Comprehensive REVIEWS in Food Science and Food Safety

Dynamic Changes in Health-Promoting Properties and Eating Quality During Off-Vine Ripening of Tomatoes

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Abstract: Tomato (*Solanum lycopersicon* L.) fruit is rich in various nutrients, vitamins and health-promoting molecules. Fresh tomatoes are an important part of the Mediterranean gastronomy, and their consumption is thought to contribute substantially to the reduced incidence of some chronic diseases in the Mediterranean populations in comparison with those of other world areas. Unfortunately, tomato fruit is highly perishable, resulting in important economic losses and posing a challenge to storage, logistic and supply management. This review summarizes the current knowledge on some important health-promoting and eating quality traits of tomato fruits after harvest and highlights the existence of substantial cultivar-to-cultivar variation in the postharvest evolution of the considered traits according to maturity stage at harvest and in response to postharvest manipulations. It also suggests the need for adapting postharvest procedures to the characteristics of each particular genotype to preserve the optimal quality of the fresh product.

Keywords: eating quality, health-promoting properties, physical attributes, postharvest, tomato

Introduction

Fresh tomato (*Solanum lycopersicon* L.) fruits pose an important set of challenges for postharvest storage due to their high-water content and soft texture. These attributes make tomatoes highly perishable and difficult to store for long periods without incurring substantial losses and additional costs. After harvest, tomato fruits are no longer supplied with water and solutes by the parental plant; thus, storage conditions play a fundamental role in slowing down fresh product decay quality traits. During tomato fruit ripening and senescence several biodegradation processes occur, including macromolecule depolymerization, substrate consumption, chloroplasts-to-chromoplasts transition and pigment alterations, mostly due to the hydrolytic activity of glycosidases, esterases, dehydrogenases, oxidases, phosphatases and ribonucleases (Tadesse, Workneh, & Woldetsadik, 2012). Ripening and senescence are also associated with the *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, posttranscriptional, translational and/or posttranslational regulation mechanisms (Workneh & Osthoff, 2010).

In order to preserve satisfactory health-promoting, eating and processing quality, consider all the major physiological and biochemical characteristics of tomato fruits is important. 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, transport and marketing is the relatively fast quality deterioration resulting in short shelf-life potential. Hence, more intensive research efforts are required to cut quality loss and extending shelf-life. Tomato fruit ripening regulation has been a central investigation focus throughout the last years. This paper reports a brief review of the 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

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doi: 10.1111/1541-4337.12395

delaying oxidative reactions arising from the presence of metabolically or environmentally originated free radicals. These extremely reactive species 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 and efficiently counteract radical-driven damage, especially during aging and/or stressful conditions. Thus, the antioxidant power and chemical composition of fresh fruits are becoming determinant attributes in tomato marketing as they 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 the health claims remain in many cases to be clearly established *in vivo* (Espín, García-Conesa, & Tomás-Barberán, 2007).

In this context, tomato is thought to contribute substantially to decrease the occurrence of some chronic diseases in the Mediterranean population compared to other world areas, as it is a major source of the above-mentioned nutrients (Abushita, Daood, & Biacs, 2000; Carluccio, Lenucci, Piro, Siems, & Luño, 2016; Martínez-Valverde, Periago, Provan, & Chesson, 2002). Carotenoids are the major phytochemicals in tomato, lycopene accounting for up to 90% there of (Ilahy et al., 2018; Ilahy, Hdider, Lenucci, Tlili, & Dalessandro, 2011). 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 the qualitative and quantitative profiles of some of the most important bioactive molecules of fresh tomato fruits.

Total phenolics

Phenolic acids and two flavonoid families (flavanones and flavonols) represent the most abundant phenolics in tomato. Phenolic acids account for up to 75% of total phenolics in tomato fruit, with large genotype variability. They are distributed both in the pericarp (skin) and inner (mesocarp and endocarp) fruit tissues, mainly as chlorogenic acid (Martínez-Valverde et al., 2002; Moco et al., 2007). Most (98%) of flavonols occur, instead, in the fruit skin with concentrations largely variable across cultivars (Stewart et al., 2000). Finally, the stilbenoid 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 the different families of phenolics are complex, closely interrelated, and profoundly influenced by endogenous and exogenous factors (Dixon & Steele, 1999; Manach, Scalbert, Morand, Rémésy, & Jiménez, 2004). Accordingly, significant changes in the content of total phenolics in tomato are expected in response to pre-and postharvest conditions (Dumas, Dadomo, Di Lucca, & Grolier, 2003; Slimestad & Verheul, 2005). Owing to the quantitative and qualitative relevance of lycopene and β-carotene, research on health-promoting properties of tomato fruits has preferentially focused on these constituents, generally overlooking flavonoids.

Substantial cultivar-to-cultivar variation in the metabolism of phenolics and flavonoids during tomato ripening and postharvest has been reported (Table 1). Focusing on phenolics and flavonoids accumulation in ripening ordinary and high-lycopene tomato cultivars, Ilahy et al. (2011) reported significant differences in the total phenolic levels even among cultivars of the same typology. Cultivar “HLY18” attained a peak [310 mg Gallic Acid Equivalent (GAE)/kg Fresh Weight (FW)] of phenols at the orange-red stage, while in “HLY13” fruits, two peaks 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 “Rio Grande” exhibited the lowest levels of total phenols (113 and 138 mg GAE/kg FW, respectively). The flavonoid levels varied widely throughout ripening stages. The dynamic of change in flavonoids was identical in high-lycopene cultivars, but quantitatively different in “Lyco2” fruits. Flavonoid contents remained essentially stable at later maturity stages. It should be underlined that flavonoid contents were higher in high-lycopene tomato cultivars studied throughout ripening.

The effect of storage on phenolics is well documented in tomato fruits. The amount of chlorogenic acid and chalconaringenin, quantitatively prominent flavonoids in cherry tomatoes, has been reported to decrease sharply during 3 weeks postharvest storage at 20 °C (Slimestad & Verheul, 2005), although this loss was less pronounced at lower storage temperature. This change 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, suggesting that other compounds compensate the decrease. Actually, an earlier report found higher amounts of total phenolics in “Moneymaker” tomatoes after 16 days at 20 °C (Giovanelli, Lavelli, Peri, & Nobili, 1999). Cold storage (6 °C) for up to 4 weeks also led to a decreased content of total phenols and chlorogenic acid in Micro-Tom’ tomato fruit (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 °C 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 °C, 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 24 hr following the treatment (Dannehl, Huyskens-keil, Eichholz, Ulrichs, & Schmidt, 2011). Delactosed whey permeate (DWP), a novel bio-active product for fresh products storage, has been shown to improve total phenols in “Moneymaker” tomatoes after 21 days at 15 °C, 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 expression 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

Table 1–Variation in total phenolics and flavonoid content during ripening and postharvest of tomato fruit.

Compounds	Tomato cultivar name	Harvest conditions and applied treatments	Observed changes	References
Total phenolics	Cv. Rio Grande and high-lycopene tomato cvs HLY13, HLY18, and Lyco2	Ripening from green to red-ripe stage	Cultivar-dependent	(Ilahy et al., 2011)
Flavonoid			Almost unchanged	
Chalconaringenin and chlorogenic acid	Cherry cv. Jennita	Postharvest ripening at 20 °C for 3 weeks in darkness of green to red ripe tomato fruits	Sharp decrease	(Slimsestad and Verheul, 2005)
		Postharvest ripening at low temperature	Low decrease	
Total phenolics	Cv. Moneymaker	7 different ripening stages/Postharvest storage for 16 days at 20 °C	Increased content	(Giovanelli et al., 1999)
Total phenols and chlorogenic acid	Cv. Micro-Tom	Cold storage of breaker and red-ripe tomato fruits for 4 weeks at 4 °C	Decreased content	(Gómez et al., 2009)
Total phenolics	Cv. Newton	Storage of mature green fruit at 1 °C for 3 weeks followed by 3 or 6 μM brassinolide dip (5min)	Increased content	(Aghdam et al., 2012)
	Cv. Chaoyan-219	HVEF treatment applied to green mature tomato fruits followed by storage at 13 °C (24 days)	Increased content	(Zhao et al., 2011)
	Cv.Pannovy	DC application on red-ripe fruits	Increased content	(Dannehl et al., 2011)
	Cv. Moneymaker	DWP treatment of ripe tomato followed by a storage at 15 °C (21 days)	Increased content	(Ahmed et al., 2013)
Flavonol	Cvs Micro-Tom and "Moneymaker	Expression of flavonol-specific transcriptional activator	65-fold increase	(Luo et al., 2008)
Total phenolics and flavonoids	Manapal (*hp-2^{dg}*)	Integration of *hp* and *ip* mutations in tomato cultivars compared to ordinary cvs (green, breaker and ripe stages of maturity)	High initial content and lower postharvest decrease than the wild type	(Bino et al., 2005)
	Line (n-935) (*hp-2^{dg}*)			(Kolotilin et al., 2007)
	Different *hp* and *ip* cvs			(Ilahy et al., 2017)

Cvs, cultivars; DC, Direct Electric Current; DWP, Delactosed Whey Permeate; hp, high pigment; hp-2^{dg}, high-pig;ent dqrk green; HVEF, high voltqge electric field; ip, intense pigment.

achieved promising results in increasing 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 few compounds are enhanced. However, the use of *hp* and *ip* genotypes ensures a simultaneous increase in most secondary metabolites without quality compromise (Bino et al., 2005; Ilahy et al., 2017; Kolotilin et al., 2007).

