



# Tomato cv. 'Micro-Tom' as a model system to study postharvest chilling tolerance

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## ABSTRACT

Storage at low temperature is a common practice to extend the market life of many vegetables. Among other horticultural crops, tomato fruit suffers chilling injury when it is stored under refrigerated conditions. Much effort has been made to understand the mechanisms of generation of this physiologic disturbance, but many aspects need to be clarified yet. Tomato (*Solanum lycopersicum*) cv. "Micro-Tom" is a miniature tomato plant with various properties that make it useful as a model system in plant biology. In this work, the potential of tomato cv. "Micro-Tom" fruit as a model to study chilling injury was investigated. The effect of postharvest chilling was compared on cvs. "Micro-Tom" and "Minitomato", another variety with fruit of similar size. Green mature fruits cvs. "Micro-Tom" and "Minitomato" were harvested and stored during 4 weeks at 4 °C. It was observed that tomato cv. "Micro-Tom" fruit was clearly tolerant to chilling while tomato cv. "Minitomato" fruit developed severe chilling injury symptoms and avoided ripening. Harvest and chilling altered the length of time between the different ripening stages, the development of red full color and smell. Also, it was shown that harvesting fruits by visual appreciation is a rapid and useful method for distinguishing the different ripening stages during tomato cv. "Micro-Tom" fruit ripening. These results showed that tomato cv. "Micro-Tom" fruit was able to counteract the strain resulting from the imposed chilling stress. Altogether these data indicate that tomato cv. "Micro-Tom" fruit is a good model to study the mechanism of postharvest chilling response and tolerance in tomato.

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## 1. Introduction

The market life of fruits and vegetables can be extended through storage at low temperature (Kader, 2003). This practice decreases metabolic and pathogenic activities and facilitates exportation by allowing long distance shipment and more regulated supply of fruit in the market. However, storing these products below critical temperatures may result in a physiological disorder known as chilling injury that generates high economic losses and stresses applied to fruit production. While physiological and biochemical events involved in chilling injury have been extensively described, much

remains to be understood about the precise molecular mechanisms of its generation and tolerance mechanisms.

Tomato (*Solanum lycopersicum*) fruit is chilling sensitive at temperatures below 10 °C if held for longer than 2 weeks or at 5 °C for longer than 6–8 days affecting the final fruit quality (<http://postharvest.ucdavis.edu/pfvegetable/Tomato/>). Symptoms of chilling injury are failure to ripen and to develop full color and flavor, premature softening, skin depressions (pitting), browning of seeds, and increased decay. Development of chilling injury symptoms depends upon several factors: preharvest conditions, maturity at harvest, postharvest handling including storage time and temperature and cultivar sensitivity. It has been reported that green mature fruit cv. "Micro-Tom", a dwarf cultivar bred for home gardening purpose (Scott and Harbaugh, 1989), stored at 4 °C during a month is capable of ripening to the red stage inducing its antioxidant system (Malacrida et al., 2006). Tomato cv. "Micro-Tom" small size, rapid growth, short life cycle for the fruit harvest after sowing and easy transformation (Sun et al., 2006), have made tomato cv. "Micro-Tom" plants a convenient model system for research on different fields. Several studies have been conducted on tomato genetics (Meissner et al., 1997), carbohydrate metabolism

**Abbreviations:**  $G_{on}$ ,  $Y_{on}$ ,  $O_{on}$  and  $R_{on}$  green, yellow, orange and red fruit ripened on the vine;  $Y_{off}$ ,  $O_{off}$  and  $R_{off}$  yellow, orange and red fruit ripened off the vine;  $G_{ch}$ , green fruit chilled;  $Y_{ch}$ ,  $O_{ch}$  and  $R_{ch}$  yellow, orange and red fruit chilled and ripened off the vine.

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(Obiadalla-Ali et al., 2004), hormonal functions and interactions (Campos et al., 2010), microbial plant interaction (Park et al., 2007), arbuscular mycorrhizal symbiosis (Salvioli et al., 2012), Solanaceae genomics (Aoki et al., 2010), amino acids metabolism (Ferraro et al., 2012; Scarpeci et al., 2007; Sorrequia et al., 2010), and in molecular breeding of tomato fruit shelf-life (Okabe et al., 2012). The “Micro-Tom” phenotype is due to at least three mutations: *self-pruning* (producing a determinate phenotype), *dwarf* (reducing internode length and producing smaller, rugose, and dark-green leaves) and *miniature* (likely to be associated with gibberellin signaling) (Marti et al., 2006; Meissner et al., 1997). An important characteristic of tomato cv. “Micro-Tom” fruit is that it can ripen after postharvest chilling at 4 °C. Additionally, this fruit showed a high antioxidant response (Malacrida et al., 2006). These data led us to evaluate deeply the behavior of tomato cv. “Micro-Tom” fruit after postharvest chilling.

