Research Paper

Quality Comparison of Different Tomato Varieties and Harvesting Stage for Processing

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Abstract

Effects of variety, level of maturity, and postharvest ripening environmental conditions on vine red-riped (VR) and postharvest red-ripened (PR) tomatoes were assessed focusing on processing suitability. Three locally developed hybrids; *HTH3, Bathiya*, and *Maheshi,* and four locally developed open-pollinated varieties; *Thilina, Lanka Sour, Rashmi*, and *T245*, were used. Morphological, physicochemical, and biochemical characteristics of VR fruits and PR fruits harvested from different maturity levels were evaluated. Fruit quality characteristics were diverse among the varieties. *HTH3, Bathiya*, and *Thilina* varieties recorded a higher shape index (> 1), pericarp thickness (6.6-7.4 mm), firmness (32.0-36.2 N), soluble solids content (SSC, 6.9-7.0%), and taste index (10.8-10.9) and thus could be suggested as suitable for long-distance transportation and processing. The variety, level of maturity at harvest and postharvest ripening environment conditions affected the time to reach full redness, fruit weight loss, and firmness. *Thilina, Lanka Sour, Rashmi*, and *T245* varieties reached red faster at ambient conditions, *while HTH3, Bathiya*, and *Maheshi* varieties showed less sensitivity to postharvest ripening environmental conditions. The firmness, SSC, titratable acidity (TA), pH, and lycopene content of PR tomatoes varied among the varieties and levels of maturity. Harvesting at later ripeness resulted in an optimum redness with a less reduction in fruit weight, firmness, and SSC. Thus, this research provides guidance to growers and processors in selecting relevant varieties, levels of maturity and postharvest environment conditions of tomato for processing.

Keywords: **Maturity, Postharvest-ripened, Processing, Tomato variety, Vine-ripe**

Introduction

Tomato (*Solanum lycopersicum* L.) ripening is a biochemical process, which is accompanied by changes in the content of several molecules such as soluble carbohydrates, organic acids, and amino acids, accumulation of lycopene and carotene, and degradation of cells and loss of firm texture (Liu *et al*., 2015). Nevertheless, a considerable genetic variation exists in tomato in respect to ripening (Pesaresi *et al*., 2014). Maturity at harvest is the second most important factor, after genotype, influencing flavor quality of ripe fruits. Vine red-ripe (VR) fruits reach the complete physiological ripeness in the vine/plant, and postharvest red-ripened (PR) fruits are harvested before attaining complete ripeness and ripened off the vine/plant. Tomato being climacteric, can be harvested at primary stages of maturity, which however, can affect postharvest performance and fruit quality (Thole *et al*., 2021).

In fact, tomato is one of the most popular and widely grown crops of commercial significance and important nutritious fruits due to the carotenoids, fibers, and vitamins they contain (Chen *et al*., 2020). It is eaten fresh or made into various food products. Ripe fruits are used for producing tomato paste, powder, ketchup, and sauce.

Tomato processors face problems, such as difficulty of finding right varieties with correct ripeness for processing and dependence of fruit quality of PR tomato on postharvest ripening environmental conditions.

In that context, it is hypothesized that VR fruits have more quality in terms of color and flavor than PR fruits. Therefore, the objective of this work aimed to evaluate fruit quality characteristics of vine-ripe and postharvest ripened seven varieties of tomato harvested at different levels of maturity. Specific objectives were to assess tomato varieties focusing on suitability for processing, find relationships associated between quality characteristics to enable to predict important physicochemical and biochemical characteristics based on fruit morphology and determine how variety, harvesting maturity, and postharvest environmental conditions affect fruit quality characteristics when they reach fully red-ripe stage.

Materials and Methods

Materials

Tomato fruits from three locally developed hybrids (*HTH3, Bathiya*, and *Maheshi*) and locally developed four open-pollinated (OP) varieties (*Thilina, Lanka Sour, Rashmi*, and *T245*) were collected from the field of Horticultural Research and Development Institute (HORDI), during March-April from 2021 to 2023, and brought to the laboratory of Food Research Unit in Kandy, Sri Lanka.