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 (Table 2). AsA was found to increase in the first phases of ripening and remain either steadily stable or slight decline at the end of the process (Giovanelli et al., 1999; Tigist, Workneh, & Woldetsadi, 2013). The 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 on 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 to 217 mg/kg FW) was observed in the soft ripe ones (Singh, Ray, & Mishra, 1983). When AsA levels were evaluated in the 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, & Arnao, 2003; Jiménez et al., 2002). Similarly, a progressive increase in AsA content between the green and the red-ripe stages was reported in the fruits of "Pant T-3," "Pant 2466-27," and "Pusa Hybrid-1" tomato genotypes, whereas in "SG-12" and "MTH-1" lines AsA peaked at the yellow stage (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 "Rio 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 "Rio 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

Table 2–Variation in ascorbic acid content during ripening and postharvest of tomato fruit.

Compounds	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
AsA	Cv. Moneymaker	Different ripening stages	Initial increase followed by a decrease at final stages	(Giovanelli et al., 1999)
	Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola)			(Tigist et al., 2013)
	Cv Sabour Prabha			(Singh et al., 1983)
	Cvs DRW 3042, Primato, Floriset, Katinka, Selma, Revido, DRW 3126, Gitana, Ultimo, Relento, Pankor, Delfino, Tampo, Monica and Falcato		Peak at turning yellow stage followed by a decrease	(Abushita et al., 1997)
	Cv. Momotaro		Peak at the pink stage	(Islam et al., 1996)
	Cv. Himsona			(Pila et al., 2010)
	Cv. Marmande-Cuarenteno		Constant during maturation and increase at full red-ripe stage	(Cano et al., 2003)
	Cv. Ailsa Craig			(Jiménez et al., 2002)
	Cvs SG-12, Pusa Hybrid-1, Marglobe, Roma and Pusa Ruby,		Cultivar-dependent trend	(Siddiqui et al., 1986)
Total Vitamin C	Cv. Rio Grande and high-lycopene tomato cvs HLY13, HLY18, and Lyco2)	Ripening of *hp* tomato cultivars	Higher trends and accumulation levels compared to "Rio Grande'	(Ilahy et al., 2011)
AsA	Cv. Moneymaker	Off-vine ripening	Lowest levels at green stage increasing till the red-ripe stage	(Giovanelli et al., 1999)
	Cvs Marglobe and Roma VF			(Getinet et al., 2008)
	Cvs Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola	Postharvest storage of green-mature fruits for 20 days at room air temperature 15.4-16.2 °C and relative humidity of 34.8-52.4%	First increase followed by a decrease after 20 days	(Tigist et al., 2013)
	Cv. Zhenfen	Storage of tomato fruits at different ripening stages in the dark at 14 °C, 95% RH for up to 37 days	Increase from green to red-ripe stage	(Liu et al., 2011)
	Rio Grande	Different packaging systems ($CaCl_2$-treated and nontreated green mature tomato fruits)	Significant increase along ripening with a peak between the pink-red and the red stages of ripening. Pretreatememt with $CaCl_2$ prior to packaging resulted with the highest ascorbic acid levels followed by nontreated packed fruits	(Sammi & Masud, 2007)
	Cv. Tradiro	Storage the light-red fruits for 7, 15, 25 °C for a period of 10 days.	Slight increase	(Toor & Savage, 2006)
	Cv. Roma VF	Long-term storage of half-ripen tomato fruits	Sharp decrease	(Moneruzzaman et al., 2008)
	Red-fruited cv. Cheers Yelow-fruited cv. 6205	Processing of red and yellow tomato cultivars	80% decrease	(Georgé et al., 2011)
Vitamin C	Red intense tomatoes from commercial varieties	Pasteurization of tomato purée prepared from red-ripe tomato fruits	90% decrease	(Pérez-Conesa et al., 2009)
AsA	Peeled canned tomato product	Cooking, boiling, frying, drying	Considerable loss	(Giovanelli et al., 2002)
	Cvs Excell and Aranca			(Sahlin et al., 2004)
	NA	Milder treatment and lower temperature	Better retention	(Davey et al., 2000)

AsA: Ascrobic acid; hp: high-pigment; NA: not available; RH: relative humidity

"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 observed according to the maturity stage at harvest. Mature-green harvested tomato fruits showed the lowest AsA content, with increasing levels as the ripening process advanced (Getinet, Seyoum, & Woldetsadik, 2008; Giovanelli et al., 1999). Accordingly, Liu et al. (2011) reported that AsA contents increased from the green till the red-ripe stage of ripening (from 27.2 to 92.3 mg/kg FW) during dark storage of "Zhenfen" tomato fruits for up to 37 days at 14 °C, 95% relative humidity (RH). Generally speaking, higher AsA contents were detected in light-red tomato fruits, but

Table 3–Variation in carotenoid content during off-vine ripening of tomato fruit.

Compounds	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
Lycopene	NA	Different ripening of ordinary tomato cultivars	Linear increase throughout the ripening stages	(Collins et al., 2006)
	Cvs Neris, Svara, Vytėnų didieji, Jurgiai and Vaisa F1			(Radzevičius et al., 2009)
	Cv. Arka Ahuti			(Namitha et al., 2011)
	Cv. Laura	On-vine vs off-vine ripened greenhouse tomato fruits	On-vine tomato has 32% less lycopene than off-vine ripened	(Arias et al., 2000)
	NA	Tomato fruit harvested before full redness (at either the breaker or turning stages)	Similar or higher lycopene content accumulated compared to those harvested at the soft red stage	(Collins et al., 2006)
Carotenoids and lycopene	Cvs HLY02, HLY13, HLY18, and Kalvert	Ripening of *hp* tomato cultivars	Higher trend in *hp* cultivars with respect to ordinary cvs	(Lenucci et al., 2006)
	Different *hp* and *ip* cvs			(Ilahy et al., 2018)
Lycopene	Cvs Excell and Aranca	Long storage periods of green-mature and red-ripe	Increased	(Sahlin et al., 2004)
	Cvs Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola			(Tigist et al., 2013)
	Cvs Vaisa, Svara and Neris	Different ripening stages	Lycopene content ranged from 2.5 to 14.2 mg/kg FW in Vaisa and Svara at the green stage respectively. Cultivar Neris had the highest lycopene contents attaining 125.1 mg/kg FW at the red-ripe stage	(Radzevičius et al., 2009)
	Cv. Tradiro	Storage of light-red tomato fruits at 7, 15 and 25 °C	Brighter red color at 15 to 25 °C than at 7 °C	(Toor & Savage, 2006)
	Cv Pyramid and a fresh market cv	Hydroponic and ordinary red-ripe tomato fruits divided into halves and stored at 22 °C for 14 days	Sharp increase	(Ajlouni et al., 2001)
	Cv. Himsona	10 days storage at ambient conditions	Progressive increase up to 33.1 mg/kg FW	(Pila et al., 2010)
	Cvs FL7692D, Suncoast carrying old gold mutation, 97E212S carrying ripenin inhibitor gene and cvs Agriset, Equinox, FL7655 and Solar Set	Storage of tomatoes harvested at the breaker stage	Peak after 6 days at room temperature	(Thompson et al., 2000)
	Cvs FL7692D, Suncoast carrying (*og*), 97E212S (*rin*) and cvs Agriset, Equinox, FL7655 and Solar Set	Transition from pink to firm or soft red stages, over 3 to 8 days of storage	Lycopene contents doubled	(Thompson et al., 2000)
	Cv Lemance F1			(Brandt et al., 2006)
	NA			(Collins et al., 2006)
	Cv. Zhenfen	Storage in the dark at 14 °C, 95% RH for up to 37 days	Increase from 0.16 to 6.80 mg/kg FW	(Liu et al., 2011)
	Cv. Clermon	Tomatoes harvested at light-red to red ripe stages and stored up to 14 days at room temperature and under refrigeration	Higher increases at room temperature	(Javanmardi & Kubota, 2006)
	Cv. UC-82B Cv. Money Maker	Mature-green tomato fruit storage in the dark at 23 °C and 80% relative humidity for 16 days	Lycopene accumulation	(Alba et al., 2000)
		Brief postharvest red-light treatment of mature-green fruit	2.3-fold accumulation during ripening	
		Red-light treatment of tomato fruit	Lycopene accumulation	
		Far-red light treatment	Decreased content	
	Cv Red Ruby	tomato fruits harvested at the breaker stage and stored in the dark at 12–14 ° C	Increased 3.5-fold in comparison with those at day 4	(Liu et al., 2009)
Carotenoids	Cv. Ailsa Craig or Rapsodie	4 days storage of red-ripe tomato discs	No change observed	(Schofield & Paliyath, 2005)
		4 days of incubation in darkness	Increased content	
		Treatment by red light or red light followed by far-red light	Increased content	

(*Continued*)

Table 3–Continued.

Compounds	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
β-carotene	Cvs DRW 3042, Primato, Floriset, Katinka, Selma, Revido, DRW 3126, Gitana, Ultimo, Relento, Pankor, Delfino, Tampo, Monica and Falcato	Different ripening stages	Increased content in proportion to the advanced ripeness in immature fruit	(Abushita et al., 1997)
	Cv. Moneymaker			(Giovanelli et al., 1999)
	Cv. Arka Ahuti			(Namitha et al.,2011)
	Cvs Neris, Svara, Vytėnų Didieji, Jurgiai and Vaisa F1			(Radzevičius et al., 2009)
	Cv Ailsa Craig		Increase from the green stage to the fully ripe stage	(Fraser et al., 1994)
	Cvs Pusa Ruby and Vashali hybrid		Increase up to the light-pink stage and declined afterwards during full and over ripe stages	(Thiagu et al., 1993)
	Cv. Ventura		Maximum level in yellow colored fruit and then decline	(Biacs et al., 1987)
	Cv. Ventura		Increase from green to breaker stage and then decreased	(Biacs et al., 1987)
	Cv. Marmande-Cuarenteno			(Cano et al., 2003)
	High-pigment cvs Lyco1, Lyco2, HLY02, HLY13, HLY18 and Kalvert	Ripening of *hp* compared to ordinary tomato cultivars	High accumulation pattern and levels in *hp* compared to ordinary tomato cv	(Hdider et al., 2013)
	Cv Red Ruby	21 days of storage and treatment (untreated, red light and UV-C treated)	No significant change	(Liu et al., 2009)
		21 days of storage and sun-light treatment	Content decreased significantly	

Cvs, cultivars; FW, fresh weight; hp, high-pigment; NA, not available; og, old gold mutation; RH, relative humidity; rin, ripening inhibitor; UV-C, ultraviolet-C.

decreased fast following storage under ambient conditions (Getinet et al., 2008).

