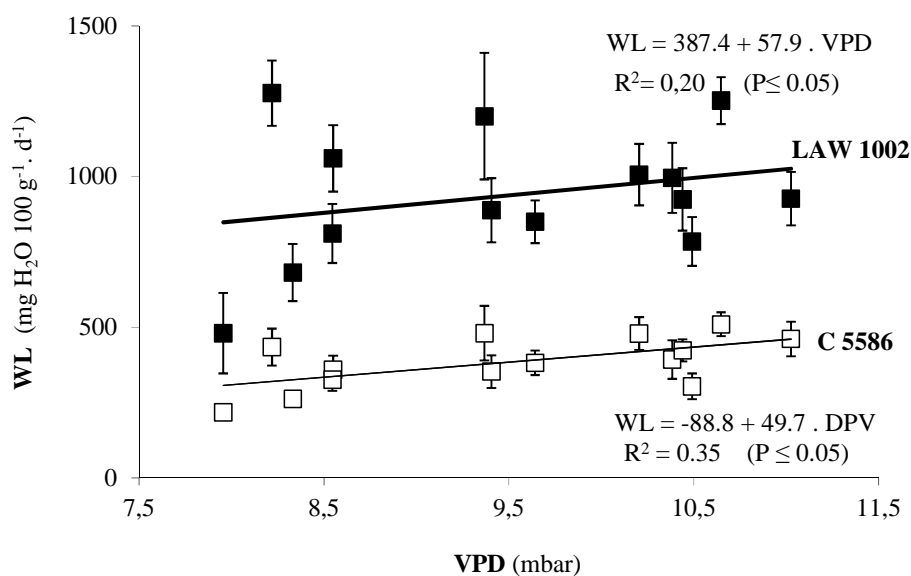


Fig. 4. Effects of daily vapour pressure deficit (VPD) on average water loss (WL) of 'LAW 1002' and 'C5586' cultivars. Solid lines were fitted by linear regression and vertical bars represent SE

Now, considering the highest and lowest water loss (WL) 'LAW 1002' and 'C5586' were chosen for study of other physical factors that were related with the difference of water loss during the postharvest storage. Although the mean value of the VPD was 9.5 mbar, its fluctuation was recorded daily to observe its effect on fruit water loss (WL) for 'LAW 1002' and 'C5586' cultivars. A linear positive relationship between VPD and WL was observed for both cultivars (fig. 4), which was in accordance with the previous equation where VPD represents the magnitude of water potential differences between inside and outside of the fruit. Similar effects of VPD on WL were obtained in

pears, whereas in tomato fruit the rates of softening depends on both temperature and VPD [Maarten et al. 2004]. Linear equation for 'LAW 1002' had significant slightly higher slope than that of 'C5586' (57,9 vs 49,7) (fig. 4), but depended in the y-intercept value which was near 4.4-fold higher for 'LAW 1002'. Consequently, the water loss of 'LAW 1002' was at least 550 mg H₂O 100 g⁻¹ d⁻¹ significant higher in comparison with 'C5586' (fig. 4). VPD is important for fruit water loss as when a tomato fruit is stored at 85% RH, the water vapor loss is halved compared with 50% RH [Shirazi and Cameron 1993].

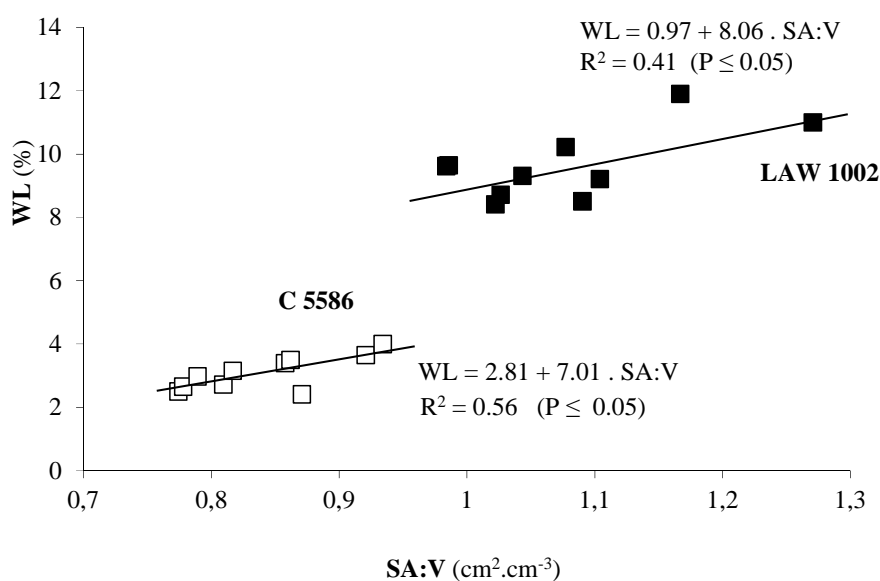


Fig. 5. Relationship of Surface Area: Volume ratio (SA : V) on water loss (WL) on tomato fruits of 'LAW 1002' and 'C5586' cultivars. Solid lines were fitted by linear regression

