Dynamic changes in health-promoting properties and eating quality during off-vine ripening of tomatoes

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Comentario [IL1]: Two Tunisian institutions designated by the same superscript (3). Could it be that it is a mistake?

Review content:

Abbreviations

AsA: ascorbic acid; **AVG:** aminoethoxyvinylglycine; **ºBrix:** degree Brix; **DHA:** dehydroascorbic acid; **DPPH:** 2,2-diphenyl-1-picrylhydrazyl assay; **DWP:** delactosed whey permeate; **FRAP:** ferric reducing antioxidant power assay; **FW:** fresh weight; **GAE:** gallic acid equivalent; **HAA:** hydrophilic antioxidant activity; **HVEF:** high-voltage electrostatic field; **LAA:** lipophilic antioxidant activity; **PLW:** physiological loss in weight; **RH:** relative humidity; **ROS:** reactive oxygen species; **RSA:** radical scavenging activity; **SS:** sucrose synthase; **TA:** titratable acidity; **TEAC:** trolox equivalent antioxidant capacity assay; **TS:** total sugars; **TSS:** total soluble solid; **UV-B:** ultraviolet-B; **UV-C:** ultraviolet-C.

Abstract

Tomato (*Solanum lycopersicon* L.) fruit is rich in various nutrients, vitamins and health-promoting compounds. Fresh tomatoes are an important part of the Mediterranean gastronomy, and their consumption is thought to contribute substantially to the lower incidence of some chronic diseases in the Mediterranean populations in comparison with other world areas. Unfortunately, tomato fruit is also highly perishable; this poses a challenge to storage and commercialization, and results in important economic losses. This review presents summarizes the current knowledge on some important health-promoting and eating quality traits of tomato fruits after harvest. This literature survey highlights the existence of substantial cultivar-to-cultivar variations in the postharvest evolution of the considered parameters, as well as according to maturity stage at harvest and in response to postharvest manipulation. It also suggests the need of adapting postharvest procedures to the characteristics of each particular genotype to preserve the optimal quality of the fresh product.

Keywords: acidity, antioxidant activity, aroma, bioactive molecules, fruit firmness, physiological loss in weight, shelf-life, soluble solids, sugars**.**

INTRODUCTION

Fresh tomato (*Solanum lycopersicon* L.) fruit pose an important set of challenges for postharvest storage due to their high water content and soft texture. These attributes make them highly perishable in nature and difficult to store for a long period without incurring losses and additional costs. After harvest, tomato fruit are no longer supplied with water and solutes by the parental plant; thus, storage conditions play a fundamental role in slowing down decay of the fresh produce and in preserving its quality traits. During tomato fruit ripening and senescence, several biodegradation processes occur, including macromolecule depolymerization, substrate consumption, chloroplast-to-chromoplast transition and pigment alterations, arising mostly from the hydrolytic activity of glycosidases, esterases, dehydrogenases, oxidases, phosphatases and ribonucleases (Tadesse, Workneh and Woldetsadik, 2012). Ripening and senescence are also associated to *de novo* biosynthesis of proteins, nucleic acids, lipids and secondary metabolites including carotenoids (particularly lycopene) and flavor-related aroma volatiles, as well as to processes involved in mitochondria maintenance through transcriptional, post-transcriptional, translational and/or post-translational regulation mechanisms (Workneh and Osthoff, 2010).

Comentario [IL2]: When refeerring to a batch of the same item, the plural form of "fruit" is also "fruit"

In order to preserve satisfactory eating and processing quality, it is important to consider all the major physiological and biochemical characteristics of tomato fruit. Besides flavor, good quality involves appearance, texture and functional properties, attributes that generally deteriorate over time until delivery to the final consumer. The major issue with fresh tomato storage and marketing is the relatively fast quality deterioration which results in short shelf-life potential. Hence, more intensive research efforts are required for reducing quality loss and extending shelf-life of these commodities. The regulation of tomato fruit ripening has been a pivotal investigation focus throughout the last decades. This paper reports a brief review of recent investigations related to postharvest alterations occurring in the content of bioactive molecules, health-promoting properties, biochemical attributes and physical parameters of tomato fruit in response to different factors, including genotype and postharvest manipulation.

CHANGES IN BIOACTIVE MOLECULES AND HEALTH-PROMOTING PROPERTIES DURING OFF-VINE RIPENING OF TOMATO

Health-promoting properties of fruits originate from their content in bioactive molecules capable of partially preventing or delaying the oxidative reactions arising from the presence of metabolically- or environmentally-originated free radicals. These extremely reactive oxygen species (ROS) display one or more unpaired electrons, and comprise mainly superoxide anions, hydroxyl and peroxyl radicals. Although human cells possess endogenous antioxidant systems, the dietary intake of exogenous phytochemicals is required to match the overall antioxidant activity required and to efficiently counteract radical-driven damage, expecially during aging and/or stress conditions. Therefore, the evaluation of the antioxidant power and chemical composition of fresh fruits is becoming an important determinant for their commercialization, as these molecules purportedly contribute to the health-promoting properties of the product. A large part of the health benefits derived from the consumption of plant-derived foods has been attributed to hydrophilic and lipophilic bioactives, mainly ascorbic acid (AsA), glutathione, folates, tocols, carotenoids and phenolics, although these health claims remain in many cases to be clearly established *in vivo* (Espín, García-Conesa, and Tomás-Barberán, 2007).

In this context, tomato is thought to contribute substantially to the lower occurence of some chronic diseases in the Mediterranean population in comparison to other world areas, as it is a major source of the above-mentioned nutrients (Abushita, Daood, and Biacs, 2000; Martínez-Valverde, Periago, Provan, & Chesson, 2002). Carotenoids are the major phytochemicals in tomato, lycopene accounting for up to 90% thereof (Ilahy, Hdider, Lenucci, Tlili, & Dalessandro, 2011; Ilahy et al., 2018). However, available information on changes in the content of bioactive compounds during postharvest ripening is generally scarce. In the following subsections, we provide a brief overview of the published reports on postharvest modifications in quality attributes and quantitative profiles of some of the most important bioactive molecules in fresh tomato fruits.

Total phenolics

Phenolic acids and two flavonoid families (flavanones and flavonols) represent the most abundant phenolics in tomato. Large variation in flavonol concentration has been found across tomato cultivars, but 98% of detected flavonols occurs in the skin (Stewart et al., 2000). The concentration range for phenolic acids among cultivars is also broad, chlorogenic acid being the most prominent compound within this family (Martínez-Valverde et al., 2002), which collectively accounts for up to 75% of total phenolics in tomato fruit. Contrarily to flavonols, phenolic acids reportedly display higher concentrations in the pericarp and inner tissues than in the fruit epidermis (Moco et al., 2007). Finally, the stilbenoid compound resveratrol has also been found in tomato fruit skin at full ripeness (Ragab, Fleet, Jankowski, Park, & Bobzin, 2006).