Cultivar-to-cultivar variation was also observed in AsA content after harvest: although AsA levels of six fresh market tomato varieties exhibited a similar increasing trend during 20 days postharvest storage under ambient conditions (15.4 to 16.2 °C) and (34.8 to 52.4% RH) the content declined thereafter, the processing cultivars maintaining roughly 60% higher contents with respect to the fresh market varieties at day 32 after harvest (Tigist et al., 2013) (Table 2).

Sammi and Masud (2007) studied the effect of ripening and packaging systems on the postharvest storage and quality of "Rio Grande" fruits. The authors found that AsA level was significantly increased along ripening, the highest amounts being attained between the pink-red and red-ripe stages. A prepackaging fruit treatment with calcium chloride increased AsA content compared the untreated packed fruits. Slight AsA accumulation was observed during storage of hydroponically grown tomatoes at 7, 15, and 25 °C (Toor & Savage, 2006). Moneruzzaman, Hossain, Sani, and 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). It has been noticed a sharp decrease in AsA content following longer storage periods. The maximal AsA content (122.3 mg/kg FW) was recorded in half-ripe tomato fruits following 12 days of storage.

It is widely recognized that high temperature treatments (cooking, boiling, frying, pasteurization, and drying) of fresh and processed tomato products lead to extensive AsA loss (Giovanelli, Zanoni, Lavelli, & Nani, 2002; Sahlin, Savage, & Lister, 2004). Georgé et al. (2011) reported about 80% AsA loss after thermal processing of red and yellow tomato cultivars. Similarly Pérez-Conesa et al. (2009) found that pasteurization of tomato purée caused 90% loss of vitamin C. Satisfying AsA retention was, instead, achieved by milder thermal treatments (Davey et al., 2000).

Carotenoids (lycopene and β-carotene)

One of the main evident changes during tomato ripening is the sharp increase in the levels of carotenoids resulting in a progressive shift from the green to the orange/red pigmentation of the fruit. This change of color is the outcome of the *de novo* synthesis of lycopene and β-carotene occurring during the chloroplasts-to-chromoplasts transition and of the concurrent fast degradation of chlorophylls and thilacoidal pigments (Dávila-Aviña et al., 2011; Lenucci et al., 2012). Radzevičius et al. (2009) reported that lycopene concentration significantly increase throughout fruit ripening of different tomato cultivars ("Neris," "Svara," "Vytėnų didieji," "Jurgiai," and "Vaisa F1"). Accordingly, Collins, Perkins-Veazie, and Roberts (2006) reported a lycopene content 50% higher in soft red-ripe tomato fruits than in those at the pink stage of ripening, which was, in turn, 70% higher than that of light red fruits. Similarly, Namitha, Archana, and Negi (2011) observed a gradual lycopene increase between the green and the 5th day postbreaker stages, up to 153.3 mg/kg FW in "Arka Ahuti" tomatoes (Table 3). Arias, Lee, Logendra, and Janes (2000) found that hydroponically grown on-vine ripened greenhouse tomato fruits had 32% lower lycopene content than off-ripened fruits. Fruit harvested before full redness (at either the breaker or turning stages) developed similar or higher lycopene content than those harvested at the soft red-ripe stage (Collins et al., 2006).

Various researchers focused on high-lycopene tomato cultivars as these offer higher functional quality and, possibly, longer shelf-life than ordinary cultivars (Ilahy et al., 2017; Lenucci, Cadinu, Taurino, Piro, & Dalessandro, 2006). Ilahy et al. (2011), 2018) monitored carotenoid accumulation in the fruits of

Table 4–Variation in antioxidant activity during ripening and postharvest of tomato fruit.

In vitro assays	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
Hydrophilic antioxidant activity (TEAC + FRAP)	Cv. Rio Grande and high-lycopene tomato cvs HLY13, HLY18, and Lyco2	Different ripening stages	Decrease along ripening	(Ilahy et al., 2011)
Lipophilic antioxidant activity (TEAC + FRAP)			Increase along ripening	(Ilahy et al., 2011)
Antioxidant activity using *in vitro* radical scavenging assay Antioxidant activity using rat liver microsomes	Cv. Belissimo	Storage of fresh-cut tomato from 3 different maturity stages at 5 °C.	Decrease depending on the initial levels at harvest	(Lana & Tijskens, 2006)
Antioxidant content and enzymes	Cv. Rhapsody	Storage of mature-green tomato fruits at 4 °C for up to 4 weeks	Decrease along storage	(Yahia et al., 2007)
Antioxidant content and activity	Cv. Micro-Tom	Storage at 6 °C of tomato fruit harvested at breaker and red-ripe stages for 27 days	Significant decrease in antioxidant activity, phenolics, ascorbic acid and lycopene	(Gómez et al., 2009)
Antioxidant system	Cv. Rhapsody	Hot air treatment (38 °C) of green-mature tomato fruit and storage for up to 4 weeks	Detrimental effects	(Yahia et al., 2007)
Antioxidant activity and antioxidant system		Exposure of green-mature fruits to 34 °C for 24 hr and storage at 4 or 20 °C	Promoted antioxidant system	
	Cv. Chaoyan-219	Postharvest HVEF pretreatments prior to storage of green mature tomato fruits	Enhanced activity of antioxidant enzymes and content of nonenzyme antioxidant compounds (phenols, glutathione and ascorbic acid)	(Zhao et al., 2011)
Total antioxidant activity using the TEAC assay	Cv.Pannovy	Postharvest DC applications in red-ripe tomato fruits	Substantial increase in total antioxidant activity with augmented levels of phenolics, lycopene and β-carotene	(Dannehl et al., 2011)
Antioxidant activity	Cv. Moneymaker	DWP treatments and storage at 15 °C of red-ripe tomato fruits	Increased 26% the antioxidant activity with higher ascorbic acid and total phenol levels	(Ahmed et al., 2013)

Cvs, cultivars; DC, direct electric current; DWP, delactosed whey permeate; FRAP, ferric reducing antioxidant power; HVEF, high-voltage electric field; TEAC, trolox equivalent antioxidant capacity.

high-lycopene tomato cultivars and revealed that the amount of total carotenoids and lycopene notably increased during ripening. Regardless of ripening stage, the carotenoid concentration was considerably higher in high-lycopene tomato cultivars ("HLY18," "HLY13," and "Lyco2") than in the ordinary "Rio 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 was respectively 2.6-, 2.2-, and 1.9-fold higher than in the ordinary cultivar "Rio Grande." Total carotenoids followed a similar trend as lycopene. This important discrepancy between ordinary and high-lycopene tomato cultivars was primarily attributed to their genome carrying spontaneous high-pigment mutations leading to more deeply pigmented fruits compared to the ordinary currently grown tomato cultivars (Armendáriz, Macua, Lahoz, Gamica, & Bozal, 2006; Mustilli, Fenzi, Ciliento, Alfano, & Bowler, 1999).

Lycopene content showed considerable cultivar-dependent variability (Sahlin et al., 2004; Tigist et al., 2013) and increased following prolonged storage periods. Inherent genetic variation across genotypes underlies this variation in carotenoid contents (Tigist et al., 2013). In a survey on different tomato genotypes, lycopene concentration at the green stage ranged from 2.5 mg/kg FW in the fruits of the "Vaisa" hybrid to 14.2 mg/kg FW in those of the cultivar "Svara," while the highest content (125.1 mg/kg FW) was observed in the fully ripe fruits of the cultivar "Neris" (Radzevičius et al., 2009; Table 3).

Carotenoid levels are also affected by storage conditions (Table 3). Toor and Savage (2006) pointed out that tomato fruits stored at 15 and 25 °C exhibited visually deep red color compared to those kept at 7 °C, due to the accumulation of up to 1.8-fold higher lycopene. In another study conducted on two different medium-sized tomato cultivars from hydroponic ("Pyramid") and nonhydroponic production bought from a local supermarket, Ajlouni, Kremer, and Masih (2001) noted an increase in lycopene levels during storage at 22 °C 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 nonhydroponic fruits, 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.

Besides storage conditions, maturity stage at harvest is an influential factor on postharvest lycopene levels. Tomato fruits harvested at the breaker ripening stage attained a peak in lycopene after 6 days storage at room temperature (Thompson et al., 2000). Lycopene content doubled between the pink and the firm or soft red stages of ripening following a 3 to 8 days storage, depending

Table 5–Variation in shelf-life and physical attributes in harvested tomato fruit.