Evaluation of morphological, physicochemical, and biochemical characteristics

Fruit shape, peel color (at the stem region of fruit as per documented descriptors), fruit fresh weight, polar and equatorial diameters (by vernier caliper), pericarp thickness (by vernier caliper) and number of locules/fruit were taken in 25 red-ripe

(Rd-ripe) fruits of each variety. Ten random sampled Rd fruits from each variety were used to estimate physicochemical and biochemical characteristics as described follows.

Evaluation of fruit quality characteristics during postharvest fruit ripening

Fresh fruits of seven varieties were harvested from maturity stage 1 to 5; Mature green (MG), breaker (Br), turning (Tn), pink (Pk), and light red (LR) (USDA, 1991). The fruits harvested at maturity stage 1 to 5 were divided into two, and one set was kept at cold conditions which was at 15±2 °C and 90%-95% relative humidity (RH) and the other set was kept at ambient conditions which was at 26±2 °C and 70%-75% RH and then allowed for ripening. Peel color assessment was performed daily, and when fruits reached Rd stage, the tests for fruit quality attributes were performed immediately. Number of days until fruits reach Rd-ripe was recorded. Fruit fresh weight loss (%), pericarp firmness, soluble solids content (SSC), titratable acidity (TA), pH, and lycopene content of pulp after reaching Rd stage were determined in five fruits from each sample as described follows. Additionally, some Rd fruits were harvested from seven varieties and their pericarp firmness, SSC, TA, pH, and lycopene content were tested.

Determination of physicochemical characteristics

The fruits were rinsed, cut, and then blended in a house-use blender (HL 7699/09, Philips Co., Amsterdam, Netherlands) for 3 min to obtain a fine pulp. The SSC was measured as percent (%) by using a hand-held digital refractometer (PR-32A, Atago Co., Tokyo, Japan) immediately after the blending. The TA was measured with 0.1 N NaOH by using phenolphthalein as an indicator. The pH was measured directly using a pH meter (Glassco Scientific & Analytical Company, Milwaukee, Romania). The % weight loss of fruit samples was determined by considering the difference between the initial weight and final weight (at each storage interval) of fruits divided by the initial weight and multiplied by 100.

The dry mass (DM) content was determined by the percent difference of their masses before and after drying in an oven at 60 °C to a constant mass. The moisture content (MC) was calculated by deducting percent DM content from 100. The pericarp firmness was evaluated as force needed to penetrate at stem region of an intact fruit by using a digital penetrometer (FHP - 803, AgTec LLC, Hampden, USA) fitted with an 8-mm diameter plunger tip and to a depth of 8 mm.

Lycopene content was determined by a method reported by Fish *et al*. (2002) with some modifications, and using equation 1.

Briefly, an aliquot of 0.3 g of the sample was mixed with 10 mL ((50% hexane, 25% acetone, 25% ethanol and 0.1% BHT) in a centrifuge tube with a lid. The centrifuge tubes were vortexed for 10 s twice and then centrifuged at 320 g for 15 min. Then 3 mL of distilled water was added and left for 5 min at room temperature to allow phase separation to occur. The upper organic layer was collected and analyzed spectrophotometrically (Ultrospec 3000 pro, GE health Sciences, USA) at 503 nm. A blank cuvette containing pure hexane was used as a reference cell.

$$\text{Lycopene content } (\mu g/g) = \frac{A \times MW \times Volhexane \times 1000}{E \times L \times g} \quad (1)$$

Where A was the absorbance at 503 nm (λ_{max} for lycopene in hexane), MW was the molecular weight of lycopene (536.9 g M^{-1}), E was the extinction coefficient for lycopene in hexane (17.2 × 10^4 M cm^{-1}), L was cuvette path length of cuvette in cm and g was sample weight.