The metabolic pathways involved in the biosynthesis of different families of phenolics are complex, closely interrelated, and profoundly influenced by internal and external factors (Dixon and Steele, 1999; Manach, Scalbert, Morand, Rémésy, & Jiménez, 2004). Accordingly, significant changes in the content of total phenolics in tomato are expected in response to preharvest factors and postharvest conditions (Dumas, Dadomo, Di Lucca, & Grolier, 2003; Slimestad and Verheul, 2005). Owing to the quantitative and qualitative relevance of lycopene and β-carotene, research on health-promoting properties has focused preferentially on these constituents and has generally overlooked tomato flavonoids. Substantial cultivar-to-cultivar variation in the metabolism of phenolics and flavonoid during tomato ripening and postharvest has been reported (Table 1). When studying the dynamics of phenolics and flavonoid accumulation during ripening of ordinary and high-lycopene tomato cultivars, Ilahy et al. (2011) reported significant differences in total phenolic levels even among cultivars of the same typology. Phenolics levels peaked (310 mg gallic acid equivalent (GAE)/kg Fresh Weight (FW)) at the orange-red stage in cultivar 'HLY18', while for 'HLY13' fruit the highest contents were detected at the green and orange-red ripening stages (223 and 240 mg GAE/kg FW, respectively). However, at the same ripening stages, the ordinary cultivar 'Río Grande' exhibited the lowest phenolics levels (113 and 138 mg GAE/kg FW respectively). The flavonoid levels varied widely throughout ripening stages. The dynamics of flavonoid accumulation was identical in high-lycopene cultivars, although quantitative differences were found in 'Lyco2' fruits. The flavonoid content remained essentially unchanged at later maturity stages, but was consistently higher in high-lycopene tomato cultivars studied throughout ripening in comparison with ordinary cultivars.

The effect of the storage on the phenolic content of tomato fruits is well documented. The content of chlorogenic acid and chalconaringenin, a quantitatively prominent flavonoid in cherry tomatoes, has been reported to decrease sharply during postharvest storage at 20 ºC during 3 weeks (Slimestad and Verheul, 2005), although this loss was less pronounced in fruit stored at lower temperatures. This is an important issue if the health-promoting properties of the product must be preserved, because direct correlation was observed between chalconaringenin levels and antioxidant activity. However, the total amount of phenolics was unchanged during the same period, which means that some other compounds must have compensated for those decreases. Actually, an earlier report found higher amounts of total phenolics in 'Moneymaker' tomatoes after 16 days at 20 ºC (Giovanelli, Lavelli, Peri, &

Nobili, 1999). Cold storage of 'Micro-Tom' tomato fruits at 6 ºC for up to 4 weeks also led to a decreased content of total phenols and chlorogenic acid (Gómez et al., 2009).

Some treatments have been proposed to alleviate the postharvest decrease in total phenolics. Brassinolide treatments (immersion in 3 or 6 μM solution for 5 min) were found to significantly increase the total phenolic content of tomatoes after 3 weeks storage at 1 ºC compared to untreated fruits (Table 1). Interestingly it was associated with the simultaneous increase of phenylalanine ammonia-lyase activity, a key enzyme of phenol biosynthesis (Aghdam, Asghari, Farmani, Mohayeji, & Moradbeygie, 2012). High-voltage electrostatic field (HVEF) pretreatments also increased the levels of total phenols of green ripe tomato fruits after 24 days storage at 13 ºC, compared to the control samples (Zhao, Hao, Xue, Liu, & Li, 2011). Similarly, direct-electric-current application in 'Pannovy' tomatoes increased total phenols by up to 120% in the 24h following the treatment (Dannehl, Huyskens-keil, Eichholz, Ulrichs, & Schmidt, 2011). Delactosed whey permeate (DWP), a novel bio-active product for fresh product storage, has been shown to improve total phenols in 'Moneymaker' tomatoes after 21 days at 15 ºC, concurrently preserving firmness, appearance and aroma, and reducing decay incidence (Ahmed, Martín-Diana, Rico, & Barry-Ryan, 2013).

Furthermore, tissue-specific expression of AtMYB12 (an *Arabidopsis thaliana* transcriptional activator of the caffeoyl quinic acid biosynthesis) in 'Micro-Tom' and 'Moneymaker' tomato backgrounds was found to trigger the accumulation, at very high levels (up to 65-fold higher than controls), of flavonol antioxidants in the ripe fruits, as a result of the up-regulation of most genes involved in phenyl propanoid biosynthetic pathway, including those encoding for phenylalanine ammonia-lyase, chalcone synthase and flavonol-3-glucosyltransferase, whose expression was increased over 100-fold (Luo et al., 2008). This led to a significant increase of the hydrophilic antioxidant activity in the transgenic fruits, and exemplifies the possibility of obtaining fruits fortified in phenolics. Although transgenic approaches achieved promising results in increasing the content of several phytochemicals in tomato fruit (Fraser et al., 2002; Ronen, Carmel-Goren, Zamir, & Hirschberg, 2000; Rosati et al., 2000), some criticism occurred because only a single or a few compounds were enhanced. However, the use of *hp* and *ip* genotypes naturally insure a simultaneous increase in most carotenoid metabolites without quality compromise (Bino et al., 2005; Ilahy et al., 2017; Kolotilin et al., 2007).

Comentario [IL3]: Briefly explain why they could be relevant in this aspect.

Ascorbic acid

AsA is a major indicator of the nutritional value of fresh plant products; thus, the monitoring of the dynamic changes in its level after harvest and during storage is of interest. A cultivar-dependent pattern of change in AsA levels has been reported during ripening of tomato fruit (Table 2). AsA was found to increase in the first phases of ripening and to remain either steady or to slightly decline at the end of the process (Giovanelli et al., 1999; Tigist, Workneh, and Woldetsadi, 2012). This decline was attributed to the involvement of AsA in detoxifying the reactive radicals generated by the increase in respiration rates typical of climacteric fruits (Dávila-Aviña et al., 2011). Accordingly, a survey of different cultivars found the highest AsA contents (184 to 233 mg/kg FW, depending on the cultivar assessed) in firm ripe fruits, while a slight decrease (165-217 mg/kg FW) was observed in the soft ripe ones (Singh, Ray, & Mishra, 1983). When AsA levels were evaluated in fruits of the tomato cultivar ‘Floriset’ at four sequential ripening stages, the highest concentration was observed when the fruits were turning yellow, followed by a decrease at more advanced maturity stages (Abushita, Hebshi, Daood, & Biacs, 1997). In turn, Islam, Matsui, and Yoshida (1996) and Pila, Gol and Rao (2010) observed the highest AsA amounts at the pink stage. In contrast, AsA contents in ‘Marmande-Cuarenteno’ and ‘Ailsa Craig’ tomatoes were observed to remain essentially stable along ripening, and to increase slightly in fully ripe fruit (Cano, Acosta, and Arnao, 2003; Jiménez et al., 2002). Similarly, a progressive increase in AsA content between the green and the red-ripe stages was reported in fruits of ‘Pant T-3’, ‘Pant 2466-27’ and ‘Pusa Hybrid-1’ tomato genotypes, whereas AsA peacked at the yellow stage in ‘SG-12’ and ‘MTH-1’ lines (Siddiqui, Gupta, & Pandey, 1986).