A positive relationship between the SA : V ratio and fruits water loss (%) was also observed. The magnitudes of the SA : V ratios were in accordance with that measured in other cultivars of tomato [Dodds and Ludford 1990] but in our experiment the SA : V ratio of 'C5586' was consistently lower in comparison without 'LAW 1002', thus fruits of 'C5586' were of smaller size compared with the fruit of 'LAW 1002' (fig. 5). The variation in WL rate from various fruits and vegetables can be explained by the surface area and volume ratio [Ben-Yehoshua 1987, Bartz and Brecht 2005] but very few studies were conducted on tomato. Similar results were observed in eggplant because fruit transpiration rate declined with fruit size [Díaz-Pérez 1998], which means that fruit transpiration decline occur due a reduction in the SA : V ratio. Similarly, in pepper the water loss rate was negatively correlated with surface area [Lownds et al. 1993]. As was observed with the VPD (fig. 5), the equation that expresses the relationship between

SA : V with WL for both varieties showed similar slope but different in the y-intercept values (figs 4 and 5). This means that any changes in the driving force to water movement caused the same effect in the water loss of both varieties, but it also means that the resistance to water movement of both varieties was very different.

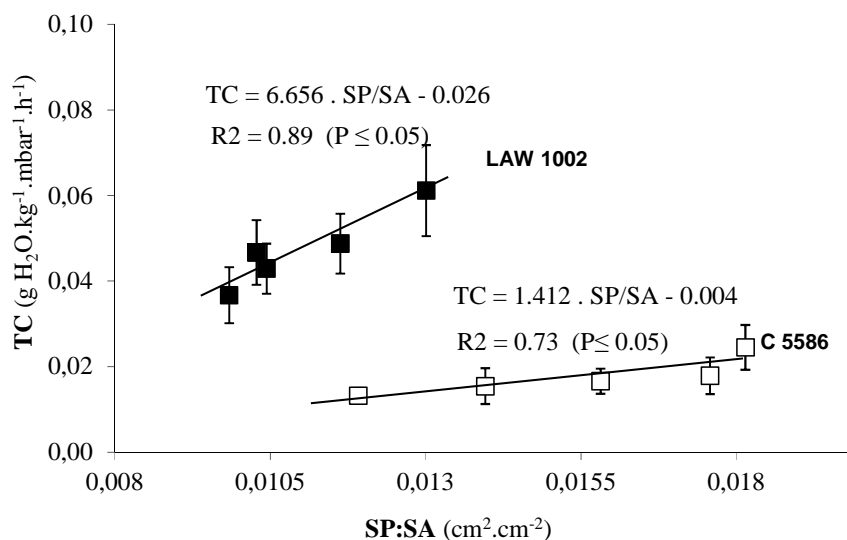


Fig. 6. Relationship between stem scar : surface area (SP : SA) ($\text{cm}^2 \text{cm}^{-2}$) and the Transpiration Coefficient (TC) ($\text{g kg}^{-1} \text{mbar}^{-1} \text{h}^{-1}$) of 'LAW 1002' and 'C5586' tomato cultivars. Solid lines were fitted by linear regression and vertical bars represent SE

Similarly as found with the previous physical characteristics, a positive linear relationship between SP : SA ratio ($\text{cm}^2 \text{cm}^{-2}$) and the transpiration coefficient (TC, $\text{g kg}^{-1} \text{mbar}^{-1} \text{h}^{-1}$) was observed (fig. 6). The slope of the fitted line was significant different in both varieties, being almost five times higher in 'LAW 1002' than in 'C5586'. This is evidence of importance of the stem scar on fruit water loss, which appears as cultivar dependent (fig. 5). However, the relative stem scar surface can not explain the difference in water loss between varieties because 'C5586' had higher relative scar surface but lower transpiration coefficient in comparison with 'LAW 1002'. Although anatomical differences were not observed in the microscopic analysis of two genotypes [Saladié et al. 2007] these comparisons were not in our work. Stem scar was defined as an avenue for fruit water loss, with a relative contribution in tomato fruit transpiration near 70% [Cameron and Yang 1982]. Moreover, the importance of stem scar in water flow can be seen in another direction by the results obtained in studies conducted to measure infiltration of tomatoes by water [Bartz and Showalter 1981]. The water-vapor diffusion occurs through the stem scar (i.e. openings) and the cuticle (i.e. polymer), being the gas diffusion through holes in the stem scar more temperature dependent than diffusion through polymers [Shirazi and Cameron 1993].