To reduce the degree of variability in ripening experiments, assessment of ripening stages should be as accurate and rapid as possible. The harvest of tomato fruit is usually based on a comparison of color fruit to color charts, time from anthesis (Zhang et al., 2009), time from breaker stage or green mature stage, determination of the color parameters or the firmness, or both, and Raman spectroscopy (Qin et al., 2012). Several of these techniques are time-consuming and not adequate when immediate fruit processing is required. On the other hand, when tomato cv. “Micro-Tom” fruits were harvested employing periods’ based methods and visually inspected (externally and internally), they do not show developmental synchrony. In this work, it is shown that external visual appreciation of color corresponds with color parameters. This criterion helps to make a quick harvesting of fruits and fulfills the requisite of uniformity in fruit developmental stages. Additionally this approach was used to evaluate the chilling effect on the final quality of tomato cv. “Micro-Tom” fruit.

## 2. Materials and methods

### 2.1. Plant material

Tomato (*S. lycopersicum*) plants (cvs. “Micro-Tom” and “Minitomato”) (Kisaka and Kida, 2003) were grown in a controlled environment cabinet under a light intensity of 400  $\mu\text{mol s}^{-1} \text{m}^{-2}$  at the top of the plants containing the fruit. The temperature ranged from 25 °C during the light period (14 h) to 18 °C in the dark, and the relative humidity was 70%. Plants were grown in soil, continuously maintained under optimal irrigation, and supplied weekly with half strength Hoagland solution (Malacrida et al., 2006).

Fruit ripening was tested under three different conditions (Fig. S1): on the vine (fruits were allowed to ripen naturally on the plant), off the vine (fruits were picked at the mature green stage and directly placed on a shelf in the growing cabinet), and chilled (fruits were harvested at the mature green stage, stored for four weeks at 4 °C, and then transferred back to the growing cabinet). Fruits were collected by visual appreciation at the mature green (G), yellow (Y), orange (O), and red (R) stages. G, Y, O and R are accompanied by a subscript referring to the ripening conditions: on-ripening on the vine, off-ripening off the vine, ch—4 weeks postharvest storage at 4 °C and ripening on the shelf. Mature green fruit was collected when fruit stopped growing and had a whitish coloration at the blossom end.

### 2.2. Chilling injury evaluation

Chilling injury severity was assessed by determining the capacity of the fruits to reach the red stage under the different ripening conditions. Their maturation was checked visually during 15 days.

Also, the fruits were inspected to determine deterioration, infections and pitting (decay). Fifty fruits for each variety and treatment were tested.

### 2.3. Determination of the duration of transition periods between different ripening stages

Flowers were tagged at anthesis and the development and ripening of fruits on the vine, off the vine and off the vine with previous chilling were registered and monitored daily. The ripening stage (G, Y, O and R) was defined by visual appreciation.

### 2.4. Color determination

Fruits were cleaned, dried, cut transversely through the center and placed on the scanner (Hewlett Packard) with the cut side down and a black background. The images obtained were analyzed employing “Tomato Analyzer Color Test” (Rodriguez et al., 2010) designed to quantify the color parameters R (red), G (green), and B (blue) of the RGB color space. The average RGB values were employed to calculate  $L^*$ ,  $a^*$ ,  $b^*$  of the CIELAB color space and Hue and Chroma color descriptors. The scanner color calibration was achieved employing Color checker Munsell Color X-write.

### 2.5. Assessment of total soluble solids and firmness

The soluble solids content was determined employing a hand SO-RH digital refractometer, previously calibrated with distilled water. Values were expressed as a percentage of glucose and fructose in the juice from ripe fruits (1 °Bx). Firmness was determined on two points of each fruit using a Fruit Pressure Tester-12.5-N type shore with a tip of 0.1 in 0–100 scale. Analyses were carried out in forty fruits.