The β-carotene content was determined according to the procedure described by Knockaert *et al*. (2012) and using equation 2. Briefly, the sample (5 mL) was added with NaCl (1 g), mixed with 50 mL of solvent (50% hexane, 25% acetone, 25% ethanol and 0.1% BHT) and stirred for 20 min at room temperature. Then distilled water (15 mL) was added and stirred for 10 min at room temperature. The organic phase, which contained carotenoids, was separated from the water phase using separating funnel. The TCC was determined spectrophotometrically at 450 nm using a solution of hexane and 0.1% BHT as the blank.

$$\beta\text{-carotene content } (\mu g/mL) = \frac{A \times V1 \times 10000}{E \times V} \quad (2)$$

where A was the absorbance at 450 nm (λmax for β-carotene in hexane) (Spectrophotometric method, using UV-1800, Shimadzu, Japan), V1 was the total volume of extract (mL), V was the volume of juice (mL) and E was the extinction coefficient (2560) for β-carotene in hexane.

Analysis of total phenolic content and total hydrophilic antioxidant activity

Methanolic extraction was performed according to the method elaborated by Chandrasekara and Shahidi (2010). The total phenolic content (TPC) was measured by the Folin–Ciocalteu method (Singleton *et al*., 1999) and expressed as mg gallic acid equivalents (GAE) in 100 g fresh weight (FW) (Wellala *et al*., 2020). Antioxidant activity in terms of Ferric Reducing Antioxidant Power (FRAP) was measured in a linear range between 100 and 800 µmol L^{-1} and expressed as Trolox equivalent (TE), where one TE equals to one µmol Trolox (Wellala *et al*., 2020) and radical scavenging activity (DPPH) was measured in a linear range between 10 and 100 µmol L^{-1} and their results were expressed as Trolox equivalent (TE), where one TE equals to one µmol Trolox (Wellala *et al*., 2020).

Statistical analysis

Mean values were estimated initially for each dry season and then computed for three consecutive dry seasons. The results were expressed as mean ± standard deviation. The SAS software package (version 9; SAS Corporation, Cary, NC, USA) was used for statistical analysis. Morphological, physicochemical, and biochemical data were subjected to one-way analysis of variance (ANOVA) and Tukey's test as mean difference test was used to separate the means at $p < 0.05$. Three-way ANOVA was performed for postharvest ripening experiments, considering variety, fruit maturity, and postharvest ripening environmental conditions as main factors.

Pearson correlation coefficients between variables were calculated.

Results and Discussion

Fruit Morphological characteristics

A wide and significant variation was recorded for fruit polar diameter (PD) and equatorial diameter (ED) (Table 1). The variation of ED was higher than that of PD, thus shape index (SI) (PD/ED) was calculated. Based on the SI and shape, the varieties were categorized. *HTH3* and Thilina were heart-shaped, while Bathiya was rounded, and those three varieties showed a SI > 1 (Table 1). *Rashmi* and *T245* were slightly flat-rounded with 0.80 and 0.81 shape indices, whereas *Maheshi* and *Lanka Sour* (*LS*) were flat-rounded with 0.75 and 0.63 of shape indices, respectively. Besides, LS was characterized by irregular-shaped ridges and furrows that were not present in other varieties.

Tomato fruit shape and average weight are crucial characteristics that provide homogeneity and ease of handling (Laayouni *et al*., 2020). The average fruit weight varied significantly (Table 1). The higher weighted tomato showed a lower SI. Similarly, Rodríguez-Burruezo *et al*. (2005) reported that the varieties with the highest fruit weight are flattened, while a rounded shape is predominant in small-fruited varieties. Furthermore, Ilahy *et al*. (2018) indicated that cultivars having smaller-size fruits (42 to 90 g weight) are found to be suitable for long-distance transportation and processing. Besides, van der Knaap and Tanksley (2003) showed that the heart shape with higher length than width can bear transportation shocks, hence suitable for processing. Accordingly, *HTH3, Bathiya*, and *Thilina* varieties, which have a SI > 1 and average fruit weight ranging from 75 to 90 g, could be suggested as suitable for processing.

The heart/rounded-shaped varieties (*HTH3, Bathiya*, and *Thilina*) had a lower number of locules (NoL) (2-3), whereas the flat-fruited varieties (*Maheshi, LS, Rashmi*, and *T245*) had more NoL (> 4) (Table 1). In general, the NoL of different tomato varieties varies from two to more than ten (Muños *et al*., 2011). The pericarp thickness (PT) of *HTH3, Thilina,* and *Bathiya* varieties was significantly higher than that of *Maheshi, LS, Rashmi*, and *T245* (Table 1). In line with the results of the present study, Vishwanath *et al*. (2014) reported 3.6 mm to 8.4 mm of PT in tomato. Tomatoes with thicker pericarp are desirable for canning and would stand long-distance transport and keep well (Laayouni *et al*., 2020).