High-pigment or high-lycopene tomato cultivars were claimed to have superior functional quality, leading to good postharvest quality. Therefore, Ilahy et al. (2011, 2018) compared the levels of AsA, dehydroascorbic acid (DHA) and total vitamin C (AsA + DHA) in various high-lycopene tomato cultivars during ripening and the ordinary cultivar ‘Río Grande’ (Table 2). Again, the levels of AsA, DHA and total vitamin C were significantly different throughout ripening, and a genotype-dependent pattern of change was observed. The fruits of the cultivars ‘HLY18’, ‘HLY13’ and ‘Río Grande’ exhibited a peak in total vitamin C content at the orange-red ripening stage (333, 230 and 221 mg/kg FW, respectively). However, ‘Lyco2’ fruits showed the highest total vitamin C content at the green-orange and red-ripe stages. Nevertheless, the fruits of both ‘Lyco2’ and ‘HLY18’ high-lycopene cultivars exhibited higher amounts of total vitamin C than the ordinary cultivar ‘Río Grande’ all along ripening. Therefore, besides higher functional quality, high-lycopene cultivars should exhibit higher postharvest storage potential without quality compromise (Ilahy et al., 2017).

In addition to cultivar-dependent variation, substantial differences in AsA content during postharvest storage have been also observed according to maturity stage at harvest. Tomato fruit harvested at the mature-green stage showed the lowest AsA content, with increasing levels as the ripening process advanced (Getinet, Seyoum, and Woldetsadik, 2008; Giovanelli et al., 1999). Accordingly, Liu et al. (2011) reported that AsA contents increased progressively from the green to the red-ripe stage of ripening (27.2 up to 92.3 mg/kg FW) during dark storage of ‘Zhenfen’ tomato fruits for up to 37 days at 14 °C and 95% relative humidity (RH). Generally speaking, higher AsA contents were detected in light-red tomato fruits, but contents decreased quickly following storage under ambient conditions (Getinet et al., 2008).

Cultivar-to-cultivar variation was also observed in AsA content after harvest: although AsA levels in six fresh market tomato varieties followed a similar, increasing trend during postharvest storage under ambient conditions (15.4-16.2 °C and 34.8-52.4% RH) for up to 20 days to decline thereafter, the processing cultivars maintained roughly 60% higher contents with respect to the fresh market varieties at day 32 after harvest (Tigist et al., 2012) (Table 2).

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Sammi and Masud (2007) studied the effect of ripening and packaging systems on the postharvest storage and quality of 'Río Grande' fruit. The authors found that AsA level was significantly increased along ripening, the highest amounts being attained between the pink-red and the red stages of ripening. Additionally, a pre-packaging treatment of fruit with calcium chloride led to the highest AsA content in comparison with non-treated, packed fruit. Moderate AsA accumulation was observed during storage of hydroponically-grown tomatoes at 7, 15, and 25 ºC (Toor and Savage, 2006). Moneruzzaman, Hossain, Sani, & Saifuddin (2008) detected the highest AsA content in half-ripe tomato (200.5 mg/kg FW) and the lowest content in mature-green fruit (85.8 mg/kg FW). A sharp decrease in AsA content was found after longer storage periods. The maximal AsA content (122.3 mg/kg FW) was recorded in half-ripe tomato fruits following 12 days of storage.

Georgé et al. (2011) reported as much as 80% AsA loss after processing fruit of red and yellow tomato cultivars. Similarly Pérez-Conesa et al. (2009) noted that pasteurization of tomato purée caused a 90% loss of vitamin C. It is widely recognized that cooking, boiling, frying and drying of tomato and tomato pulp under high temperatures lead to extensive loss of AsA (Giovanelli, Zanoni, Lavelli, & Nani, 2002; Sahlin, Savage, and Lister, 2004).

Therefore, Davey et al. (2000) recommended that better AsA retention would be attained under milder treatments and lower temperatures.

Carotenoids (lycopene and β-carotene)

One of the main apparent changes during tomato ripening is the sharp increase in the levels of carotenoids resulting in a progressive shift from green to orange/red pigmentation of the fruit surface. This change of color is the outcome of the *de novo* synthesis of lycopene and β-carotene occurring during chloroplast-to-chromoplast transition and of the concurrent fast degradation of chlorophylls and thilacoidal pigments (Dávila-Aviña et al., 2011; Lenucci, Serrone, De Caroli, Fraser, Bramley, Piro, & Dalessandro, 2012). Radzevičius et al. (2009) reported that lycopene content significantly increased througout fruit ripening of different tomato cultivars (‘Neris’, ‘Svara’, ‘Vytėnų didieji’, ‘Jurgiai’ and ‘Vaisa’ F1). Accordingly, Collins, Perkins-Veazie, and Roberts (2006) observed that lycopene content in soft red-ripe tomato fruits was 50% higher compared to pink tomato fruit, which in turn was 70% higher than that observed in light-red samples. Similarly, Namitha, Archana and Negi (2011) observed the lycopene content to increase gradually between the green and up to the 5^{th} day post-breaker stages, attaining 153.3 mg/ kg FW in ‘Arka Ahuti’ tomatoes (Table 3). Arias, Lee, Logendra, & Janes (2000) found that hydroponically-grown, on-vine ripened greenhouse tomato fruits had 32% lower lycopene content with respect to off-vine ripened fruits. Fruit harvested before full redness (at either the breaker or turning stages) developed similar or higher lycopene content as compared to soft red-ripe stage (Collins et al., 2006).

Various researchers focused on high-lycopene tomato cultivars for their offering higher functional quality and possibly longer shelf-life than traditional cultivars (Ilahy et al., 2017; Lenucci, Cadinu, Taurino, Piro, & Dalessandro, 2006). Ilahy et al. (2011, 2018) monitored carotenoid accumulation in ripening high-lycopene tomato cultivars and revealed that the total carotenoids and lycopene contents notably increased during fruit maturation. Regardless the ripening stage, values were considerably higher in high-lycopene tomato cultivars (‘HLY18’, ‘HLY13’ and ‘Lyco2’) with respect to the ordinary ‘Río Grande’ cultivar. Red-ripe ‘HLY18’ fruits displayed the highest levels of total carotenoids (278 mg β-carotene equivalent/kg FW) and lycopene (254 mg/kg FW). In ‘HLY18’, ‘HLY13’ and ‘Lyco2’ cultivars, lycopene amount in fruits was respectively 2.6-, 2.2- and 1.9-fold higher compared to those from the traditional cultivar ‘Río Grande’. Total carotenoids followed a similar trend as lycopene. This important discrepancy between ordinary and high-lycopene tomato cultivars is primarily attributed to their genome carrying spontaneous high-pigment mutations leading to deeply pigmented fruits compared to traditional and currently grown tomato cultivars (Armendáriz, Macua, Lahoz, Gamica, & Bozal, 2006; Mustilli, Fenzi, Ciliento, Alfano, & Bowler, 1999).

Lycopene content has been found to show considerable cultivar-dependent variation (Sahlin et al., 2004; Tigist et al., 2012) and to increase following prolonged storage periods. Inherent genetic variation across genotypes underlies this variation in carotenoid contents (Tigist et al., 2012). In a survey on different tomato genotypes, lycopene concentration at the green stage ranged from as low as 2.5 mg/kg FW in fruit from the ‘Vaisa’ hybrid to 14.2 mg/kg FW in the cultivar ‘Svara’, while the highest lycopene contents (125.1 mg/kg FW) were observed for fully ripe ‘Neris’ fruit (Radzevičius et al., 2009) (Table 3).