Traits	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
Shelf-life				
	Cv. DRK 453	Combination of different pressure and temperature during the shelf-life of early-breaker stage tomato fruits	Hyperbaric treatment at 20 °C extended tomato shelf-life during short treatment duration	(Liplap et al., 2013)
	Beefsteak cv. Grando F1	AVG (1 g/L) application on postharvest storage and shelf-life in tomato fruits harvested at the breaker stage	Vacuum pressure of -30KPa reduced ethylene production rate, lycopene content, a^* and c^* color indices and fruit firmness. Extended shelf-life and storage up to 20 days at 12 °C	(Candir et al., 2017)
	Cv. Dotaerang	Blue light (440 to 450 nm) treatment of mature green fruit for 7 days	Extended shelf-life	(Dhakal & Baeck, 2014)
	Cv. Zhenzhu	Ultraviolet irradiation at a dose of 4.2 Kj/m² of tomato fruits harvested at the green mature stage	Extended (up to 35 days) shelf-life at 18 °C	(Bu, Yu, Aisikaern, & Ying, 2013)
	Cv. Climberley	Pulsed light application at fluence of 2.68 and 5.36 j/cm² on whole red-ripe tomato fruits	Reduced microbial load during storage	(Aguiló-Aguayo et al., 2013)
Physiological loss in weight (PWL)				
	Cv. Grandela	Mineral oil coating and carnauba wax treatment of fruit picked at the breaker stage and storage at 10 °C for 28 days	Decreased PWL in comparison with control fruit	(Dávila-Aviña et al., 2011)
		Mineral oil coating and carnauba wax treatment of fruit picked at the pink stage and storage at 10 °C for 28 days	Decreased PWL in comparison with control fruit	
		Exposure of fruit to 20 °C for 2 days after cold storage	Decreased PWL in comparison with control fruit	
	Cvs Akoma, Pectomech and Power	Storage of red-ripe fruits for 7, 14 and 21 days at 10 °C then transfer to ambient condition (20.49 °C and 54.05% RH)	Increased PWL. Similar levels among varieties	(Kumah et al., 2011)
	Cv Money Maker	Storage of green mature tomato fruits	PLW ranging from 9- 11%	(Ali et al., 2010)
		Storage of green mature tomato fruits coated with gum Arabic	Decreased PWL in comparison with control fruit	
	Cv 508	Storage (20 days at 12 and 22 °C) of tomato fruit harvested at pink to light red stage	Increased PLW along storage. Higher PLW at 22 °C than at 12 °C	(Assi et al., 2009)
	Cvs Marglobe and Roma VF	Storage of fruit from different cultivars picked at different maturity stages	PLW levels highly dependent on all 3 factors considered	(Getinet et al., 2008)
	Cv. Clermon	Storage at ambient conditions of light-red and red-ripe tomato fruits from both open pollinated varieties and hybrids	Linear decrease along storage	(Javanmardi & Kubota, 2006)
	9402x Azad Type-3, 8731 x Azad Type-3 and Azad Type-1			(Kumar et al., 2007)
	NA	Storage at ambient condition of tomato fruits at different maturity stages	Higher PWL when harvested at breaker or turning stages	(Collins et al., 2006)
	Early pear-type and Cv. "S-12"	Tomato fruits harvested at red ripe stage and stored 7 days at room temperature	55 and 33% PWL respectively	(Kaur et al., 1977)
		Tomato fruits harvested at breaker stage and stored 7 days at room temperature	Minimum PWL of 23 and 46% respectively	
	Cv. Kuber	Storage during 12 days of tomatoes harvested at turning stage and at red ripe stage	Minimum PWL when compared to those harvested at the red-ripe stage	(Gaur & Bajpai, 1982)
	Cv. Roma VF	Storage of mature green tomato fruits	Increase during storage (up to 13.31% at 12th day)	(Moneruzzaman et al., 2008)
		Storage of full-ripen tomato fruits	Total PWL was lowest during storage, being 5.72% at 3rd day and 11.96% at 12th day of storage	
	Cv. Rio Grande	Storage of tomato fruits from different ripening stages in different packaging systems (systems (CaCl2-treated and nontreated)	Increase with advancing ripening. Reduction (50% less) in packed fruit	(Sammi & Masud, 2007)
	Cv. Roma VF	Storage of tomato fruits during 6 days under ambient condition.	7.7 to 9.7%	(Mallik et al., 1996)
	Cv. Clermon	Light-red and red-ripe tomato fruits stored at room and cold temperatures (5 and 12 °C)	Increased PWL along storage irrespective of temperature. Reduced PWL in cold-stored fruit	(Javanmardi & Kubota, 2006)
	Cv. Himsona	Storage of partially ripe orange-yellow tomato fruits at 34 ± 1°for 10 days	Progressive increase till full ripeness	(Pila et al., 2010)

(*Continued*)

Table 5–Continued.

Traits	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
		Treatment of tomato fruits with chemicals (GA3, $CaCl_2$, and salicylic acid) then storage at 34±1°for 10 days	Lesser weight loss in relation to controls	
	Cv. Josefina	modified atmosphere packaging (5% O_2 and 5% CO_2)	Extend the shelf-life of the cherry tomato cv Josefina up to 25 days	(Fagundes et al., 2015)
Fruit firmness	Cv. Belissimo	Storage for up to 32 days of tomato fruits at different ripening stages	Decreased firmness	(Lana et al., 2005)
	Cv. "870"	Storage of light-red tomato fruits	Decreased firmness	(Mizrach, 2007)
	Cvs Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola	Storage of mature-green tomato fruits under ambient conditions	Decreased firmness	(Tigist et al., 2013)
	Cvs Akoma, Pectomech and Power	Full ripe fruits stored for7, 14 and 21 days at 10 °C and then transferred to ambient condition (20.49 °C and 54.05 % RH)	Decreased firmness	(Kumah et al., 2011)
	Cv. Money Maker	Gum Arabic coating of green-mature tomato fruits stored at 20 °C and 80–90% RH for 20 days.	Decreased firmness down to 10N	(Ali et al., 2010)
	Cv. Grandela	Storage (28 days at 10 °C) of tomato fruits cv. "Grandela," harvested at breaker and pink color stage	Initially, similar firmness (15-16 N) in breaker and pink samples decreasing with storage	(Dávila-Aviña et al., 2011)
		Coating with mineral oil or carnauba, and then storage (28 days at 10 °C) of "Grandela" fruit harvested at breaker and pink color stage	Firmness of breaker fruit was 7.73, 5.43 and 7.03 N for control, mineral oil-coated and carnauba-coated samples, respectively Firmness of pink fruit was 6.5, 8.08 and 8.13 N for the control, mineral oil-coated and carnauba-coated samples, respectively	
	Cv. 508	Storage of pink to light-red tomato fruits at 12 and 22 °C for 10 days	Rapid decline in firmness. Firmer fruit at 12 °C than at 22 °C	(Assi et al., 2009)
	Cv. Zhenfen	UV-B irradiation and storage during of mature-green fruits 37 days of	Decreased firmness (26.68 to 8.59 N)	(Liu et al., 2011)
	Cv Red Ruby	21 days of storage of mature-green treated daily with short bursts of UV-C, redlight or sun light.	Gradual decrease in firmness No effects of red light treatment. Significant decrease in UV-C- and sun light- treated tomatoes	(Liu et al., 2009)

a*, b*, c*, color indexes; AVG, aminoethoxyvinylglycine; GA3, gibberellic acid; PLW, physiological loss in weight; RH, relative humidity.

on the considered genotype (Brandt, Pék, Barna, Lugasi, & Helyes, 2006; Collins et al., 2006; Thompson et al., 2000). In accordance with these reports, lycopene content in mature green tomatoes increased from 1.6 to 68.0 mg/kg FW during a 37-day storage period (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 fruits kept at room temperature with respect to those refrigerated (Javanmardi & Kubota, 2006). Light conditions have also been found to strongly impact lycopene biosynthesis and accumulation during off-vine ripening. Dark-stored tomato fruits showed a notable increase of lycopene content throughout 16 days. Alba, Cordonnier-Pratt, and Pratt (2000) showed that lycopene biosynthesis was stimulated in mature-green harvested tomato fruits following a brief red-light treatment (2.3-fold higher) during fruit ripening. A far-red light treatment of reversed the observed light-induced accumulation of lycopene, suggesting the regulation by fruit-localized phytochromes. When lycopene was assayed in "Red Ruby" tomato fruits harvested at the breaker stage and stored at 12 to 14 °C in the dark, a 3.5-fold increase (85 mg/g Dry Weight) was observed after 15 days storage (Liu, Zabaras, Bennett, Aguas, & Woonton, 2009). Carotenoid content in tomato discs remained unchanged until the fourth day of storage, and started to increase afterwards following 4 days of darkness incubation or the exposure to either red-light or red-light followed by far-red light treatment (Schofield & Paliyath, 2005).

Abushita et al. (1997) and Giovanelli et al. (1999) found a simultaneous increase of β-carotene and lycopene concentration during tomato fruit ripening (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 increases linearly from the green (3.3 mg/kg FW) stage to the full-ripe stage (36.8 mg/kg at 3 weeks postbreaker; Fraser, Truesdale, Bird, Schuch, & Bramley, 1994). Thiagu, Chand, and Ramana (1993) showed that the level of β-carotene continuously increased till the pink stage of ripening and sharply declined afterwards. Radzevičius et al. (2009) showed that β-carotene contents in tomato fruits increased during ripening. A nonsignificant decrease in β-carotene level after full ripeness stage was noted only in "Svara" tomato fruit. A limited increase, between not fully ripened and fully ripened stages, was noted in "Vaisa" F1 fruits. Biacs, Daood, Czinkotai, Hajdú, and Kiss-Kutz (1987) reported a peak of β-carotene in yellow-colored fruits of the processing cultivar "Ventura," followed by a reduction in the following ripening stages. Biacs et al. (1987) and Cano et al. (2003) highlighted that

Table 6–Variation in eating quality-related attributes during ripening and postharvest of tomato fruit.