Fruit physicochemical characteristics

The firmness under compression is an important mechanical property relevant to the processing. The firmness was highest in *HTH3*, followed by *Bathiya, Thilina*, and *LS* (Table 1). Firmness is specific to the fruit variety (Tilahun *et al*., 2019) and influenced by fruit quality characteristics such as epidermis thickness, cell shape, and internal structures (Li & Thomas, 2016). Thus, the differences in firmness of ripe fruits in the present study could result, not only from cell wall degradation during ripening, but also from variety-specific cellular organization of pericarp that occurs during early fruit development (Johnston *et al*., 2001).

Table 1. The morphological and physicochemical characteristics of vine red-ripe fruits of seven tomato varieties

Variety	Polar diameter (mm)	Equatorial diameter (mm)	Shape Index	Fruit weight (g)	No Locules	Pericarp thickness (mm)	Firmness (N)	DM content (%)	SSC (%)	TA (%)	SSC/ TA	pH
HTH3	54.6 ± 2.7^{a}	53.9 ± 2.8^{c}	1.01	89.6 ± 37.4^{b}	3	7.4 ± 0.9^{a}	36.2 ± 1.5^{a}	7.8 ± 0.3^{a}	7.0 ± 0.1^{a}	0.64 ± 0.01^{b}	10.9	4.37 ± 0.02^{a}
Bathiya	53.8 ± 1.1^{a}	52.0 ± 4.8^{c}	1.03	79.1 ± 17.2^{b}	3	6.6 ± 0.5^{ab}	35.1 ± 1.8^{ab}	7.9 ± 0.4^{a}	6.9 ± 0.0^{b}	0.64 ± 0.02^{b}	10.8	4.19 ± 0.04^{c}
Maheshi	51.6 ± 1.6^{a}	69.2 ± 6.1^{a}	0.75	138.3 ± 14.3^{a}	6	3.6 ± 0.6^{c}	27.0 ± 0.8^{d}	6.2 ± 0.3^{c}	5.8 ± 0.0^{d}	0.61 ± 0.01^{c}	9.5	4.31 ± 0. 04^{a}
Thilina	53.6 ± 3.6^{a}	52.6 ± 5.2^{c}	1.02	85.6 ± 14.7^{b}	2	7.1 ± 1.0^{a}	32.1 ± 1.1^{bc}	7.2 ± 0.2^{b}	6.9 ± 0.1^{b}	0.64 ± 0.01^{b}	10.8	4.35 ± 0.03^{a}
Lanka Sour	37.8 ± 1.9^{c}	59.9 ± 4.7^{b}	0.63	93.2 ± 15.3^{b}	6	3.4 ± 0.4^{c}	31.2 ± 1.3^{c}	6.1 ± 0.1^{c}	6.0 ± 0.1^{c}	0.90 ± 0.02^{a}	6.6	4.37 ± 0.02^{a}
Rashmi	45.9 ± 3.6^{b}	56.9 ± 3.9^{bc}	0.80	128.8 ± 8.2^{a}	5	4.6 ± 0.5^{bc}	24.5 ± 1.2^{e}	6.1 ± 0.1^{c}	6.0 ± 0.0^{c}	0.64 ± 0.01^{b}	9.4	4.16 ± 0.02^{bc}
T245	46.5 ± 1.4^{b}	57.1 ± 5.8^{bc}	0.81	90.3 ± 12.3^{b}	4	5.2 ± 0.5^{b}	27.0 ± 1.2^{d}	7.0 ± 0.4^{b}	6.9 ± 0.1^{b}	0.90 ± 0.02^{a}	7.6	4.07 ± 0.02^{c}

Values are the means ± SD. Different letters in each column indicate significant differences among treatments at 0.05 level.