Carotenoid levels are also impacted by storage conditions (Table 3). Toor and Savage (2006) pointed out that tomato fruits stored at 15 and 25 ºC exhibited visually deeper red color compared to those kept at 7 ºC, due to the accumulation of up to 1.8-fold higher contents of lycopene, in average. In another study conducted on two different medium-sized tomato cultivars from hydroponic (‘Pyramid’) and non-hydroponic production bought from a local supermarket, Ajlouni, Kremer, and Masih (2001) noted an increase in lycopene levels during storage at 22 ºC for 14 days, from an initial level of 36/mg/kg FW in both cultivars to 90 and 115 mg/kg FW for hydroponic- and non-hydroponic-produced fruit, respectively. Similarly, Pila et al. (2010) studied lycopene accumulation patterns in partially ripened, orange-yellow and uniformly sized ‘Himsona’ tomato fruit freshly grown under open field conditions in Gujarat, India, throughout 10 days storage at ambient conditions, and revealed progressive increases during the experimental period, ripe fruit reaching values of up to 33.1 mg/kg FW.

In addition to storage conditions, maturity stage at harvest is likewise an influential factor for postharvest lycopene levels. For instance, tomato fruit harvested at the breaker ripening stage attained a peak in lycopene after six days at room temperature (Thompson et al., 2000). Lycopene content doubled during the transition between the pink and the firm or the soft red stage of ripening following 3-8 days storage, depending on the considered genotype (Brandt, Pék, Barna, Lugasi, & Helyes, 2006; Collins et al., 2006; Thompson et al., 2000). In accordance with these earlier reports, lycopene content in mature green tomatoes increased during the course of 37 days storage from 1.6 to 68.0 mg/kg FW (Liu et al., 2011). The lycopene contents of hydroponically-grown tomatoes harvested at light-red to red-ripe stages increased significantly during storage for up to 14 days, and were higher in fruit kept at room temperature with respect to those kept under refrigeration (Javanmardi and Kubota, 2006). Light has also been found to have an impact on lycopene contents, which increase notably throughout 16 days in dark-stored tomato fruit. In fact, Alba, Cordonnier-Pratt, and Pratt (2000) showed that lycopene biosynthesis during ripening of tomato fruit harvested at the mature-green stage was stimulated (2.3-fold higher) following a brief red-light treatment. A far-red light treatment of the same fruit reversed the observed light-induced accumulation of lycopene, suggesting the regulation by fruit-localized phytochromes. When lycopene was analyzed in ’Red Ruby’ tomato fruits harvested at the breaker stage and stored at 12-14 °C in the dark, a 3.5-fold increase (85 mg/gDW) was observed after 15 days storage (Liu, Zabaras, Bennett, Aguas, & Woonton, 2009). Carotenoid contents in tomato discs remained unchanged until the fouth day of storage, to increase afterwards following 4 days of dark incubation or following exposure to either red-light or red-light followed by far-red light treatment (Schofield and Paliyath, 2005).

Abushita et al. (1997) and Giovanelli et al. (1999) detected that β-carotene concentration increased during ripening in parallel with rapid lycopene biosynthesis as shown by changes in fruit coloration (Table 3). Namitha et al. (2011) reported a gradual increase in β-carotene content (4.6 to 103.7 mg/kg FW) between the mature-green and 10 days post-breaker stages of ripening. It has been reported that β-carotene content increases linearly from the green (3.3 mg/kg FW) to the full-ripe stages (36.8 mg/kg at 3 weeks post-breaker) (Fraser, Truesdale, Bird, Schuch, & Bramley, 1994). Radzevičius et al. (2009) also showed that β-carotene contents in tomato fruits increased during ripening, whereas Thiagu, Chand, and Ramana (1993) found that the levels of β-carotene continued to increase till the pink stage of ripening and sharply declined afterwards. A non significant decrease in β-carotene level after full ripeness stage was noted only in 'Svara' tomato fruit. A limited increase between not fully ripe and fully ripe stages was noted in 'Vaisa' F1 fruit. Biacs, Daood, Czinkotai, Hajdú, & Kiss-Kutz (1987) observed a β-carotene peak in yellow-colored fruit of the processing cultivar 'Ventura', which then dropped. Biacs et al. (1987) and Cano et al. (2003) reported that β-carotene level increased from the green to the breaker stages up to 4.9 mmol/kg FW and then decreased to 3.4 mmol/kg FW.

Hdider, Ilahy, Tlili, Lenucci, & Dalessandro (2013) assessed six high-pigment tomato cultivars ('Lyco1', 'Lyco2', 'HLY02', 'HLY13', 'HLY18' and 'Kalvert') in comparison to the ordinary 'Donald' variety. These authors reported that β-carotene and lycopene contents showed similar variation trends. At the red ripe stage, 'HLY13' and 'HLY18' tomatoes also exhibited the highest level of β-carotene (19.8 and 19.3 mg/kg FW, respectively) indicating that, in these varieties, high lycopene amounts were associated with accordingly high β-carotene contents. Such contrasting differences between high-lycopene and ordinary tomato cultivars were ascribed to genotypic differences and growing conditions (Dumas et al., 2003; Ilahy et al., 2016, 2017, 2018). High-pigment tomato cultivars carry spontaneous high-pigment mutations leading to exaggerated light-responsiveness and deep red-pigmented mature fruit compared to ordinary and traditional tomato cultivars (Atanassova, Stoeva-Popova, and Balacheva, 2007; Mustilli et al., 1999). For all the studied cultivars, β-carotene levels were lowest at the green stage, increasing afterwards till the table ripeness red stage. This increase was 3.7-fold in 'Donald' tomato fruits, whereas in high-lycopene tomato cultivars it was 3.7- to 7.1-fold higher compared to the ordinary tomato cultivar, with the exception of 'HLY02' (Hdider et al., 2013). The β-carotene contents remained almost unchanged (12 μg/g DW in average) in non-treated, red-light-treated and UV-C-treated tomato fruit throughout 21 days of storage after treatment, in contrast to the observations for sun light-treated fruit (Liu et al., 2009) (Table 3).

Changes in antioxidant activity

Different analytical assays have been developed to measure antioxidant capacity, none of which reflects accurately all ROS sources or all antioxidant systems existing in plants (Prior, Wu, and Schaich, 2005). Radical scavenging activity (RSA)-based methods are mostly used, even though results may not always be transposable to the in *vivo* situation. The lack of a standardized method may also lead to inconsistent results, and thus hinder interpretation of published data. Even so, very few studies have been published on postharvest dynamic changes affecting antioxidant activity in fresh tomato fruits, although some reports exist on changes during on-vine ripening (Cano et al., 2003; Jiménez et al., 2002).

Ilahy et al. (2011, 2018) monitored the hydrophilic (HAA) and lipophilic (LAA) antioxidant activity respectively using the Trolox equivalent antioxidant capacity (TEAC) and the ferric reducing antioxidant power (FRAP) assays in ordinary and high-pigment tomato cultivars during maturity (Table 4). Regardless the analytical method and cultivars used, the highest HAA value was found in green-mature fruit, and the lowest was observed in red-ripe fruit. While HAA significantly dropped throughout maturity stages, a concomitant increase in LAA was found for all the tested tomato cultivars along ripening. LAA increases were 50% and 91% using the TEAC and the FRAP assays respectively. Although HAA decreased and LAA increased during tomato fruit ripening in all cultivars under analysis, values at the red-ripe stage were higher in the high-pigment tomato cultivars ‘Lyco2’, ‘HLY13’ and ‘HLY18’ as compared to ‘Río Grande’. All of the above-reported data demonstrate the higher antioxidant profile of high-pigment cultivars which suit the ever-increasing consumer demands of nutritive and healthy foods.