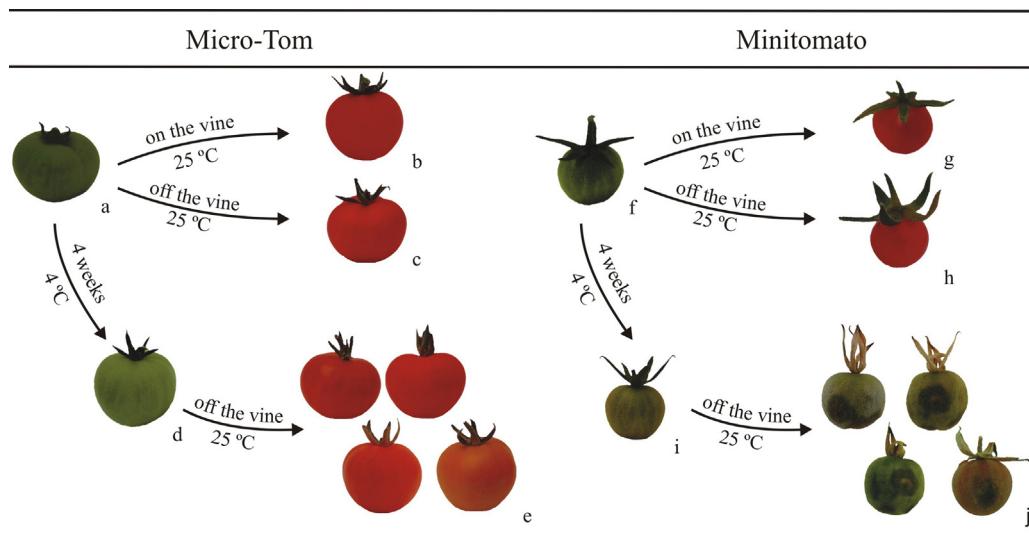
### 2.6. Sensory analyses

Ten tomatoes from each treatment were washed, dried and placed on white trays labeled with three-digit numbers. The same ten tomatoes were evaluated by all panelists for skin color and appearance. Another ten tomatoes from each treatment were washed with tap water, dried and cut in half in order to evaluate odor and sweetness, acidity and juiciness-by-mouth. Two tomatoes were evaluated by each panelist. Ten panelists (5 men, 5 women) who responded affirmatively to liking and frequently consuming tomatoes were recruited from students or staff at IBR. Sensory attributes and their definitions were discussed. All panelists were given the opportunity to practice the procedure in advance. Panelists evaluated the attributes of tomato samples on four-point scales.

## 3. Results

### 3.1. Chilling injury of tomato cvs. “Micro-Tom” and “Minitomato” fruits

Tomato cvs. “Micro-Tom” and “Minitomato” fruits were harvested at mature green stage and evaluated for chilling injury symptoms after storage during four weeks at 4 °C. These varieties were chosen for comparison because of their fruit similar size, and to avoid the effect of surface to area volume ratio. Green fruits of the two varieties (Fig. 1a and f) were also picked from the plant and ripened off the vine. These fruits evolved on the shelf to a red-ripe stage (Fig. 1c and h) visually similar to tomatoes fully ripened on the vine (Fig. 1b and g). When tomato cvs. “Micro-Tom” and “Minitomato” fruits were taken off the camera after four weeks at 4 °C storage, they were still green and were mostly free of chilling



**Fig. 1. Postharvest chilling of tomato fruits cvs. "Micro-Tom" and "Minitomato".** Fruits were harvested at the mature green stage (a and f), stored during four weeks at 4 °C (d and i) and then, let to ripen at 25 °C. Tomato cv. "Micro-Tom" fruit reached red stage (e). Tomato cv. "Minitomato" fruit developed chilling injury symptoms (j). Control fruits ripened on the vine (b and g) and off the vine (c and h) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

injury symptoms (Fig. 1d and i). However, a clear difference was observed between the two varieties after being returned to growth temperature. Tomato cv. "Minitomato" fruit, within four days, had developed clearly visible symptoms of chilling injury, only 10% of the fruits turned red and 75% deteriorated or rotted (Table 1 and Fig. 1j). On the other hand, tomato cv. "Micro-Tom" fruit did not decay and developed color. Within these fruits, 88% reached the red stage while the rest did not reach full red color (Table 1 and Fig. 1e). Overall, these results showed that tomato cv. "Micro-Tom" fruit is clearly tolerant to chilling while tomato cv. "Minitomato" fruit is highly susceptible and developed chilling injury symptoms.

### 3.2. Determination of the ripening stages of tomato cv. "Micro-Tom" fruits

When sampling tomato cv. "Micro-Tom" fruits at a specific ripening stage according to days after anthesis, after mature green or breaker stage, huge heterogeneity was observed. Therefore, visual appreciation of fruit ripening stages while ripening on the vine, off the vine and after the postharvest chilling storage was evaluated.

Fruits, which were ripened on the vine, off the vine and off the vine after storage during four weeks at 4 °C were initially classified by visual evaluation performed according to four color categories: green, yellow, orange and red. Green fruit was harvested when fruit stopped growing and had a whitish coloration at the blossom end (Ré et al., 2012). There were definite color changes in the fruits during ripening, and there were no fruits showing combination of

different colors. Next, fruit color was internally analyzed by quantitative measurements of  $L^*$ ,  $a^*$ ,  $b^*$ , hue, chroma, red, green, and blue values using tomato analyzer (Fig. 2). Analyses of these data employing k-means clustering identified four fruit groups: red fruit ripened on the vine (Group 1), red fruit ripened off the vine and after postharvest chilling (Group 2), orange fruits ripened in all conditions (Group 3) and another group formed by all green and yellow fruits (Group 4). Yellow (Group 4a) and green fruits (Group 4b) were differentiated as different groups when only parameter values determined for these fruits were employed for clustering analyses (Table 2). The color data obtained were also represented by a PCA 2D plot (Fig. 3) defined by 2 PCs (PC1: 24.71% and PC2: 61.66%). The PCA 2D illustrates how the fruits harvested by visual appreciation are distinguishable on the basis of their color parameters.