A significant variation in dry matter (DM) content was observed (Table 1). Similar values, *i.e*., between 5.09% and 9.49%, were also obtained in other studies (Ilahy *et al*., 2018). The DM is represented by soluble carbohydrates (mainly glucose and fructose represent about half of the DM), organic acids (>10%), minerals (about 8%), and dietary fiber (about 7%) (Garcia & Barrett, 2006). Thus, the presence of higher content of DM in *HTH3, Bathiya, Thilina*, and *T245* than in other varieties could be related to higher contents of SSC and TA. Moreover, previous research pointed out that the varieties with high DM contents are more suitable for processing as the DM has an influence on the physical, mechanical, electrical, thermal, and chemical properties affecting efficiency of the processing phase (Zhang & McCarthy, 2012).

Soluble solids content (SSC) consist of soluble carbohydrates, organic acids, vitamin C, amino acids, and some pectins (Siddiqui *et al*., 2015). The mean SSC of the studied varieties was higher than 5.8% (during *Yala*), although a significant variation was recorded (Table 1). According to Garcia and Barrett (2006) and Barrett *et al*. (2007), SSC of the industrial tomatoes must have at least 5-6 %. Less energy is required to remove water from tomato having high SSC. Thus, use of high-SSC tomato is a way of saving energy in industrial production (Barrett *et al*., 2007; Graça *et al*., 2015).

The TA was higher than 0.61% in all varieties in the present study. It has been pointed out that the minimum acidity requirement of tomatoes for processing is 0.35%, since the processed products from low acid fruits could contribute to food safety through inhibition of microorganisms (Garcia & Barrett, 2006; Ilahy *et al*., 2018). Citric and malic acids are the main organic acids found in tomatoes. Higher citric acid levels give glucose a high apparent sweetness index, and therefore, the ratio of SSC to TA or the taste balance could be an important quality index. Moreover, Graça *et al*. (2015) reported that the tomato varieties with higher SSC and relatively higher acid contents and aroma volatiles are the best flavored. Accordingly, *HTH3, Thilina*, and *Bathiya* varieties due to presence of higher SSC/TA ratios at vine red-ripe stage could impart more favorable taste. LS and T245 contained relatively higher TA, and the consequent lower SSC/TA ratio could result in a tart taste (Shi & Le Maguer, 2000).

Although a significant varietal difference was recorded for pH in the vine red-ripe (VR) fruits (Table 1), the range of pH can be considered desirable in accordance with Anthon *et al*. (2011), who suggested that pH ranged from 4.25 to 4.40 is optimum and desirable to ensure food safety of fresh tomato fruit.

The color is an important consumer quality characteristic, particularly in processed tomato products. Accumulation of lycopene, which is the most characteristic hydrophobic antioxidant, is found to be responsible for the tomato red color (Siddiqui *et al*., 2015). In line with results of previous research (Tigist *et al*., 2013), the lycopene and β-carotene contents showed a variety-dependent variability (Figure 1).

LS is a red color wild genotype and has a significantly higher lycopene content. Similarly, Dorais *et al*. (2001) showed that higher concentrations of lycopene were found in wild cultivars than in commercial cultivars. Besides, *HTH3, Bathiya, Thilina*, and *T245* varieties were reddish orange, while *Maheshi* and *Rashmi* varieties were more towards orange in color, thus their lycopene and β-carotene contents varied accordingly.

Total phenolic content and total hydrophilic antioxidant activity

The contents of total phenolic compounds (TPC) varied from 26-38 mg/100g (Figure 1) and similar values were reported by Alenazi *et al*. (2020). The DPPH activity was not significant among varieties (Figure 1), while the FRAP activity was significant. The methanolic extracts were used in the current study to present the DPPH and FRAP activities of hydrophilic compounds such as phenolic compounds and ascorbic acid (Alenazi *et al*., 2020). The TPC and FRAP activity were highest in Bathiya, followed by *Thilina* and *LS* varieties. Besides, the TPC and FRAP showed an inter-correlation as well.