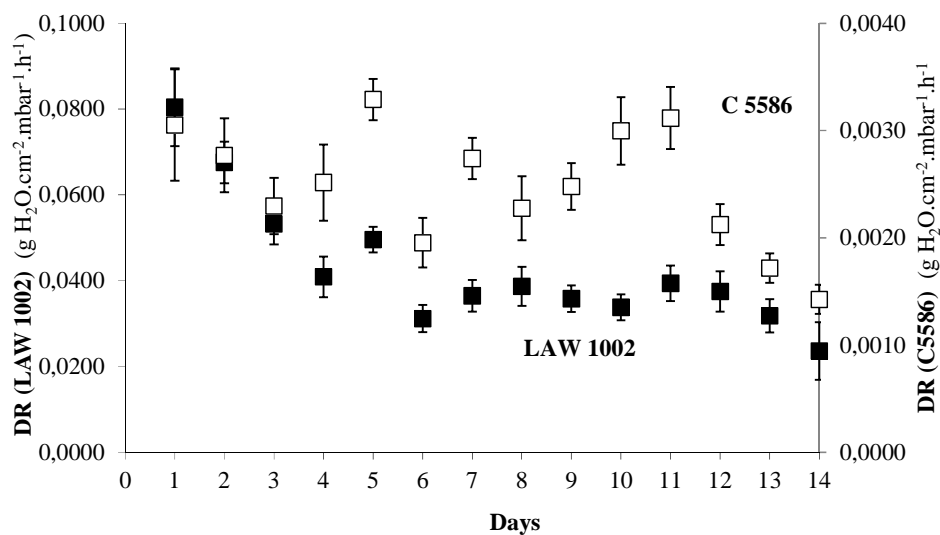


Fig. 7. Relationship between the Diffusion Rate (fruit transpiration rate), DR ($\text{g cm}^{-2} \text{mbar}^{-1} \text{h}^{-1}$) and time (days) after harvest (initial time of this study) for 'Law 1002' and 'C5586' tomatoes cultivars. Vertical bars represent SE

Additionally, the relative importance of both pathways on fruit water loss changes with fruit development because skin permeability decreased with time due to wax deposition on the cuticle [Shirazi and Cameron 1993]. Therefore, the relative importance of water vapor loss through stem scar increases with fruit maturity [Díaz-Pérez et al. 2007].

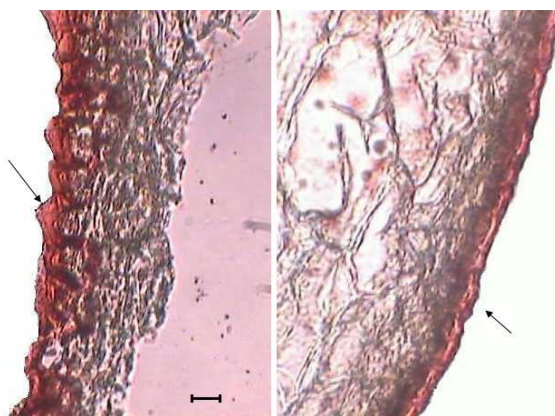


Fig. 8. Photomicrographs of the cuticle (stained with Sudan 4 and indicated with arrows) for the tomato fruit cultivars 'LAW 1002' ($17.5 \mu\text{m}$) and 'C5586' ($17.2 \mu\text{m}$). In the image on the left horizontal line represents $10 \mu\text{m}$

Based on the above, the sealing of stem scar, to reduce water loss appears as an interesting alternative to increase shelf life of tomato fruit; however, the covering of stem scar with lanolin caused a faster deterioration of the fruits [data not shown]. The stem scar is also an important route for oxygen, ethylene and carbon dioxide diffusion, that in tomato can reach values near 97% for O₂ and CO₂ [Cameron and Yang 1982], and consequently, its obstruction can cause serious metabolic disturbances that reduce fruit shelf life, possibly due to the fermentative metabolism.

Transpiration rate during the postharvest period did not show the same pattern of evolution in the two tomato varieties. In 'LAW 1002', the diffusion rate of vapour water was high at the beginning of the storage period and showed a continuous decline during the first five days of storage. In the other hand, DR during postharvest remained stable in 'C5586' and always lower than that of 'LAW 1002' (fig. 7).