### 3.3. Duration of developmental and ripening periods of tomato cv. "Micro-Tom" fruit

Giving that visual appreciation was supported by quantitative color measurements and clustering analyses, this method was employed to determine the elapsed time from anthesis to mature green stage and between the different ripening stages. The period from anthesis to the green stage spanned from 23 days to 66 days with a maximum frequency at 23–29 days (Fig. 4). It is worth to note that all green mature fruit harvested, and let to ripen on the shelf, developed red color, showing that they were mature fruits, physiologically competent to ripen off the vine.

**Table 1**

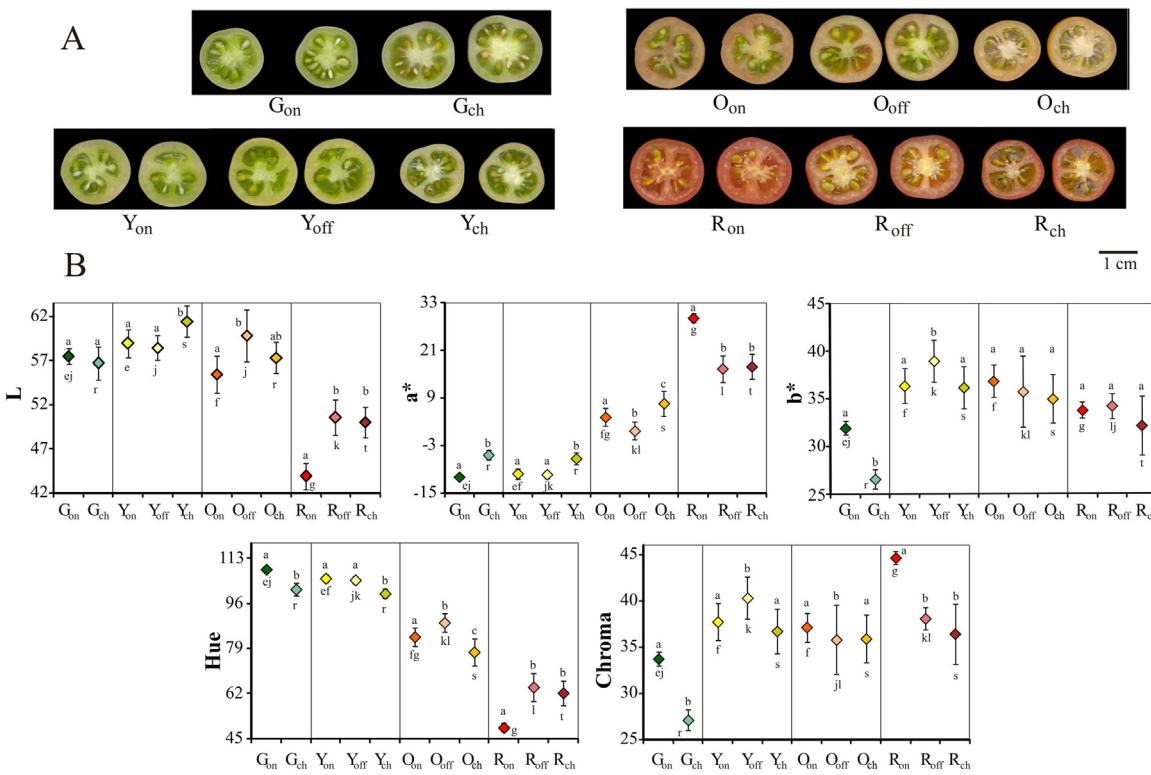
Chilling injury after four weeks postharvest conservation at 4 °C of tomato fruits cvs. "Micro-Tom" and "Minitomato".

	Decay (%)	Reach red stage (%)
<b>cv. "Micro-Tom"</b>		
On the vine	0	100
Off the vine	0	100
Chilled	0	88 ± 3
<b>cv. "Minitomato"</b>		
On the vine	0	100
Off the vine	0	100
Chilled	75 ± 3	0

**Table 2**

Description of fruit groups obtained by cluster analyses of color parameters of fruits harvested by visual appreciation. The numbers indicate the number of each fruit type in the group. R, O, Y, G (red, orange, yellow and green). The subscript refers to the ripening conditions: on—ripening on the vine, off—ripening off the vine, ch—4 months postharvest storage at 4 °C and ripening on the shelf.