Traits	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
Total soluble solids (TSS)	Cv. Roma VF	Different ripening stages	Highest (6.82%) and lowest (5.85%) TSS values in fully ripe and mature green fruit, respectively	(Moneruzzaman et al., 2008)
	NA		No significant changes	(Collins et al., 2006)
	Cvs Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola	Fresh market mature-green tomato varieties stored for 20 days at ambient conditions	Highest TSS contents at day 16	(Tigist et al., 2013)
		Processing tomato varieties stored for 20 days at ambient conditions	Highest TSS contents at day 20	
	Cv. Money Maker	Storage of gum Arabic-coated mature-green tomato fruits	Increasing trend of TSS during storage with treated fruit characterized by lower TSS at final day of storage	(Ali et al., 2010)
	Cv. Kuber	8 days storage of tomatoes harvested at the turning and pink stages	5.2% and 5.9% increase in fruit harvested at turning and pink stages, respectively	(Gaur & Bajpai, 1982)
		8 days storage of red-ripe tomato fruit	Substantial decline (6.6 to 4.3)	
	Cvs Akoma, Pectomech and Power	Storage of tomato fruits harvested at mature green stage for 7, 14 and 21 days at 10 °C then transferred to ambient condition (20.49 °C and 54.05 % RH)	Increase up to 8 days of storage depending on the cultivars and storage temperature	(Kumah et al., 2011)
	Cv. Malike	Storage of tomato fruits at the middle-red ripe stage for 21 days at 10 °C	Slight increase	(Znidarcic and Pozrl, 2006)
	9402x Azad Type-3, 8731 x Azad Type-3 and Azad Type-1	Storage of different red-ripe tomato fruits from open pollinated and hybrids cvs for 9 days at ambient temperatures	Poststorage increase in all genotypes	(Kumar et al., 2007)
	Cvs Marglobe and Roma VF	Storage for 32 days of Marglobe and Roma tomato fruits harvested at mature-green, turning, and light red maturity stages	Increase with significant interaction between cultivars and maturity stages	(Getinet et al., 2008)
		Storage of tomato fruit harvested at different ripening stages at different temperatures	Increase with color and maturity, depending on the stage of ripeness at harvest and storage temperature	(Trejo & Cantwell, 1996)
	Cv. Malike			(Znidarcic and Pozrl, 2006
	Cv. Sunny			(Atta-Aly et al., 2000)
	Cv. Grandela	Storage at 10 °C of breaker tomato fruits	Minor changes	(Dávila-Aviña et al., 2011)
		Storage at 10 °C of pink tomato fruits	15% to 20% decrease with respect to the initial TSS	
	Cv. Himsona	Storage at 34 ± 1 °C for 10 days	Increasing trend	(Pila et al., 2010)
		GA, $CaCl_2$, and salicylic acid treatments prior to storage for 10 days at 34 ± 1 °C	Lower TSS in treated samples	
	Cv 508	Pink or light red tomatoes held at 12 and 22 °C	Significant increase over time	(Assi et al., 2009)
	Cv. Rio Grande	Packaging of ripening fruit at ambient conditions	Increase along ripening.Highest TSS in packed fruit up to pink red stage	(Sammi & Masud, 2007)
	Cv. Clermon	Tomatoes harvested at light red to red ripe stage and stored at different temperatures during 14 days	No variation	(Javanmardi & Kubota, 2006)
	Cv Red Ruby	Breaker tomato fruits storage at 12 to 14 °C during 21 days	No significant changes	(Liu et al., 2009)
	Cv. Clarion	14 days room temperature stored mature green and full ripe tomato fruits	No significant changes	(Wills & Ku, 2002)
	Cv. BR124	10 days of storage at 12 °C	No significant changes in TSS	(Kagan-Zur & Mizrahi, 1993)
	Different high-pigment tomato cvs	Processing of high-pigment tomato cultivars into purée	Important TSS loss in all cases	(Siddiqui and Singh, 2015)
	Ordinary tomato cvs	Processing of ordinary tomato cultivars into purée	Important TSS loss in all cases	
Acidity				
	Cv Ailsa Craig	Fruit ripening of standard cultivars	Decrease in some organic acids	(Chen et al., 2001)

(*Continued*)

Table 6–Continued.

Traits	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
	Cv Santa Clara			(Castro et al., 2005)
	9402x Azad Type-3, 8731 x Azad Type-3 and Azad Type-1			(Kumar et al., 2007)
	Cvs Marglobe and Roma VF			(Getinet et al., 2008)
	Cv. Himsona			(Pila et al., 2010)
	Cv. Micro-Tom	Ripening "Micro-Tom" fruit stored at different temperature	Significant decreases in tartaric, malic, ascorbic, and citric acids Slow increase in succinic acid Low acid content in immature fruit, with the highest levels at the breaker stage and a rapid decrease thereafter	(Gómez et al., 2009)
	Cv. Roma VF	Ripening conditions (different temperature and relative humidity)	Differences in ascorbic acid content	(Moneruzzaman et al., 2008).
	Cv. Ohio 7814	Ripening	Highest organic acid content at the pink stage, and then a decline with ripening. Highest citric than malic acid concentration throughout fruit development Very small amounts of oxalic acid, with similar change patterns as those for citric and malic acids	(Knee & Finger, 1992)
	Cv. Momotaro			(Islam et al., 1996)
	Cv. Roma VF	Ripening	TA content peaks at the pink stage	(Moneruzzaman et al., 2008)
	Cv. Momotaro	Storage at 15 °C	Linearly decreased concentration with increasing temperature	(Islam et al., 1996)
	Cv. Grandela	Coating with mineral oil and carnauba wax tomato during ripening	Decrease with maturity irrespective of coating treatments	(Dávila-Aviña et al., 2011)
	Cvs Marglobe and Roma VF	Storage for 32 days of Marglobe and Roma tomato fruits harvested at mature-green, turning, and light red maturity stages	Declining trend (cultivar-specific)	(Getinet et al., 2008)
	9402x Azad Type-3, 8731 x Azad Type-3 and Azad Type-1	Storage of different open pollinated and hybrids varieties cvs and hybrids for 9 days at ambient temperatures	Decline during storage	(Kumar et al., 2007)
	Cv. Money Maker	Storage of coated and uncoated tomato fruits	Declining trend irrespective of treatments	(Ali et al., 2010)
	Cv. Pronto	Short term storage (4 days after harvest: air temperature 20 °C, relative air humidity 55%, air velocity B 0.1 ms^{-1})	Increased by 22%	(Auerswald et al., 1999)
	Cv. Rio Grande	Freshly harvested mature green tomatoes packed in polyethylene packaging with or without treating with calcium chloride, boric acid and potassium permanganate within the different stages of ripening.	Decrease during ripening with faster rate in packed fruits	(Sammi & Masud, 2007)
	Cv. Tradiro	Storage under refrigeration, at 15 and 25 °C	Significantly higher TA at 15 and 25 °C than that of refrigerated tomatoes	(Toor & Savage, 2006)
	Cv. Red Spring	Bottled tomato pulp stored at room temperature (20.0 ± 1.8 °C) for 0 to 180 days	Significant decreases in malic (51%) and citric acid (71%)	(Ordóñez-Santos et al., 2009)
		Tomato paste stored at different temperatures	Gradual increase in acidity	(Gould, 1992)
Total sugars				
Sugar content	Roma VF, Melkasalsa, Melkashola, Metadel, Eshete, Marglobe Improved, Fetane, Heinz-1350 and Bishola)	Ripening Different ripening stages	Increase from the green mature to the red ripe stage	(Tadesse et al., 2012)
Total sugars	Cvs. Sunny and Solar Set		Initial increment followed by no further changes or a slight decrease	(Baldwin et al., 1991)
Sugars content	Cv. Moneymaker		Content depending on harvest maturity	(Sinaga, 1986)

(*Continued*)

Table 6–Continued.

Traits	Cultivar name	Harvest conditions and applied treatments	Observed changes	References
Reducing sugars and soluble sugars	Cvs Moscow and Fireball		Reducing sugars increased during ripening and storage	(Dalal et al., 1965)
Sugars	Cv. Rio Grande		Peak at green to turning stage and then decrease as ripening proceeds	(Sammi & Masud, 2007)
Reducing sugars Sucrose	Cv. Momotaro		More rapid increase at later than at earlier stages of ripening Highest sucrose concentration in immature and mature green fruit and then decline with maturation	(Islam et al., 1996)
Glucose and fructose	Cv. Micro-Tom	Storage at 20 °C of tomato fruits at different maturity stages	Increased accumulation was lowered under chilling storage	(Gómez et al., 2009)
Reducing sugar content	9402 x Azad Type-3, 8731 x Azad Type-3 and Azad Type-1	Storage of tomato fruits at different ripening stages from for 9 days at ambient temperatures	Increase gradually during storage	(Kumar et al., 2007)
Total sugars	Cv. Marglobe	Mature green fruit stored at 14 to 19 °C for 28 days	Increased levels up to 8 days of storage and decreased afterwards	(Melkamu et al., 2008)
Reducing sugars	Cv. Pronto	Short term storage of ripe tomato fruits (4 days after harvest: air temperature 20 °C, relative air humidity 55%, air velocity B 0.1 ms^{-1})	No important change up to 7 days	(Auerswald et al., 1999)
Total sugars	Cv. Roma VF	Tomato fruits harvested at Mature green, half ripen and full ripen were kept under 3 different conditions; open condition (control), covering with white polythene and finally treatment by $CaC_2{}^{+}$ polythene.	Highest total sugars in packed fruit at the end of the storage Increase with ripening irrespective of maturity condition	(Moneruzzaman et al., 2008)
Aroma				
	Cv. Vanessa	Off-vine ripening of tomato	Hexanal content increased and correlated positively with sweetness	(Krumbein et al., 2004)
	Ordinary fresh market tomatoes harvested at mature green Cherry tomato cvs Roma type tomato fruits, Cv. Early Girl	Ripening	Phenyl acetaldehyde and 3-methylbutanal formed during ripening Contribution of furaneol to the flavour of fresh tomato	(Buttery et al., 2001)
			Volatile monoterpenes present in minute quantity	(Galliard et al., 1977)
	NA	Ripening of vine vs off-vine tomato	Higher content of benzaldehyde, citronellyl propionate, citronellyl butyrate, decanal, dodecanal, geranyl acetate, geranyl butyrate, nonanal, and neral in vine-ripened tomato as compared to artificially ripened tomatoes Higher content of butanol, 2,3-butanedione, isopentanal, isopentyl acetate, 2-methyl-3-hexanol, 3-pentanol, and propyl acetate in artificially ripened tomatoes, as compared to field-ripened tomato	(Madhavi & Salunkhe, 1998)

Cvs, cultivars; GA3, gibberellic acid; NA, not available; TA, total acidity; TSS, total soluble solids.