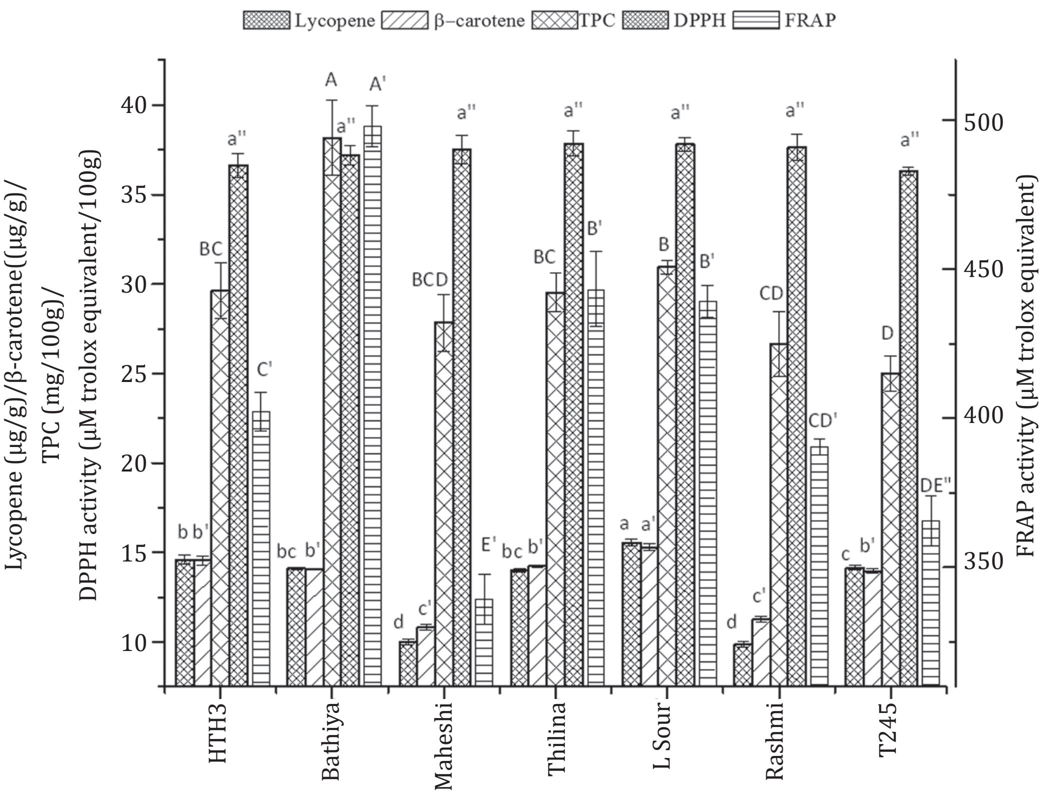

Figure 1. The carotenoid and total phenolic contents and hydrophilic antioxidant activity (DPPH and FRAP) of vine red-ripe fruits of seven tomato varieties.

Correlations between morphological, physicochemical, and biochemical characteristics

Correlation-based method using Pearson's correlation coefficient test was used to find positive and negative correlations among independent variables (Table 2). *LS* being a local selection, was shown to have unique morphological characteristics associated with its genotype, and different to other studied varieties, thus it was not used for correlation analysis.

The SI showed significant positive correlations with PT, fruit firmness, DM content, and FRAP activity, but a negative correlation with ED, fruit weight, and NoL. The SI, being a genotypic trait and a nondestructive morphological characteristics, is preferred to predict fruit structural and functional characteristics (Zhang & McCarthy, 2012).

The firmness showed significant positive correlations with the fruit PD, PT, and DM content. The NoL and ED exhibited significant positive correlations with fruit weight, such that the increase in NoL and ED was accompanied by large-sized tomato. Regardless of variety, the SSC showed significant positive correlations with DM content and PT but significant negative correlations with NoL and fruit weight. Moreover, the SSC also showed significant positive correlations with lycopene and β-carotene contents, indicating that the selection of varieties/cultivars with high values for traits related to improved taste will also have higher contents of bioactive compounds. Moreover, in ripe fruits, both lycopene and β-carotene contents showed significant positive correlations with PT and negative correlations with fruit weight and NoL. Therefore, in general, the tomato varieties/cultivars that have higher SI and PT and lower NoL, when ripe could have higher contents of soluble carbohydrates and bioactive compounds, such as lycopene and β-carotene.