Group	Fruit description
1	9R <sub>on</sub>
2	9R <sub>off</sub> –9R <sub>ch</sub> –10 <sub>on</sub> –10 <sub>ch</sub>
3	8O <sub>on</sub> –9O <sub>off</sub> –8O <sub>ch</sub>
4a	9Y <sub>on</sub> –9Y <sub>off</sub> –9Y <sub>ch</sub>
4b	9G <sub>on</sub> –9G <sub>ch</sub>



**Fig. 2. Color parameters of the fruits harvested by visual appreciation.** Panel A: Cross section fruits used for color analysis through tomato Tomato Analyzer 3.0. Panel B: Color parameters of fruits ripened on the vine, off the vine and chilled. Values are mean  $\pm$  standard deviation. Means with the same letter are not significantly different ( $p \leq 0.05$ ).

Also the duration of the ripening transitions: green to yellow, yellow to orange, and orange to red were determined on the vine, off the vine, and off the vine after postharvest chilling (Fig. 5). Green to yellow was slowed down by postharvest chilling while it was not practically affected by harvesting. Yellow to orange and orange to red transitions were shortened when the fruit ripened off the vine with previous chilling or not. The ripening process was shortened down from  $13 \pm 2$  days to  $10 \pm 3$  days when the fruit ripened off the vine immediately after it was harvested after  $4^{\circ}\text{C}$  storage during a month.

### 3.4. Effect on tomato qualities

The influence of harvesting the mature green tomato fruit and chilling during four weeks on the quality of the final product, the Micro-Tom red fruit, was evaluated.

#### 3.4.1. Color

The color parameters ( $L^*$ ,  $a^*$ ,  $b^*$ , Hue and Chroma) obtained with Tomato Analyzer 3.0 were also analyzed to evaluate the influence of ripening conditions on color. Red fruits were clustered in Group 2 ( $R_{\text{off}}$  and  $R_{\text{ch}}$ ) and group 1 (only  $R_{\text{on}}$ ) (see Table 2). All  $R_{\text{on}}$  parameters, except  $b^*$ , were significantly different from the values of red fruits ripened off the vine after cold storage or not (Fig. 2). Hierarchical cluster analysis (Euclidean distance) was conducted for each cluster or group formed by PCA analyses (Fig. 3, Table 2), in order to identify the formation of subgroups that show the influence of different ripening conditions on color (Fig. S2). Orange fruits (group 3:  $O_{\text{on}}$ ,  $O_{\text{off}}$  and  $O_{\text{ch}}$ ) did not differ according to whether they were ripened. Also, red fruits ripened on the shelf with cold storage or not (group 2:  $R_{\text{off}}$  and  $R_{\text{ch}}$ ) were not distinguished by this test. By contrast, among the green fruits (group 4b) there is a clear distinction between those that were stored at  $4^{\circ}\text{C}$  ( $G_{\text{ch}}$ ) and recently harvested

( $G_{\text{on}}$ ). The  $G_{\text{on}}$  fruits presented more negative  $a^*$  values and greater Hue and Chroma values than after cold storage, indicating lower proportion of green color and more paleness in the  $G_{\text{ch}}$ . Among the yellow fruits (group 4a in Table 2), the fruits that have been cold storage ( $Y_{\text{ch}}$ ) formed a subgroup that differed from the ripened on the plant ( $Y_{\text{on}}$ ) and on the shelf ( $Y_{\text{off}}$ ).

#### 3.4.2. Firmness and soluble solids

Significant difference in soluble solids content was found between Micro-Tom red fruit ripened on the vine and red fruit ripened off the vine following  $4^{\circ}\text{C}$  storage or not. However, no difference was observed between the red fruits ( $R_{\text{off}}$  and  $R_{\text{ch}}$ ) ripened off the vine. Firmness of  $R_{\text{on}}$ ,  $R_{\text{off}}$  and  $R_{\text{ch}}$  fruits were different,  $R_{\text{on}}$  being the highest (Table 3).