β-carotene level increased from the green to the breaker stages up to 4.9 mmol/kg FW and decreased afterward to 3.4 mmol/kg FW.

Hdider, Ilahy, Tlili, Lenucci, and 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 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 high β-carotene levels. 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 mutations leading to exaggerated light-responsiveness and deeply red-pigment mature fruits compared to ordinary cultivars (Atanassova, Stoeva-Popova, & Balacheva, 2007;

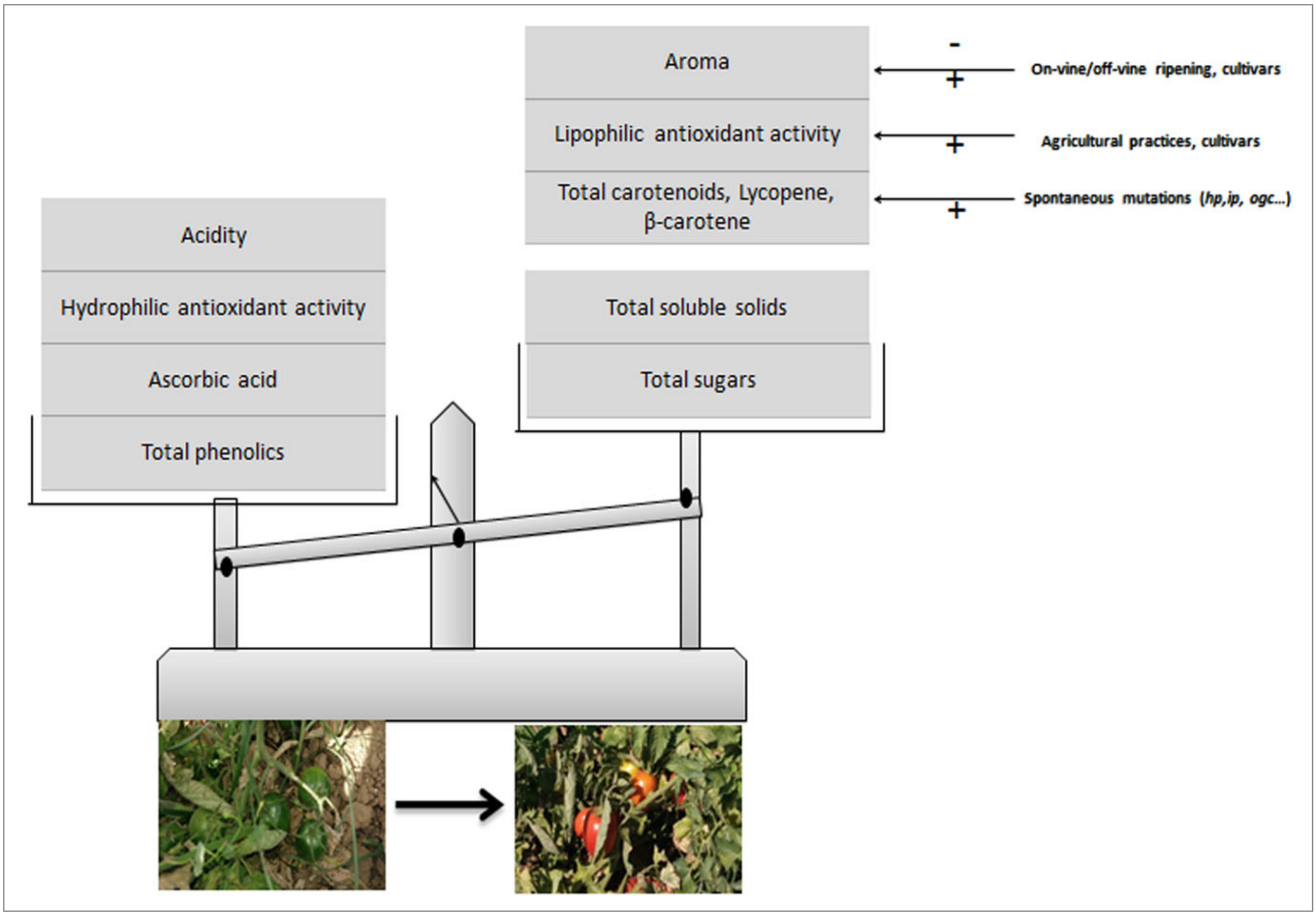

Figure 1–Major changes during ripening of tomato fruits. hp, high pigment; ip, intense pigment; ogc, old gold crimson; +, positive effect; –, negative effect.

Mustilli et al., 1999). For all the studied cultivars, β-carotene levels were lowest at the green stage, increasing afterwards till the red-ripe stage. This increase was 3.7-fold in "Donald" tomato fruits, whereas in high-lycopene tomato cultivars (with the exception of "HLY02") it was between 3.7- to 7.1-fold higher than the ordinary tomato cultivar (Hdider et al., 2013). The β-carotene contents remained almost unchanged (average of 12 μg/g D.W.) in nontreated, red-light-treated and UV-C-treated tomato fruits throughout 21 days of treatment and storage, in contrast to the observations for sun light-treated fruits (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, & Schaich, 2005). Radical scavenging activity 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 the interpretation of published data. Even so, very few reports focused 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 using the Trolox equivalent antioxidant capacity (TEAC) and the ferric reducing antioxidant power (FRAP) assays in ordinary and high-pigment tomato cultivars during the ripening process (Table 4). Regardless of the analytical method and cultivars, the highest and lowest HAA values were found in the green-mature and red-ripe fruits, respectively. Although HAA significantly dropped throughout ripening, a simultaneous increase of LAA was observed in all assessed tomato cultivars. LAA increase was between 50% and 91% using TEAC and the FRAP assays, respectively. Although the HAA values decreased and LAA increased during tomato fruits ripening in all cultivars under analysis, at the red-ripe stage, values were 28%, 61%, 110% and 66%, 59%, 124%, respectively, higher in the high-pigment tomato cultivars "Lyco2," "HLY13," and "HLY18" compared to Rio Grande. All of the above reported data highlight the higher antioxidant profile of high-pigment cultivars, which suit the ever-increasing consumer demand for nutritive and healthy foods.

Lana and Tijskens (2006) focused on the changes affecting the antioxidant activity of fresh-cut tomato during 5 °C postharvest storage. Fruits were harvest at three different maturity stages, and two methods were used for antioxidant activity determination, one of them being an *in vitro* radical scavenging assay, while the second 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 fruits at an adequate maturity stage in order to optimize the levels of the health-promoting property. Storage of "Rhapsody" tomato fruit at 4 °C was also reported to decrease the content of antioxidant molecules (Yahia, Soto-Zamora, Brecht,