Lana and Tijskens (2006) focused on the changes in the antioxidant activity of fresh-cut tomatoes during postharvest storage at 5 °C. Fruit were harvested at three different maturity stages, and two methods were used for determinations, one of them being an *in vitro* radical scavenging assay, while the second one used rat liver microsomes to mimic an *in vivo* system. Although antioxidant activity generally decreased along storage, the major factor determining this property was apparently the initial levels at harvest. This observation highlights the need to harvest the fruit at an adequate maturity stage in order to optimize the levels of this health-promoting property. Storage of ‘Rhapsody’ tomato fruit at 4 ºC was also reported to decrease the content of antioxidant compounds (Yahia, Soto-Zamora, Brecht, K., & Gardea, 2007). Similar results were found for ‘Micro-Tom’ fruit, with significant decreases in phenolics, AsA and lycopene after 27 days at 6 ºC (Gómez et al., 2009), even though glutathione content increased and the antioxidant activity measured by means of the 2,2-diphenyl-1-picrylhydrazyl (DPPH) (DPPH) assay was unaffected.

Some reports suggest that particular postharvest treatments are likely to partially avoid these detrimental effects of cold storage on the antioxidant properties of tomato fruits, although treatment conditions should be optimized carefully (Table 4). For instance, when 'Rhapsody' fruit were submitted to a hot air treatment at 38 ºC in order to improve storability and to decrease the incidence of chilling injury, detrimental effects on antioxidant activity were found. However, these effects were found to be dependent on the specific temperature applied for the heat shocks, since exposure to 34 ºC actually promoted the tomato antioxidant system (Yahia et al., 2007). Postharvest pre-treatment of 'Chaoyan-219' tomato fruits by high-voltage electrostatic field (HVEF), enhanced the antioxidative enzymatic system as well as the levels of non-enzymatic antioxidant compounds like phenols, glutathione and AsA (Zhao et al., 2011). Postharvest direct-electric-current applications in 'Pannovy' fruits also increased substantially total antioxidant activity as measured by the Trolox equivalent assay, with concomitantly augmented phenolics, lycopene and β-carotene contents (Dannehl et al., 2011). Delactosed whey permeate (DWP) treatments increased the antioxidant activity of 'Moneymaker' tomatoes by 26 % at the end of storage at 15 ºC, in parallel to higher AsA and total phenols levels (Ahmed et al., 2013).

CHANGES IN PHYSICAL ATTRIBUTES

Shelf-life potential

Liplap et al. (2013) studied the impact of the combination of different pressure levels and temperatures on tomato fruit shelf-life (Table 5), and found that a hyperbaric treatment at 20 °C was able to significantly prolong storage time without adverse effects on eating quality. Similarly, Candir, Candir, and Sen (2017) reported that postharvest shelf-life of Beefsteak

‘Grando F1’ tomato fruits was extended by a treatment with 1 g/L aminoethoxyvinylglycine (AVG) at a vacuum pressure of -30KPa. Generally, AVG-treated fruits exhibited lower ethylene production, decreased lycopene biosynthesis, altered color changes and increased firmness in comparison to non-treated ones.

Dhakal and Baeck (2014) reported that short time (one week) irradiation of mature-green tomato fruits with diode-generated blue-light (440-450 nm) is a practical approach allowing a delay in fruit ripening and softening, and thus extending shelf-life. Similarly, UV irradiation (4.2 Kj/m²) prolonged the shelf-life of green-mature harvested ‘Zhenzhu’ tomato fruit throughout 5 weeks at 18 °C (Bu, Yu, Aisikaer, and Ying, 2013). In the same context, pulsed light (2.68 and 5.36 j/cm²) was proposed as an efficient non-thermal food-grade technology to reduce the microbial charge of fresh tomatoes during postharvest storage, with no adverse effects on the the nutritional value of the produce (Aguiló-Aguayo, Florence-Charles, Renard, Page, & Carlin, 2013).

Physiological loss in weight

The physiological loss in weight (PLW) is among the main changes affecting postharvest storage of fresh produce. The commercial acceptability threshold of fresh fruits and vegetables is around 10% PLW (Acedo, 1997; Pal, Roy, and Srivastava, 1997). Several investigators have studied PLW in tomato fruit (Table 5). Storage duration, temperature and genotype significantly affect PLW (Javanmardi and Kubota, 2006). The PLW may also be attributed to changes in the levels of soluble sugars, since monosaccharides are used as substrates for respiratory purposes throughout storage (Singh and Reddy, 2006). Several reports have been published on PLW in tomato during postharvest storage, which are discussed in the next sections.

Dávila-Aviña et al. (2011) revealed that PLW of untreated, mineral oil-coated and carnauba wax-coated tomatoes, treated at the breaker stage, reached values of 3.19, 1.60 and 2.20% after one month storage at 10 °C, respectively, whereas PLW of fruit submitted to the same treatments at the pink stage was 3.76, 1.67 and 2.53%, in the same order. After exposure of tomato fruits to 20 °C for 2 days, untreated, carnauba wax-coated and mineral oil-coated fruit, lost 5.82%, 3.15%, and 3.30% of their initial weight, respectively. Kumah, Olympio, and Tayviah (2011) reported increasing PLW of tomato fruits during storage under variable temperatures. Nevertheless, no significant changes in PLW were noted among different varieties. Ali, Maqbool, Ramachandran, & Alderson (2010) reported 9-11% PLW in gum arabic-coated tomatoes during storage, lower than those of untreated samples. When '508' tomato cultivar harvested at pink to light-red ripening stages were stored at 12 and 22 °C during 20 days, PLW increased with subsequent storage, with higher values at 22 than at 12 °C (Assi, Jabarin, and Al-Debei, 2009).

Getinet et al. (2008) investigated cultivar-, maturity- and storage condition-related effects on PLW of tomatoes. The ligh-red fruits of cultivar 'Marglobe' exhibited the most important PLW when stored under room temperature. Green-mature 'Roma VF' tomato fruits showed the lowest PLW when stored in an evaporative cooler. Javanmardi and Kubota (2006) and Kumar, Singh, Singh, Singh, & Prasad (2007) reported that the average fruit weight of different varieties exhibited a significantly linear decrease with increasing storage duration at ambient conditions. Collins et al. (2006) studied the effect of ripening stage on PLW throghout storage of tomato fruit at room temperature. Generally, breaker or turning tomato fruits displayed higher PLW. Early red-ripe pear-type and 'S-12' tomato fruits showed 55 and 33% PLW, respectively, after a week of storage at ambient conditions. In contrast, 23 and 46%, PLW, in the same order, were observed when fruit were harvested at the breaker stage (Kaur, Kanwar, & Nandpuri, 1977) (Table 5). Minimal PLW was reported after 12 days of storage for turning with respect to red-ripe tomato fruit (Gaur and Bajpai, 1982). Tomatoes stored at room temperature showed higher PLW as compared to those packed in polyethylene bags due to higher transpiration and water loss rates (Lingaiah, 1982). Total PLW in mature-green tomato fruit throughout storage was reported to increase from 6.28 to 13.31% between the 3rd and the 12th days of storage (Moneruzzaman, Hossain, Sani, Saifuddin, & Alenazi, 2009). In fully ripe tomato fruits, PLW was the lowest with 5.72% after 3 days and 11.96% after 12 days of storage. Sammi and Masud (2007) observed that PLW in tomato fruits stored in different packaging systems increased significantly as the ripening proceeded. Packaging reduced PLW of fruits by 50% compared to controls at all ripening stages. Mallik, Bhattacharja, and Bhattacharja (1996) reported 7.7 to 9.7% PLW in ‘Roma VF‘ tomatoes after 6 days of storage under ambient conditions. Javanmardi and Kubota (2006) noted an increase in PLW of hydroponically-grown tomato fruits stored at ambient conditions and under refrigeration (5 and 12 °C) irrespective of temperature. However, tomatoes held at room temperature showed higher PLW (0.68% per day) as compared to those kept at 5 °C (0.15% per day) or 12 °C (0.49% per day). Similarly, Pila et al. (2010) observed that PLW of tomato fruit increased progressively during their storage, and this progression continued till the fruit attained full ripeness. Treatment with chemicals such as gibberellic acid, $CaCl_2$ and salicylic acid led to comparatively lesser PLW in relation to untreated fruit (19.89%) during storage (Table 5). Active or smart packaging is being increasingly used in food industries to prolong the shelf-life of different perishable produce. Fagundes et al. (2015) highlighted the efficiency of modified atmosphere packaging (5% O_2 and 5% CO_2) in extending the shelf-life of the cherry tomato cultivar ‘Josefina’ until 25 days.