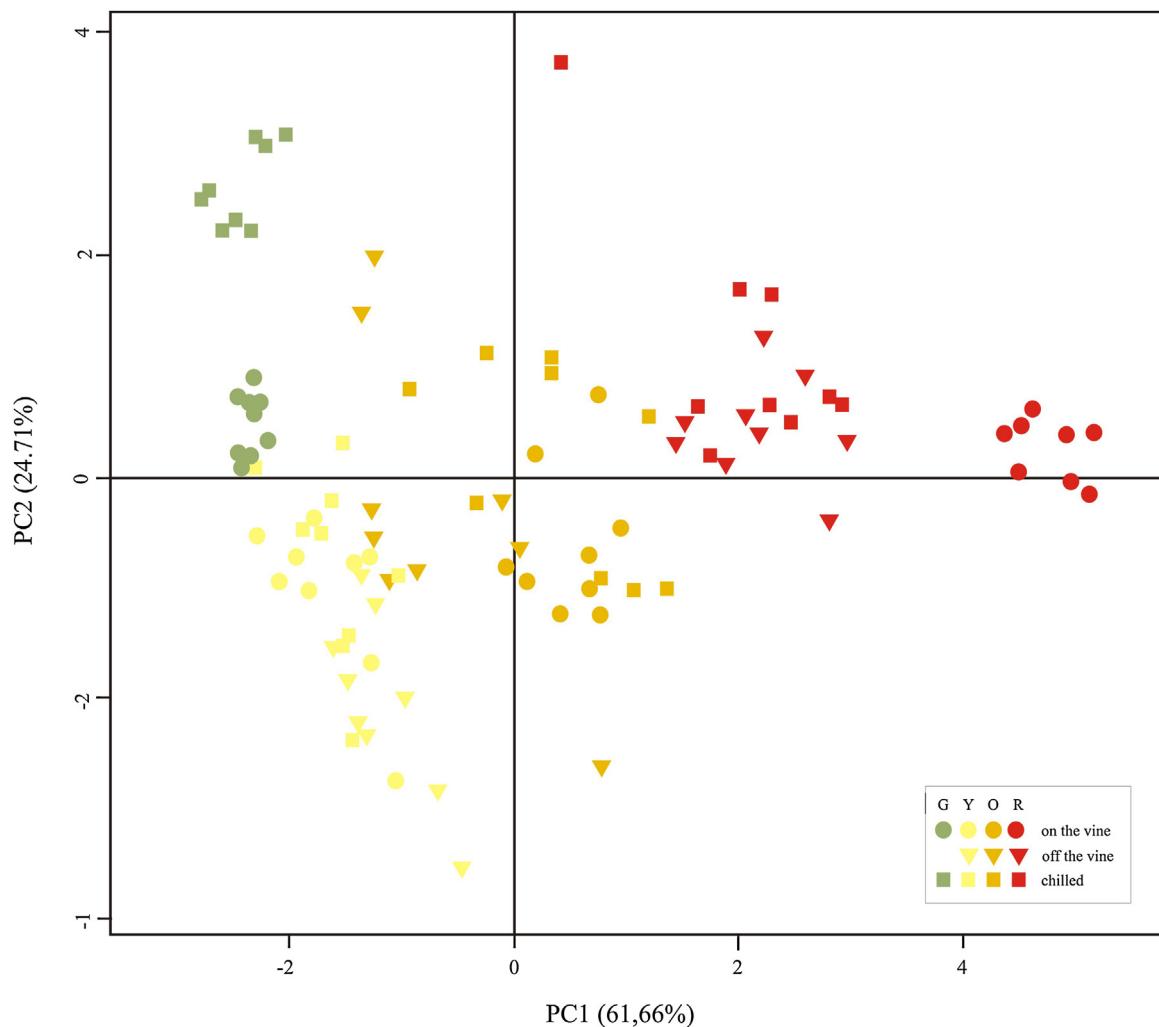
#### 3.4.3. Organoleptic qualities

The red fruits were evaluated for their sensory profile. The attributes evaluated were color, smell, sweetness, juiciness, acidity and general appearance. The mean scores for each tomato sample regarding the attributes evaluated are summarized in Table 4. Red fruits did not show a significant difference for acidity and sweetness.  $R_{\text{ch}}$  and  $R_{\text{off}}$  color, juiciness and general appearance scores were significant different when compare with  $R_{\text{on}}$  scores but not between them.  $R_{\text{ch}}$  presented the lower mean for the smell score.

**Table 3**

**Effect of postharvest chilling on quality characteristics of red fruits.** Values are mean  $\pm$  standard deviation of forty fruits. Means with the same letter within a row are not significantly different ( $p \leq 0.05$ ).

	$R_{\text{on}}$	$R_{\text{off}}$	$R_{\text{ch}}$
Soluble solids	$6.4 \pm 1.3\text{a}$	$4.6 \pm 0.8\text{b}$	$4.8 \pm 0.4\text{b}$
Firmness	$47.3 \pm 4.8\text{a}$	$37.3 \pm 2.6\text{b}$	$40.9 \pm 4.4\text{c}$

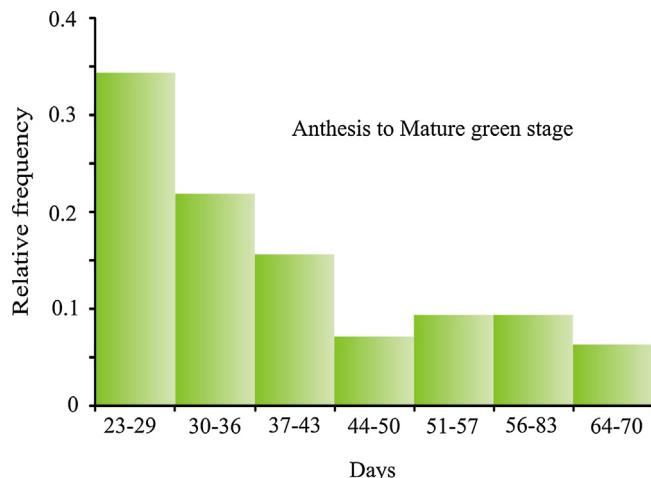


**Fig. 3.** PCA 2D plot illustration of the color parameter of fruits harvested by visual appreciation representing the sample clustering.