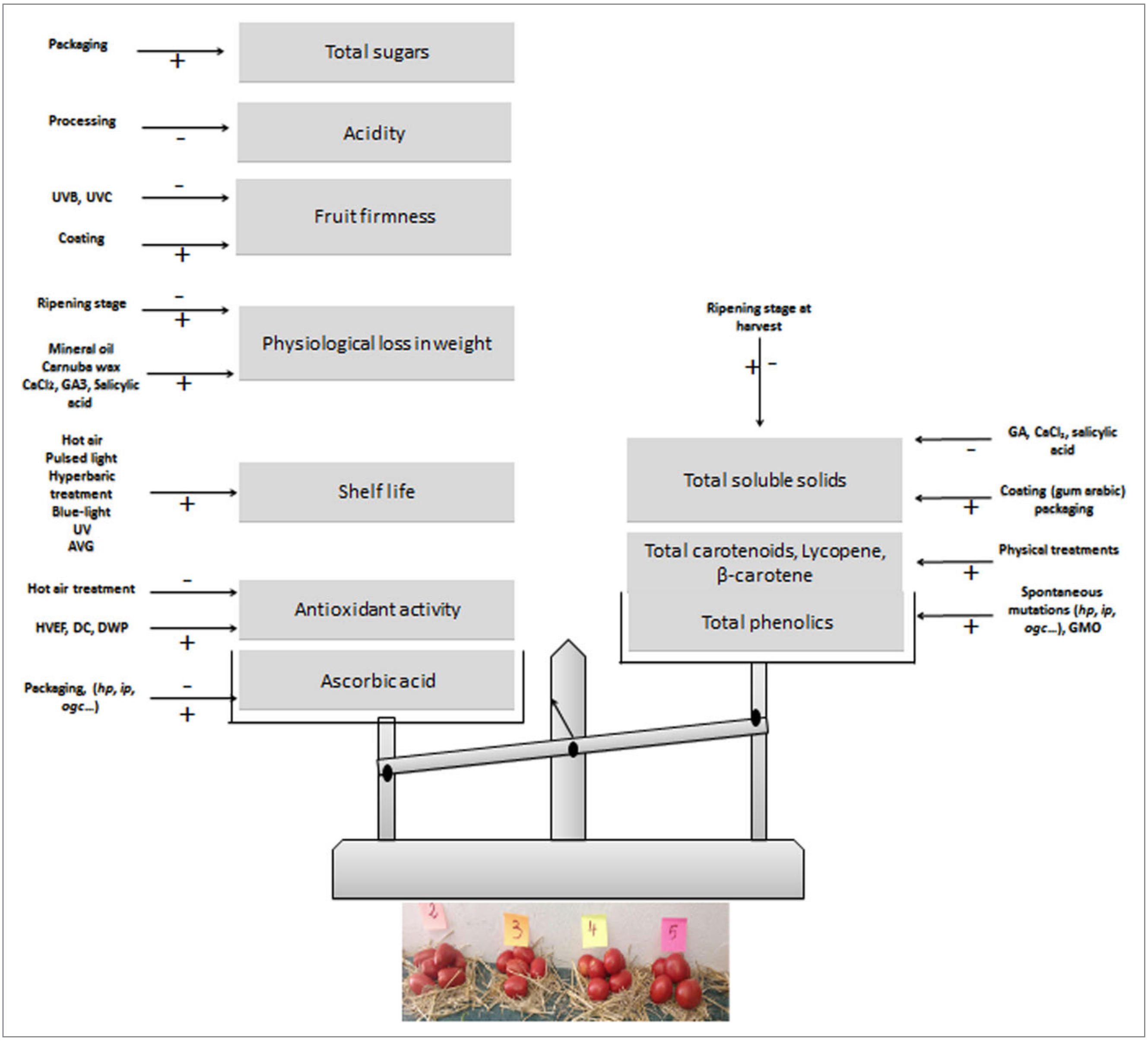

Figure 2–Major changes during postharvest storage of tomato fruits. ogc, old gold crimson; +, positive effect; –, negative effect; AVG, aminoethoxyvinylglycine; DC, direct electric current; DWP, delactosed whey permeate; GA, gibberellic acid; GA3, gibberellic acid; GMO, genetically modified organisms; hp, high pigment; HVEF, high-voltage electric field; ip, intense pigment; UV, ultraviolet; UVB, ultraviolet B; UVC, ultraviolet C.

K., & Gardea, 2007). Similarly, significant decreases in phenolics, AsA and lycopene occurred in "Micro-Tom" fruits after 27 days of storage at 6 °C, although glutathione content increased and the antioxidant capacity, determined by the 2,2-diphenyl-1-picrylhydrazyl analytical method, resulted unchanged (Gómez et al., 2009).

Some reports suggest that specific postharvest treatments may partially reduce the detrimental effects of cold storage on the antioxidant properties of tomato fruits if conditions are carefully optimized (Table 4). For instance, when "Rhapsody" fruits are submitted to hot-air pre-treatments to improve storability and decrease the incidence of chilling injury, detrimental effects on antioxidant activity were found at 38 °C, while 34 °C exposure was found to promote the antioxidant capacity of tomatoes (Yahia, Soto-Zamora, Brecht, & Gardea, 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 nonenzymatic antioxidant compounds like phenols, glutathione and AsA (Zhao et al., 2011). Postharvest direct-electric-current applications in "Pannovy" fruits also increased substantially the total antioxidant activity measured by TEAC, with concomitantly augmented phenolics, lycopene and β-carotene contents (Dannehl et al., 2011). DWP treatments increased antioxidant activity of "Moneymaker" tomatoes by 26% at the end of storage at 15 °C, 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) finding 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 −30 KPa. Generally, AVG-treated fruits exhibited lower ethylene production, decreased lycopene biosynthesis, altered color changes and increased firmness than nontreated ones.

Dhakal and Baeck (2014) reported that short time (1 week) irradiation of mature-green tomato fruits with light emitting diode-generated blue-light (440 to 450 nm) is a practical approach to delay fruit ripening and softening thus extending shelf-life. Similarly, UV irradiation (4.2 Kj/m²) prolonged the shelf-life of green-mature harvested "Zhenzhu" tomato fruits 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 nonthermal food grade technology to reduce microbial charge of fresh tomatoes during postharvest storage, with no adverse effects on the the nutritional value of the product (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 product. The shelf life threshold of fresh fruits and vegetables is attained at about 10% PLW (Acedo, 1997; Pal, Roy, and Srivastava, 1997). Storage duration, temperature and genotype significantly affect PLW (Javanmardi & Kubota, 2006). 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 & Reddy, 2006). Several reports have been published on PLW in tomato during postharvest storage (Table 5).

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 1 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, and Alderson (2010) reported 9% to 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 °C than at 12 °C (Assi, Jabarin, & Al-Debei, 2009).

Getinet et al. (2008) investigated cultivar-, maturity- and storage condition-related effects on PLW of tomatoes. The light-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, and 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) focused on the effect of ripening stage on PLW throughout storage of tomato fruits at room temperature. Generally, breaker or turning tomato fruits displayed higher PLW. Red-ripe early 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 were reported after 12 days of storage for turning with respect to red-ripe tomato fruits (Gaur & 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 fruits throughout storage was reported to be increased 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 fruits of "Roma VF" tomato 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 fruits 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 products. 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 acceptability and commercial quality evaluation 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. (2013) 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, & Tucker, 1993), by cell wall-modifying enzyme activities (very prominently pectinesterase and polygalacturonase; Page, Marty, Bouchet, Gouble, & Causse, 2008). Loosening of 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 1 till day 7 irrespective of storage temperature (cold or ambient). Fruit firmness decreased significantly during storage as measured in gum-arabic coated and noncoated tomato fruits (Ali et al., 2010). Tomato fruits kept under ambient temperature exhibited the lowest firmness values (10 N) 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 throughout 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 to 16 N) which decreased afterwards attaining values in the range of 5.4 to 8.1 N. Assi et al. (2009) studied the storage performance of tomatoes against traditional and modern handling methods followed in Jordan. Tomato fruits were stored during 10 days at 12 and 22 °C, displayed a rapid decline in firmness, although those held at 12 °C 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 upgrade mature-green fruit quality of the cultivar Rio Grande. The authors observed that sensory texture scores increased with ripening, but remained lower in untreated fruits. The 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 solids (TSS) values are considered one of the most important ripening-associated qualitative parameters in various 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, thus high TSS values, usually in the range 4.80% to 8.80%, are a good index of tomato fruit maturity and eating quality during postharvest storage (Sammi & Masud, 2007). Different studies reported a gradual increase of 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 fully ripe stage. Collins et al. (2006), instead, reported no significant changes during ripening.

Tigist et al. (2013) 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 coating on tomato quality, and found increasing trend of 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 8 days of storage for tomato fruits harvested respectively at the turning and pink stage, but a decline in TSS from 6.6% to 4.3% was found for red-ripe tomato fruits (Gaur & Bajpai, 1982). Fruits harvested at the mature-green ripening stage also displayed an increase in TSS levels after 8 days of storage, though to a different extent according to cultivar and storage temperature (Kumah et al., 2011). Žnidarcic and Pozrl (2006) found that °Brix values of tomato fruit following storage for 3 weeks at 10 °C increased slightly from 5.06 to 6.92. 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 tomato fruits TSS content variability, which increased during storage. TSS increase throughout maturation and ripening in parallel with color, and postharvest changes were reported to be related to ripening stage at harvest and the temperature of the storage conditions (Atta-Aly, Brecht, & Huber, 2000; Trejo & Cantwell, 1996; Žnidarcic & Pozrl, 2006). Dávila-Aviña et al. (2011) pointed out that TSS in tomato fruits harvested at the breaker stage remained rather unchanged throughout storage at 10 °C, except for control fruit which displayed a 15% increase when the storage period expired. Pink tomatoes showed a decrease in TSS of approximately 15% to 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. Assi et al. (2009) compared traditional and modern tomato handling methods used in Jordan, in which tomato fruits harvested at the pink or light-red stages were held at 12 or 22 °C, and found an increase in TSS with storage period, with significant differences between both storage temperatures. 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 a hydroponic system in greenhouses for TSS changes during consecutive 14 days of storage at 12 °C 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 ripening stages and stored at different temperatures did not show any variation during up to 14 days. TSS values remained unchanged for 21 days of storage of untreated and treated tomato fruits during 3 weeks of storage at 12 to 14 °C, and were not significantly affected by all the applied light treatments applied (Liu et al., 2009). Similarly, no significant variations in TSS contents were detected in tomatoes kept for 14 days at room temperature (Wills & Ku, 2002) or at 12 °C during 10 days (Kagan-Zur & Mizrahi, 1993).

Siddiqui and Singh (2015) demonstrated that puree prepared from tomato fruit of high-pigment cultivars Berika and BCT-119, lost about 45% to 58% of their original TSS values respectively, whereas the loss in ordinary cvs Patharkutchi and Punjab Chhuhara was only 43% to 56%, respectively. Similarly, Safdar, Mumtaz, Amjad, Siddiqui, and Hameed (2010) reported increased TSS contents in tomato paste during storage for 240 days at different temperatures. Since TSS is referred to as the sum of acids sugars and other secondary components (Beckles, 2012), the consumption of a part of them by micro-organisms as a food source is likely to lead to decreased TSS levels in puree during storage.

Total acidity

In many fruits, including tomatoes, titratable acidity (TA) is a good index to assess fruit maturity as its values are known to decrease in the later stages of ripening. Usually, in tomato TA is low in immature-green fruits, reaches a maximum at the turning stage and decreases rapidly afterwards (Table 6; Castro, Vigneault, Charles, & Cortez, 2005; Chen, Wilson, Kim, & Grierson, 2001; Getinet et al., 2008; Kumar et al., 2007; Pila et al., 2010). Accordingly, Islam et al. (1996) and Knee and Finger (1992) reported a peak in the amount of organic acids at the pink ripening stage.

Citric acid content was much higher than that of malic acid and oxalic acid, whose level was very limited.

A decline of TA levels also occurs during storage and has been associated with fruit quality deterioration, being strongly related to a loss of the typical sour taste of tomatoes. The progressive reduction of tomato fruit TA during ripening and storage is the result of organic acid catabolism and is partially related to the increase of respiration rates occurring in climacteric fruits, when citric and malic acids are rapidly consumed as key respiration substrates (El-Anany, Hassan, Rehab, & Ali, 2009).