Fruit firmness

Firmness is an important trait governing the commercial evaluation of quality and acceptability of tomato fruits, and it is altered by morphological and physiological fruit characteristics such as pericarp firmness, the importance of locule tissue as well as the ripening stage (Chiesa et al., 1998). Kumah et al. (2011), Lana, Tijskens and van Kooten (2005), Mizrach (2007) and Tigist et al. (2012) noted a loss in tomato firmness throughout storage (Table 5). Firmness levels and softening rates are cultivar-dependent (Xin et al., 2010), which could be attributed to differences in metabolic activity during the ripening process. Firmness loss-related events include deterioration of the cell structure and intracellular materials, compositional changes and disassembly of cell walls (Seymour, Taylor, and Tucker, 1993), largely driven by a wide range of cell wall-modifying enzyme activities (very prominently pectinesterase and polygalacturonase) (Page, Marty, Bouchet, Gouble, & Causse, 2008). Loosening of the cell wall structure of fruit epidermis, together with changes in fruit cuticle, result in softening, higher skin permeability and higher moisture loss, depending upon the genotype. Moisture loss, in turn, contributes to wilting, shrinkage and firmness loss. Reports on firmness changes in tomato during postharvest storage are discussed in the next section.

Kumah et al. (2011) observed that fruit firmness generally dropped during storage from day one till day seven irrespective of storage temperature. Fruit firmness decreased significantly during storage in treated and control tomato fruits (Ali et al., 2010). Tomato fruit kept under ambient temperature exhibited the lowest firmness values (10N) at the end of storage. Dávila-Aviña et al. (2011) outlined that firmness of mineral oil- and carnauba-coated 'Grandela' tomatoes harvested at breaker and pink color stages showed a decreasing trend throuhout a storage period of 28 days at 10°C, regardless of treatment. Tomato fruits at the breaker and pink ripening stages had initially the same firmness (15-16 N) which decreased afterwards attaining values in the range of 5.4 to 8.1 N. Assi et al. (2009) studied the storage

Comentario [ILara5]: Which treatment?

performance of tomatoes against traditional and modern handling methods followed in Jordan. Tomato fruit stored during 10 days at 12 and 22 °C displayed a rapid decline in firmness, although those held at 12 ºC remained firmer than those held at 22 °C after 10 days storage. Sammi and Masud (2007) evaluated the effect of three different packaging systems and their efficiency to prolong the storability and quality of mature-green fruit of cultivar 'Río Grande'. The authors observed that sensory texture scores increased with ripening, but remained lower in untreated fruits. Firmness of UV-B-irradiated tomatoes decreased from 26.7 to 8.6 N during storage for 37 days (Liu et al., 2011). Similarly, firmness of UV-C- and sun-light-treated tomatoes was significantly lower in comparison with controls after a storage period of 3 weeks (Liu et al., 2009) (Table 5).

CHANGES IN EATING QUALITY-RELATED ATTRIBUTES

Total soluble solids

Total soluble solid (TSS) values are considered one of the most impotant ripening-associated qualitative parameters in various fruit products, including fresh tomatoes (Tehrani, Chandran, Sharif Hossain, & Nasrulhaq-Boyce, 2011). Changes in TSS content are mainly related to the hydrolysis of starch into soluble sugars (sucrose, glucose and fructose) and to the accumulation of organic acids, and hence high TSS values, usually in the range 4.80-8.80%, are a good index of tomato fruit maturity and eating quality during postharvest storage (Sammi and Masud, 2007). Different studies reported a gradual increase in TSS throughout storage (Table 6). Moneruzzaman et al. (2008) found significant variation in TSS values of tomato juice according to the maturity stage of fruits, with the highest level (6.82%) measured at the full ripe stage. Collins et al. (2006), instead, reported no significant changes during ripening.

Tigist et al. (2012) observed that fresh market and processing tomato cultivars reached their TSS peak after 16 and 20 days of storage at ambient conditions, respectively, to diminish thereafter in all cases (Table 6). Ali et al. (2010) examined the effect of fruit coating with gum arabic on tomato quality, and found an increasing trend for TSS during subsequent storage, even though final levels were lower in comparison with untreated samples. An increase in TSS from 5.2 to 5.9% and 5.8 to 5.9% was noticed after eight days of storage for tomato fruits harvested respectively at the turning and the pink stages, but a decline in TSS from 6.6 to 4.3% was found for red-ripe tomato fruits (Gaur and Bajpai, 1982). Fruit harvested at the mature-green ripening stage also displayed an increase in TSS levels after 8 days of storage, though to different extent according to cultivar and storage temperature (Kumah et al., 2011). Žnidarcic and Pozrl (2006) found that ºBrix values of tomato fruit following storage for 3 weeks at 10 °C increased slightly from 5.06 to 6.92 °Brix. Kumar et al. (2007) studied different open-pollinated and hybrid varieties and established a range of TSS content between 3.88 and 6.35 °Brix. The TSS contents increased in all genotypes during 9 days of storage at ambient temperature. Getinet et al. (2008) observed significant interactions between genotype and maturity stage influencing TSS content variability in tomato fruit, which increased during storage. TSS values increase throughout maturation and ripening in parallel with the intensification of skin color, and postharvest changes were reported to be related to ripening stage at harvest and to storage conditions, particularly temperature (Atta-Aly, Brecht, & Huber, 2000; Trejo and Cantwell, 1996; Žnidarcic and Pozrl, 2006). Dávila-Aviña et al. (2011) pointed out that TSS in tomato fruits harvested at the breaker stage remained largely unchanged throughout storage at 10 °C, except for control fruit which displayed a 15% increase by the end of the storage period. Pink tomatoes showed a decrease in TSS of approximately 15-20% with respect to the initial value. Pila et al. (2010) observed an increasing trend for TSS in tomatoes throughout 10 days storage period at 34+ 1

°C after different treatments including gibberellic acid, $CaCl_2$ and salicylic acid. Untreated fruit showed higher TSS values as compared with treated fruits. When tomatoes harvested at the pink or light-red stages were held at 12 or 22 °C, an increase in TSS was found during the storage period, with significant differences between both storage temperatures (Assi et al., 2009). Sammi and Masud (2007) studied the impact of different packaging systems on TSS of tomatoes held at ambient conditions, and found that TSS increased with ripening stage in both unpacked and packed samples. Javanmardi and Kubota (2006) analyzed red-ripe cluster tomato fruits of cv. ‘Clermon’ grown under hydroponic system in greenhouses for TSS changes during consecutive 14 days of storage at 12° and 5° C with respect to 7 days room temperature storage for the control. The authors reported that TSS values in tomatoes harvested at the light-red to the red-ripe riening stages and stored at different temperatures did not show any variation during up to 14 days. TSS values in tomatoes submitted to different light treatments remained unchanged during 3 weeks of storage at 12-14 °C, and were not significantly affected by the light treatment applied in each case (Liu et al., 2009). Similarly, no significant variations in TSS contents were detected in tomatoes kept for 14 days at room temperature (Wills and Ku, 2002) or at 12 ºC during 10 days (Kagan-Zur and Mizrahi, 1993).