#### 4. Discussion

Tomato is one of the most important food plants in the world, and its demand is continuously increasing being necessary to

extend the commercial period and diminish the postharvest losses. When tomato is stored at low temperatures, it suffers chilling injury causing economic and effort loss (Kader, 1986). Many studies have been carried in order to understand the mechanism by which this physiological disorder is generated, but many aspects need to be clarified yet. Otherwise, it is clear that the chilling injury depends upon many factors including cultivar, preharvest conditions and chilling temperature-time combination. Tomato cv. "Micro-Tom" is a dwarf tomato widely used as a laboratory model that combines the benefits of studying a specie with economic importance with the short life cycle and small size suitable for a biological model bringing basic and applied sciences together. In addition, tomato

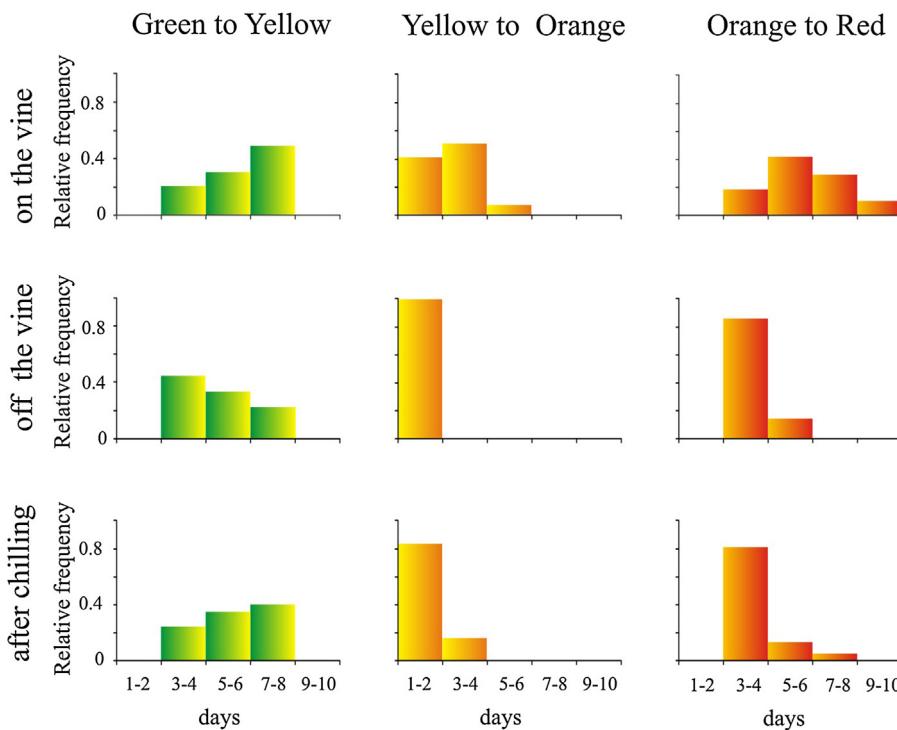


**Fig. 4.** Frequency histogram of the duration of anthesis to green mature period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 4**

**Sensory panel evaluation of chilling effect on red fruit quality.** Ten tomato fruits for each ripening condition (on the vine, off the vine and off the vine with previous chilled) were rated by an experienced sensory panel on a four point scale. Values are mean  $\pm$  standard deviation. Means with the same letter within a row are not significantly different ( $p \leq 0.05$ ).

	$R_{\text{on}}$	$R_{\text{off}}$	$R_{\text{ch}}$
Color	$4.00 \pm 0.00\text{a}$	$1.86 \pm 0.14\text{b}$	$2.00 \pm 0.00\text{b}$
Smell	$3.00 \pm 0.31\text{a}$	$2.43 \pm 0.20\text{a}$	$1.57 \pm 0.30\text{b}$
Sweetness	$2.57 \pm 0.30\text{a}$	$2.00 \pm 0.31\text{a}$	$1.71 \pm 0.29\text{a}$
Juiciness	$3.14 \pm 0.26\text{a}$	$2.28 \pm 0.28\text{b}$	$2.14 \pm 0.26\text{b}$
Acidity	$2.43 \pm 0.30\text{a}$	$2.14 \pm 0.40\text{a}$	$2.43 \pm 0.48\text{a}$
General appearance	$3.43 \pm 0.20\text{a}$	$2.14 \pm 0.14\text{b}$	$1.57 \pm 0.30\text{b}$