In summary, *HTH3, Bathiya*, and *Thilina* varieities, which consisted of SI > 1, higher PT, higher firmness, medium fruit weight, and higher contents of SSC, TA, and carotenoids could be suitable for processing. *LS* had a lower PT and a poor taste balance, although it had the highest lycopene content. *Maheshi* and *Rashmi*, despite acceptable SSC/TA ratio and pH, may not be suitable for long-distance transportation due to lower PT and firmness. Although *T245* variety had higher acidity as a negative trait, it had medium levels of PT and firmness and higher SSC as positive traits, and could be selectively used for processing.

Evaluation of quality characteristics during postharvest ripening

Main factors and interactions

Statistical analysis revealed that the variety, level of maturity, and postharvest ripening environmental conditions, and their interactions showed significant effects on fruit weight loss (% WL), firmness, SSC, TA, pH and lycopene content of postharvest red-ripened (PR) fruits harvested at mature green (MG), breaker (Bk), turning (Tn), pink (Pk), and light red (LR). The average number of days until fruits reach red-ripe, WL and firmness are presented in Table 3 and the SSC, TA, pH and lycopene content are presented in Table 4.

Table 2. The Pearson correlation matrix of morphological, physicochemical, and biochemical characteristics of vine red-ripe tomato.

	PD	ED	SI	Wt	NoL	PT	Firmness	DM	SSC	TA	pH	Lycopene	β-carotene	TPC	DPPH	FRAP
PD	1															
ED	-0.24	1														
SI	0.76	-0.81*	1													
Wt	-0.44	0.83*	-0.83*	1												
NoL	-0.55	0.88*	-0.92**	0.91*	1											
PT	0.65	-0.86*	0.96**	-0.87*	-0.95**	1										
Firmness	0.88*	-0.59	0.91*	-0.75	-0.75	0.87*	1									
DM	0.68	-0.72	0.88*	-0.91*	-0.81	0.87*	0.92*	1								
SSC	0.42	-0.81	0.79	-0.98**	-0.89*	0.88*	0.73	0.90*	1							
TA	-0.56	-0.09	-0.28	-0.30	-0.03	-0.09	-0.29	0.04	0.36	1						
pH	0.79	0.06	0.43	-0.01	-0.28	0.40	0.53	0.20	0.06	-0.68	1					
Lycopene	0.48	-0.72	0.77	-0.97**	-0.86*	0.85*	0.76	0.91*	0.99**	0.36	-0.16	1				
β-carotene	0.47	-0.79	0.81	-0.97**	-0.91*	0.90*	0.76	0.91*	0.99**	0.32	-0.09	0.99**	1			
TPC	0.54	-0.47	0.65	-0.60	-0.46	0.46	0.67	0.71	0.46	-0.19	-0.07	0.47	0.45	1		
DPPH	0.13	0.16	-0.01	0.42	0.11	-0.19	-0.20	-0.43	-0.53	-0.74	0.33	-0.57	-0.51	0.00	1	
FRAP	0.50	-0.79	0.84*	-0.71	-0.73	0.70	0.68	0.71	0.57	-0.27	0.03	0.53	0.56	0.86*	0.18	1

** - significant at 0.05; ** - significant at 0.01*

PD - polar diameter, ED - equatorial diameter, SI - shape index, Wt - fruit weight, NoL- number of locules, PT - pericarp thickness, DM - dry matter, TSS - total soluble solids, TA - titratable acidity, TPC - total phenolic content.

Number of days to reach red-ripe stage and wight loss

Regardless of variety and level of maturity, in general, the average number of days until fruits reached the Rd-ripe was less at ambient conditions (ACs) than at cold conditions (CCs) (Table 3), indicating that higher environmental temperature could accelerate respiration/ripening rate (Thole *et al*., 2021). As expected, the fruits of early-maturity took more days to reach Rd-ripe than those of latter-maturity. Moreover, *Thilina, LS, Rashmi*, and *T245* varieties reached red earlier at ACs than at CCs. In contrast, *HTH3, Bathiya*, and *Maheshi* varieties did not differ much in the number of days to reach red under the two environmental conditions, and they could be less sensitive to temperature change during ripening. Likewise, Thole *et al*. (2021) reported that some tomato genotypes were less or unaffected by 18 °C and 26 °C storage temperatures.