Siddiqui and Singh (2015) demonstrated that puree prepared from tomato fruit of the high-pigment cultivars ‘Berika’ and ‘BCT-119’, lost respectively about 45 and 58% of their original TSS values, and the loss in the ordinary cultivars ‘Patharkutchi’ and ‘Punjab Chhuhara’ was similar (43 and 56% respectively). In contrast, Safdar, Mumtaz, Amjad, Siddiqui, & Hameed (2010) reported increased TSS contents in tomato paste during storage for 240 days at different temperatures. Since TSS is considered as the sum of organic acids, sugars and other secondary components (Beckles et al., 2012), the consumption of a part of

Comentario [ILara6]: 35 ºC? Or storage at 34 ºC and then at 1 ºC?

them by micro-organisms as a food source is likely to lead to decreased TSS levels in puree during storage.

Acidity

Titratable acidity (TA) is often used as a good ripening index, as the level of organic acids decreases throughout fruit maturity. TA is also influenced by the ripening conditions (Hernández-Suárez, Rodríguez-.Rodríguez, & Díaz-Romero, 2008). A decrease in the levels of some organic acids has been generally noticed during the ripening of ordinary tomato cultivars (Castro Vigneault, Charles, & Cortez, 2005; Chen, Wilson, Kim, & Grierson, 2001; Getinet et al., 2008; Kumar et al., 2007; Pila et al., 2010) (Table 6). The progressive reduction in TA of fruit during storage is partially related to higher respiration rates as ripening advances, when organic acids such as citric and malic are used as key respiration substrates (El-Anany, Hassan, Rehab, and Ali, 2009).

'Micro-Tom' tomatoes stored at different temperatures display different change patterns for each organic acid (Gómez et al., 2009). While the levels of acids such as citric, malic, ascorbic and tartaric showed a slow but significant reduction throughout maturity, those of succinic acid slowly accumulated. Organic acid content is low in immature-green tomatoes, then attaining the highest levels at the turning stage and decreasing rapidly afterwards. Ripening conditions, mainly temperature and relative humidity, also alter the AsA content of tomato fruit (Moneruzzaman et al., 2008).

Islam et al. (1996) and Knee and Finger (1992) reported that organic acids attain a peak at the pink ripening stage to drop afterwards (Table 6). During fruit maturation, citric acid content was comparatively much higher than that of malic acid. Only minute amounts of oxalic acid were detected, which exhibited similar change dynamics as both citric and malic acids. Moneruzzaman et al. (2009) reported that TA in tomato pulp varied significantly depending on maturity stage of fruit. The pulp from half-ripe tomatoes displayed the highest TA (0.48%) as compared to fully ripe (0.47%) and mature-green fruit (0.44%). TA peaked 9 days after harvest and decreased thereafter.

During storage, organic acid content dropped with increasing temperature, and levels were significantly higher for fruit kept at 15 °C than for those kept at 25, or 30 °C (Islam et al., 1996). Dávila-Aviña et al. (2011) noticed that TA of tomatoes decreased with maturity irrespective of coating treatments. However, TA of breaker fruits treated with mineral oil and carnauba wax was respectively 40% and 25% lower in comparison with non-treated fruits. Getinet et al. (2008) found a declining trend for TA during storage of two cultivars; however, the extent of this decline was cultivar-specific. Kumar et al. (2007) observed that TA of different tomato genotypes (open-pollinated varieties and hybrids) ranged from 0.34% to 0.47%, and decreased during subsequent storage for 9 days. Accordingly, Ali et al. (2010) also found a declining trend for TA during storage of coated and uncoated tomatoes irrespective of treatment or the specific tomato variety under study. Auerswald, Peters, Brückner, Krumbein, & Kuchenbuch (1999) reported that titratable acidity of hydroponically-grown tomato fruits exhibited 22% increase after 4 days of postharvest storage. Sammi and Masud (2007) reported a time-course decrease for TA in tomatoes, with faster rates in packed fruit. Regardless the ripening stage, however, the highest TA during storage was found in unpacked tomatoes. In contrast, Toor and Savage (2006) reported that hydroponically-grown tomato fruits stored at 15 and 25 °C contained respectively 0.97% and 1.06% citric acid, which was significantly higher with respect to fruits kept under refrigeration (0.77%), and that these values increased during subsequent storage, particularly at ambient temperature.

Comentario [ILara7]: Which ones?

Ordóñez-Santos, Vázquez-Odériz, Arbonés-Maciñeira, & Romero-Rodríguez (2009) reported that the levels of malic and citric acids in tomato pulp decreased significantly during storage for 180 days (51% and 71%, respectively). Contrarily, Gould (1992) found a linear increase of TA values in tomato paste during storage at different temperatures, with higher levels (18.39%) at ambient temperature as compared to the product kept at -10 ° C (7.47%) (Table 6).

Total sugar

Total sugar (TS) is also considered an important trait for tomato quality assessments. Although fructose is characteristically sweeter than glucose or sucrose, the level of total sugars is generally regarded as a good index for consumer acceptability. Tomatoes accumulate more fructose and glucose than sucrose (Siddiqui, Ayala-Zavala, and Dhua, 2015). Sugar content was found to increase throughout ripening from the green to the red-ripe stages (Tadesse et al., 2012) (Table 6). In fruit tissues, sucrose content build-up is followed by an increase in sucrose synthase (SS) activity (Islam et al., 1996), suggesting that this enzyme plays a central role in sucrose accumulation. The degradation of polysaccharides into water-soluble sugars is likely to contribute also to increased sugar content (Pila et al., 2010). An initial increment in tomato fruit TS values over ripening has been noted, which subsequently remained unchanged or exhibited minor decreases (Baldwin, Nísperos-Carriedo, & Moshonas, 1991). Sugar content varies with maturity stage at harvest (Sinaga, 1986). Dalal, Salunkhe, Boe, & Olson (1965) found that the content of reducing sugars in tomato fruit at the mature-gree, breaker, pink, red and red-ripe maturity stages accounted respectively for about 2.40%, 2.90%, 3.10%, 3.45% and 3.65% on a fresh weight basis. The levels of soluble sugar concentration showed an increasing trend during storage regardless temperature. Sammi and Masud (2007) observed that sugar content in control fruit peaked during the transition from the green to the turning maturity stages, and decreased later as ripening proceeded. Islam et al. (1996) showed that reducing sugars accumulated more rapidly at late than at early ripening stages. A peak of sucrose was detected in immature-green and mature-green tomato fruits, which declined in later maturity stages. Among total soluble sugars, 95% are reducing sugars, fructose levels being higher than those of glucose.