It has been demonstrated that fruit pretreatments and/or postharvest storage conditions significantly affect TA decline (Hernández-Suárez, Rodríguez-.Rodríguez, & Díaz-Romero, 2008; Majidi, Minaei, Almasi, & Mostofi, 2011; Table 6). "Micro-Tom" tomatoes stored at 20 or 6 °C displayed patterns of change diverse for each organic acid. At both temperatures citric, malic, ascorbic and tartaric acids were slight but significantly reduced throughout maturity, while succinic acid slowly accumulated. Refrigeration slowed the specific kinetics of most acids, without stopping it (Gómez et al., 2009). Significant variations in TA values were also reported by Moneruzzaman et al. (2008, 2009) in freshly harvested tomato fruits grown in an open field at Mymensing (Bangladesh) and Pealing Jaya (Malaysia) and subjected to 3 different storage condition. Ripening stage, storage time and conditions (mainly temperature and RH) were all found to affect TA levels. After 9 days of storage, half-ripe harvested tomatoes had the highest TA (0.48%), followed by fully ripe (0.47%) and mature-green tomato fruits (0.44%).

Islam et al. (1996) found that organic acid levels significantly dropped with the increase of storage temperature, with fruits kept at 15 °C showing values higher than those kept at 25 or 30 °C. 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 dropped 40% and 25%, respectively, compared to nontreated fruits. Getinet et al. (2008) found a declining trend for TA during storage of 2 different tomato ("Marglobe" and "Roma VF") cultivars; however, the extent of this decline was cultivar-specific. Kumar et al. (2007) opined 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. Ali et al. (2010) found a declining trend for TA during storage of coated and uncoated tomatoes irrespective of treatment. Auerswald, Peters, Brückner, Krumbein, and Kuchenbuch (1999) reported a 22% increase in the TA level of hydroponically grown tomato fruits after a postharvest storage period of 4 days. Sammi and Masud (2007) reported a decrease in TA during postharvest tomato ripening, with a faster rate in packed tomato fruits. Regardless of the ripening stage, the highest value of TA was monitored in control tomato fruits during the storage period. Whereas, Toor and Savage (2006) reported that hydroponically grown tomato fruits stored at 15 and 25 °C had TA values of 0.97% and 1.06% citric acid, respectively, significantly higher with respect to fruits subjected to refrigeration (0.77% citric acid), and increased during subsequent storage, particularly at ambient temperature.

Ordóñez-Santos, Vázquez-Odériz, Arbonés-Maciñeira, and Romero-Rodríguez (2009) reported that the level of malic and citric acids of tomato pulp decreased significantly by 51% and 71%, respectively, during storage for 180 days. However, Gould (1992) reported that following storage of tomato paste at different temperatures, TA values increased linearly throughout the period, with higher levels (18.39%) at ambient temperature than at −10 °C (7.47%; Table 6).

Total sugar

Total sugar (TS) is also considered an important trait for tomato quality assessment. Tomatoes accumulate fructose and glucose more than sucrose (Siddiqui, Ayala-Zavala, & 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 synthesis is driven by an increase in sucrose synthase (SS) activity (Islam et al., 1996), indicating that the enzyme plays a central role in sucrose accumulation. The hydrolysis of starch also contributes to the increase of soluble-sugar content during tomato ripening (Pila et al., 2010).

An initial increment in tomato fruit TS values over-ripening has been noted, subsequently, TS remained unchanged or exhibited a minor decrease (Baldwin, Nisperos-Carriedo, & Moshonas, 1991). Sugar content varies with maturity stage at harvest (Sinaga, 1986). Dalal, Salunkhe, Boe, and Olson (1965) found that at the mature-green, breaker, pink, red, and red-ripe tomato ripening stages, reducing sugars accounted for about 2.4%, 2.90%, 3.10%, 3.45%, and 3.65% on a FW basis, respectively. Regardless of temperature, the level of soluble sugar showed an increasing trend during storage. Sammi and Masud (2007) observed that during the transition from the green to the turning maturity stages, control fruits displayed a peak of sugars. Islam et al. (1996) showed that reducing sugar accumulated more rapidly at the final than early ripening stages. A peak of sucrose was detected in immature-green and mature-green tomato fruits and dropped in later stages of maturity. In tomatoes about 95% of total soluble sugars are reducing sugars, with fructose levels higher than glucose.

Gómez et al. (2009) reported increasing levels of glucose and fructose throughout 20 °C storage period, in breaker tomato fruits, but this accumulation was decreased under refrigerated storage, with final values attaining approximately 80% of those measured in control fruits. Kumar et al. (2007) observed different tomato genotypes in which the reducing sugar content ranged between 1.98% and 3.54% and found a gradual increase during storage. Mature-green tomato fruit stored at low temperature (14 to 19 °C) for 28 days exhibited increasing TS levels up to 8 days and decreased afterwards (Melkamu, Seyoum, & Woldetsadik, 2008). Auerswald et al. (1999) reported that the level of reducing sugars in hydroponically grown tomato fruits was unaffected after a week postharvest period (Table 6). Packed fruits showed the highest TS content by the end of storage (pink-red to red-ripe maturity stages). Significant variation among different maturity stages was reported by Moneruzzaman et al. (2008) for TS content in fruit pulp. TS content increased with advancing ripening of fruit irrespective of maturity stage. A peak of TS (4.03%) was detected in fully ripe tomato fruits, while the lowest value (3.30%) was measured in mature-green harvested tomatoes after 12 days of storage.

Aroma

Being a climacteric fruit, tomatoes exhibit the characteristic increase in respiration and rate of ethylene production, as well as various typical ripening-associated quality characteristics such as chemical composition, color, texture, taste, and aroma. Aroma is a major quality attribute determining consumer choice of tomato for its use, as fresh or processing purposes. These specific processing purposes help determine the most suitable maturity stage at which to harvest the tomatoes. Since ethylene is closely associated with the initiation and subsequent integration of biochemical changes during tomato fruit ripening, most postharvest processes emphasize the control of ripening aiming to either expanding the shelf-life potential or accelerating maturity. The exogenous application of ethephon, an ethylene-releasing chemical, has been frequently used to fasten the process of off-vine ripening of commercial tomatoes. Tomato fruit aroma profiles are complex. Of the over 400 identified volatile compounds, about 30 molecules seem implicated in providing the characteristic pleasant flavors of fresh fruits and processed tomato products (Petro-Turza, 1987). The biosynthesis of aroma molecules in tomatoes, as well as in most other fruits and vegetables, depends on several pathways (El Hadi, Zhang, Wu, Zhou, & Tao, 2013; Salles, Nicklaus, & Septier, 2003). Many aroma-contributing volatiles (alcohols, carbonyls, acids and esters) originate from the metabolism of amino acids, including aspartic and glutamic acids, leucine and 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 has been reported (Petro-Turza, 1987). The alcohol 3-methylbutanol, synthesized from leucine, is an important volatile contributing to sweet and fresh ripe tomato aroma notes (Buttery & Ling, 1993). The increase in nonprotein nitrogen associated with the decrease in protein level has been correlated to an 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 flavor (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, & Brückner, 2004) (Table 6). Phenylacetaldehyde and 3-methylbutanal arise from glycosides hydrolysis throughout maturity. Furaneol contributes to the "fresh" notes in tomato fruits (Buttery, Takeoka, Naim, Rabinowitch, & Nam, 2001). Volatile monoterpenes are also present in tomato, but in small quantity. 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, & Olson, 1969). Benzaldehyde, citronellyl propionoate, citronellyl butyrate, decanal, dodecanal, geranyl acetate, geranyl butanoate, nonanal, and neral in plant-ripened tomato fruits were reported to be released in higher concentrations than in those artificially ripened, which in turn displayed higher emissions of butanol, 2,3-butanedione, isopentanal, isopentyl acetate, 2-methyl-3-hexanol, 3-pentanol, and propyl acetate (Madhavi & Salunkhe, 1998) (Table 6). Off-flavors are associated with increased productions of 2-methyl-1-butanal, particularly by off-vine ripened tomato.

Conclusions

Increasing evidence is available regarding the positive role of a regular dietary intake of fresh tomato fruits and tomato processed products on human health and wellbeing. In this review, the health-promoting, physical and eating-related properties of tomato fruit are presented and discussed as affected by ripening stages, storage conditions and their combinations. During off-vine ripening of tomato, some attributes increase such as lycopene, total carotenoids, LAA, PLW, TSS, and aroma. However, HAA, fruit firmness, and TA decrease. AsA show cultivar-dependent accumulation trends during off-vine ripening.

Storage influence health-promoting, physical as well as eating-related properties of tomato, negatively or positively according to storage duration and conditions. This review highlights that total carotenoids, particularly lycopene, total antioxidant activity, and TS increase during storage, whereas phenol content, AsA content, and fruit firmness decrease. It is relevant to emphasize that the effects of off-vine ripening on tomato quality depend mostly on the initial content of each bioactive compounds 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 high quality is obtained under low storage temperature and mild treatment. Tomato fruit is subjected to complex changes during ripening and postharvest affecting bioactive molecules and health-promoting properties, physical and eating quality-related attributes (Figures 1 and 2). All of the above-reported changes are aiming to accumulate health-promoting compounds during ripening and to preserve as long as possible the shelf-life of the fruit during postharvest storage of tomato fruits under various conditions.

Author Contributions

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

Conflict of Interests

Authors declare no conflict of interests.

Abbreviations

GAE	Gallic acid equivalent
FW	Fresh weight
HVEF	high-voltage electrostatic field
DWP	delactosed whey permeate
AsA	ascorbic acid
UV-C	ultraviolet-C
HAA	hydrophilic antioxidant activity
LAA	lipophilic antioxidant activity
AVG	Aminoethoxyvinylglycine
PLW	physiological loss in weight
RH	relative humidity
UV-B	ultraviolet-B
TSS	total soluble solids
Brix	degree Brix
TA	titratable acidity
TS	total sugars

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