**Fig. 5.** Frequency histogram of the duration of the periods between ripening stages.

is the model of choice to study fleshy fruit, whose knowledge can be extended to other fruits. In this study, tomato cv. "Micro-Tom" fruit showed chilling postharvest tolerance after 4 weeks at 4 °C when comparing with another variety (cv. "Minitomato") (Table 1). Tomato cv. "Micro-Tom" fruit has also shown to activate its oxidative system after postharvest chilling (4 weeks at 4 °C) and was able to reach the red stage despite alterations in pigments content (Malacrida et al., 2006) and protein level (Ré et al., 2012). On the other hand, tomato cv. "Micro-Tom" fruit has shown to be sensible to postharvest chilling when minor temperatures (2.5–0 °C) were employed (Luengwilai et al., 2012; Tao et al., 2014). In summary, tomato cv. "Micro-Tom" fruit is able to complete the ripening process after refrigerated storage conditions that other varieties do not resist and to respond to the stress imposed by these conditions. These facts led us to propose tomato cv. "Micro-Tom" as a chilling tolerant cultivar useful to understand the biological mechanisms involved in the fruit response to chilling storage. In addition, while numerous studies in postharvest employ tomato varieties grown under changing environmental conditions tomato cv. "Micro-Tom" fruit can be obtained in high quantities under controlled conditions in a greenhouse.

Nowadays biological processes are studied by applying high throughput technologies (genomics, transcriptomics, proteomics, metabolomics, and beyond) that require rapid methods to take and process the samples. These techniques are usually destructive procedures making impossible to monitor ripening changes on a single fruit. As a result, data from many fruit need to be combined creating much biological variation (Hertog et al., 2004). For tomato fruit, this issue is often tackled harvesting fruits at a time point for each ripening stage after anthesis, green mature or breaker stage. When tomato cv. "Micro-Tom" fruits were harvested applying these criteria, they were visually inspected externally and internally (e.g. size, shape, pigmentation, seed development, and development of the locular jelly), and they showed great heterogeneity. Also, since color is an indicator of tomato ripeness, several rating scales and color charts have been developed for classifying the stage of tomato ripeness. The most used of this scales is the USDA color

classification that considers six ripening stages defined upon percentages of color distribution and intensity (mature green, breaker, turning, pink, light red and red). Tomato cv. "Micro-Tom" fruit color changes uniformly while ripening and single colors can be observed in the same fruit, though four maturity stages (mature green, yellow, orange and red) were considered for harvesting fruits by visual appreciation. Clustering analyses and principal component analyses (Figs. 2 and 3) performed on color parameters clearly identified groups of fruits similar to each other, but different from fruits in other groups and shows that this method is useful for distinguishing the different ripening stages during tomato cv. "Micro-Tom" fruit ripening. The human perception of color has previously been reported to have a positive correlation with the color readings during ripening (Arias et al., 2000) and the results reported here support ripening stage determination by visual appreciation. Furthermore, the dispersion of the number of days from anthesis to mature green fruit (Fig. 4) and between the different ripening stages (Fig. 5) indicates that the definition of tomato cv. "Micro-Tom" fruit maturation stages based on period lengths is unreliable.

Among the physiological and biochemical changes that occur while ripening, the chloroplast to chromoplast transition is the most obvious and eye-catching because it implies change in fruit color due to the massive chlorophyll degradation and accumulation of large amounts of carotenoids within the plastids (Egea et al., 2010). When tomato cvs. "Micro-Tom" and "Minitomato" mature green fruits were removed from four weeks storage at 4 °C, they remained green indicating that the changes in the structure, morphology and composition of the plastids stopped at 4 °C. Tomato cv. "Micro-Tom" fruit was able to resume the ripening program while tomato cv. "Minitomato" fruit failed (Fig. 1). This transition is complex and highly regulated, and it was affected by harvest and chilling as it was observed in the length of time between the different ripening stages (Fig. 5).  $R_{ch}$  and  $R_{off}$  failed to attain full red color showing that also the color development was affected. The chilling storage of the green mature fruit caused a discoloration in the fruit that seemed to be the same effect observed by in the fruit ripened off the vine. Changes in the color development in tomato

resulting from chilling have been reported by other authors (Biswas et al., 2012; Rugkong et al., 2011). Besides the color, only smell was altered by chilling (Table 4) when compared with nonchilled fruits.

## 5. Conclusion

In this work we showed that tomato cv. "Micro-Tom" fruit is tolerant to postharvest chilling under conditions that other varieties do not (4 °C during 4 weeks) despite relatively weak alterations in the final quality of the red fruit. Furthermore, we demonstrated that the ripening stage determination by external visual appreciation is reliable through quantitative measurements of color. Therefore, these results show that tomato cv. "Micro-Tom" fruit is a good model system to study the mechanism of postharvest chilling response and tolerance in tomato.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.scienta.2014.12.020>.

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