Gómez et al. (2009) observed increasing levels of glucose and fructose in tomatoes harvested at the breaker stage throughout storage at 20 °C, but this accumulation was less intense in fruit kept under refrigerated storage, final values attaining approximately 80% of those measured in control tomatoes. The reducing sugar content in different tomato genotypes in which levels ranged between 1.98 and 3.54% increased gradually during storage (Kumar et al., 2007). Mature-green tomato fruit stored at moderately low temperature (14-19 °C) for 28 days exhibited increasing TS levels up to 8 days to decrease thereafter (Melkamu, Seyoum, and Woldetsadik, 2008). Auerswald et al. (1999) reported that reducing sugar levels in hydroponically-grown tomato fruits were unaffected along one week after harvest (Table 6). Packed fruits showed the highest TS content by the end of storage (pink-red to red-ripe maturity stages). Significant variations in TA content of fruit pulp among different maturity stages have been reported (Moneruzzaman et al., 2008). Total sugar content increased with advancing ripening of fruit irrespective of maturity stage at harvest. A peak (4.03%) was detected for total sugars in fully ripe tomato fruit, while the lowest values (3.30%) corresponded to mature-green tomatoes after 12 days of storage.

Aroma

Tomato being a climacteric fruit, it exhibits the characteristic increase in respiration and ethylene production rates, together with the typical ripening-associated changes in quality characteristics such as chemical composition, colour, texture, taste, and aroma. Aroma is a major quality attribute determining consumer choice and repeated purchases, either for fresh consumption or for processing purposes. Specific processing purposes further contribute to the decision of the most suitable maturity stage at which to harvest the produce. Since ethylene is closely associated with the initiation and subsequent integration of biochemical changes during tomato fruit ripening, most post-harvest processes emphasize the control of the ripening process, aiming at either expanding the shelf-life potential or at accelerating maturation. The exogenous application of ethephon, and ethylene-releasing chemical, has been frequently used commercially in order to fasten the process of off-vine tomato ripening. The aroma profiles of tomato fruit are complex, with roughly 30 aroma-active chemical compounds providing the characteristic tomato flavour among a total of over 400 identified volatile compounds emitted both by fresh fruit and processed tomato products (Petro-Turza, 1987). The biosynthesis of aroma compounds in tomatoes as well as in other numerous fruit and vegetable species depends on different metabolic pathways (El Hadi, Zhang, Wu, Zhou & Tao, 2013; Salles, Nicklaus, and Septier, 2003). Many aroma- and taste-contributing volatile alcohols, carbonyls, acids and esters derive from amino acids such as aspartic acid, glutamic acid, leucine or glutamine. Conversion of amino acids to keto acids by aminotransferases and further oxidation to aldehydes by enzymatically-catalyzed decarboxylation leading to the formation of various volatile esters have been demonstrated (Petro-Turza, 1987). The alcohol 3-methylbutanol, a leucine derivative, is an important volatile compound contributing sweet and fresh ripe tomato aroma notes (Buttery and Ling, 1993). The increase in non-protein nitrogen associated with decreased protein levels has been correlated to the increment in the synthesis of aroma volatiles. Hexanal, *cis*-3-hexenal, *trans*-2-hexenal, *cis*-3-hexenol, and hexenol are other important C6 volatile chemical compounds prominent in tomato fruit flavour, arising largely from lipid metabolism (Ruiz et al., 2005; Yilmaz, Tandon, Scout, Baldwin, & Shewfelt, 2001). The increase in hexanal production throughout off-vine tomato fruit ripening has been found to correlate negatively with perceived sourness and positively with sweetness (Krumbein, Peters, and Brückner, 2004) (Table 6). Phenylacetaldehyde and 3-methylbutanal arise from glycoside hydrolysis throghout maturity. Furaneol contributes to the “fresh” notes in tomato fruit (Buttery, Takeoka, Naim, Rabinowitch, & Nam, 2001). Volatile monoterpenes are also present in tomato aroma profiles, though in minute quantities. Some of the aroma-contributing compounds are synthesized enzymatically through the oxidation of membrane lipids, mainly after damage of fruit tissues at later ripening stages (Galliard, Matthew, Wright, & Fishwick, 1977). Carbonyls, short-chain alcohols and hydrocarbons, long-chain alcohols and esters typically form the aroma of field-ripened tomato when present in the ratio of 32:10:58, respectively (Shah, Salunkhe, and Olson, 1969). The presence of benzaldehyde, citronellyl propionoate, citronellyl butyrate, decanal, dodecanal, geranyl acetate, geranyl butanoate, nonanal, and neral in plant-ripened tomato were reported to be released in higher concentrations as compared to artificially-ripened fruit, which in turn displayed higher emissions of butanol, 2,3-butanedione, isopentanal, isopentyl acetate, 2-methyl-3-hexanol, 3-pentanol, and propyl acetate (Madhavi and Salunkhe, 1998) (Table 6). Off-flavours are associated with increased productions of 2-methyl-1-butanal, particularly by off-vine ripened tomato.

CONCLUSIONS

Tomato fruit undergo complex changes during ripening and after harvest, which affect bioactive molecules and health-promoting properties, as well as physical and eating quality-related attributes (Figures 1 and 2). The accumulation of health-promoting compounds during ripening, their preservation after harvest and the extension of shelf life potential are highly desirable objectives for the tomato fruit industry. Experimental evidence on the positive outcomes on human health of the consumption of fresh tomatoes as well as of tomato products is accumulating rapidly. In this review, currently available information on health-promoting, physical and eating quality-related properties of tomato fruit are summarized and discussed. This survey shows that some attributes such as lycopene and total carotenoid contents, LAA, PLW, total soluble solids and aroma-related compounds have been generally reported to increase during off-vine ripening of tomato, while HAA, phenolics and ascorbic acid content, fruit firmness and titratable acidity decrease.

Storage conditions influence all these properties. It is relevant to emphasize that the effects of off-vine ripening on tomato quality depend mostly on the initial content of each bioactive compound, since high-pigment and ordinary cultivars will not reach the same content of lycopene after the same storage period. Storage effects on tomato quality will also depend mostly on the applied treatment and temperature. Generally, higher quality will be obtained under low storage temperature.

Author contributions

Siddiqui MW conceptualized the idea of this review. Siddiqui MW, Lara I, Ilahy R and Tlili I scanned the litterature, retrieved and processed papers referenced in the review, and wrote the manuscript. Prasad K, Asghar A, Lenucci MS and Hdider C critically reviewed the text and enriched key parts in the manuscript. All authors contributed in the preparation of the tables and the revision of the paper before submission.

Conflict of interests

Authors declare no conflict of interests.

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Table Legends

Table 1: Reported variation in total phenolics and flavonoid content during ripening and postharvest of tomato fruit.

Table 2: Reported variation in ascorbic acid content during ripening and postharvest of tomato fruit.

Table 3: Reported variation in carotenoid content during off-vine ripening of tomato fruit.

Table 4: Reported variation in antioxidant activity during ripening and postharvest of tomato fruit.

Table 5: Reported variation in shelf-life and physical attributes in harvested tomato fruit.

Table 6: Reported variation in eating quality-related attributes during ripening and postharvest of tomato fruit.