It is evident that the resistance to fruit water loss increased by two fold with time in 'LAW 1002'. The great difference on fruit transpiration rate between both varieties, which was near 8-fold higher at the beginning of the postharvest (fig. 7), can not be explained by cuticle thickness (fig. 8) since all tomato varieties showed similar values, ranging from 15.03 µm in 'Colt 45' and 17.48 µm in 'LAW 1002' (tab. 1). However, we measured the cuticle thickness only at the beginning of the experiment and consequently it was not possible to explain if the change of the transpiration rate of 'LAW 1002' during postharvest is a consequence of changes in cuticle density. However, the cuticle permeability is not necessarily correlated with its thickness or degree of wax coverage, but is more likely to be determined by the chemical composition and/or the assembly of its compounds [Kerstiens 2006]. Other workers have suggested that there is no correlation between the amount of cutin and the permeability of the cuticle to water [Isaacson et al. 2009]. These results obtained in tomato were different in comparison with pepper, in which epicuticular wax quantity are correlated with water loss rate during postharvest [Lownds et al. 1993].

Table 1. Cuticle thickness (µm) of fruit pericarp of ten tomato cultivars. Value are means ± SE

Cultivars	Cuticle thickness (µm) ^a
LAW1030	16.9 ±2.2
LAW1002	17.5 ±3.0
Superman	16.5 ±3.5
Colt45	15.0 ±2.4
C5586	17.2 ±3.5
C5605	16.3 ±3.22
LAW1025	15.9 ±3.9
Alambra	16.2 ±3.0
Colibrí	16.5 ±3.3
Cano	16.9 ±3.9

^a – no significant differences LSD 99%

There is scarce information about fruit water loss through the stem scare during postharvest, which showed high correlation with fruit transpiration (fig. 6). Our data can not explain whether the change in postharvest transpiration rate of 'LAW 1002' was due

to changes in water loss through the cuticle, through the stem scar, or from both routes. A better understanding of the relationships between the physical characteristics of tomato fruit and fruit water loss can help phenotypic selection to improve shelf life and shipping suitability of tomato fruit.

CONCLUSIONS

Current research indicates that postharvest water loss in pink and light red tomato fruit during storage at 25°C and 9.5 mbar VPD was cultivar dependent. Cultivars that showed high fruit transpiration had high initial fruit water content (IWC). The comparison of varieties with high fruit transpiration showed a linear relationship between VPD and surface area : volumen ratio (SA : V) with fruit transpiration. With, both varieties showing the same slope but different y-intercept value. The stem scar : surface area ratio (SS : SA) was the physical fruit property that had highest correlation with fruit transpiration. Cuticle thickness showed no association with water loss at the beginning of postharvest. Transpiration rate of 'LAW 1002' but not of 'C5586' decreased with time during postharvest, but we can not explain if water loss from the cuticle, from the stem scar, or both routes of water loss were responsible for the changes in transpiration rate. Physical fruit characteristics were strongly related with genotype and they may be important in tomato breeding in order to increase fruit postharvest storage life.

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RELACJE MIĘDZY RÓŻNYMI FIZYCZNYMI WŁAŚCIWOŚCIAMI OWOCÓW POMIDORA A UTRATĄ WODY PO ZBIORZE

Streszczenie. Utrata wody przyczynia się do przyspieszenia starzenia się pomidorów (*Solanum lycopersicum* L.). Badano 10 odmian reprezentujących dwa typy owoców. Owoce przechowywano w temperaturze 25°C przy 75% wilgotności względnej. Badano cechy fizyczne w celu określenia związków między fizycznymi cechami a wskaźnikiem utraty wody w owocach pomidora. Wskaźnik utraty wody wzrastał prawie w sposób liniowy wraz z czasem przechowywania i był inny dla każdej odmiany. Zwiększony deficyt ciśnienia pary wpływał na wskaźnik utraty wody w owocach poszczególnych odmianach. Wskaźnik utraty wody był pozytywnie skorelowany z początkową zawartością wody w owocach. Zwiększenie powierzchni do objętości owocu może wyjaśniać różnice w utracie wody zaobserwowane pomiędzy odmianami. Grubość skórki nie wpływała na różnice w utracie wody podczas przechowywania. Zaobserwowano jednak dodatnią korelację między stosunkiem powierzchni blizny po szypułce a powierzchnią owocu w stosunku do utraty wody w owocach pomidora.

Słowa kluczowe: *Solanum lycopersicum* L., odmiany, transpiracja, cechy fizyczne

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