The maturity level and postharvest environmental conditions markedly affected weight loss (WL) during ripening, irrespective of variety (Table 3) and also as expected, the WL was higher at ACs than at CCs (Thole *et al*., 2021). Besides, the WL decreased as maturity proceeded, but not in a direct proportion to the level of maturity. Similarly, Tilahun *et al*. (2019) reported a WL ranging from 2.79% to 3.56% after 20 days storage period at 12 °C in two commercial varieties harvested at Bk, Pk, and Rd stages. Besides, *HTH3, Bathiya*, and *Thilina* varieties resulted in a lower WL, which could be attributed to higher PT of those varieties.

The WL could have an association with water loss. Lufu *et al*. (2020) pointed out that the respiration and transpiration continue in fresh produce after the harvest, for which carbohydrate and water reserves are continually consumed without replacement leading to progressive loss of weight during storage. At the end, the WL causes wilting and shriveling and, in addition accounts to an economic loss.

Regardless of variety, the maximum fruit firmness was depicted in VR fruits, while a minimum firmness occurred when fruits harvested at MG stage reached red (Table 3). The loss of firmness was higher at ACs than at CCs, irrespective of variety and level of maturity. The variety affected the firmness differently. For instance, irrespective of maturity level and ripening conditions, *HTH3, Bathiya,* and *Thilina* varieties remained firmer than the other varieties (Table 3), which could be due to higher PT in former three varieties.

Nevertheless, the PR fruits of LS (which were harvested from LR to MG stages) showed a greater loss of firmness and it could have an association with very thin pericarp and higher flesh softness. These results further indicate that the loss of firmness could happen due to loss of turgor pressure as results of higher water loss, in addition to enzymatic degradation of fruits' cell wall (Lufu *et al*., 2020). Ultimately, softening of fruits during ripening could result in disruption of the skin and release of the cell juice, causing fermentation, deterioration and loss of industrial output.

Table 3. The combined effect of variety, level of maturity, and postharvest ripening environmental condition on average number of days until fruits reach red-ripe, weight loss, and firmness of the postharvest red-ripened fruits compared with vine red-ripe fruits.

Variety and maturity	No Days*		Weight loss (%)		Firmness (N)	
	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)
HTH3-MG	15 ± 2	17 ± 2	3.11 ± 0.14	3.78 ± 0.17	31.77 ± 2.07	29.83 ± 2.22
HTH3-Br	14 ± 1	13 ± 1	3.01 ± 0.20	3.05 ± 0.12	31.27 ± 2.41	30.43 ± 2.31
HTH3-Tn	13 ± 1	12 ± 1	2.51 ± 0.12	2.35 ± 0.21	31.70 ± 1.97	29.87 ± 1.77
HTH3-Pk	11 ± 1	09 ± 1	2.35 ± 0.08	2.32 ± 0.10	31.47 ± 2.17	31.50 ± 2.21
HTH3-LR	07 ± 1	06 ± 1	1.23 ± 0.14	1.72 ± 0.11	32.50 ± 2.11	30.93 ± 2.07
HTH3-Rd**					36.03 ± 2.07	
Ba-MG	15 ± 1	17 ± 1	3.63 ± 0.12	4.74 ± 0.22	28.33 ± 1.77	26.08 ± 2.11
Ba-Br	14 ± 1	13 ± 1	3.65 ± 0.08	3.95 ± 0.11	30.00 ± 2.11	29.07 ± 1.87
Ba-Tn	13 ± 1	12 ± 1	2.29 ± 0.10	3.16 ± 0.07	28.87 ± 2.07	28.97 ± 1.92
Ba-Pk	09 ± 1	07 ± 1	1.72 ± 0.07	1.90 ± 0.08	32.60 ± 1.97	28.43 ± 1.77
Ba-LR	06 ± 1	05 ± 1	1.09 ± 0.06	1.30 ± 0.07	36.50 ± 1.92	30.23 ± 1.52
Ba-Rd**					35.03 ± 1.88	
Ma-MG	20 ± 2	19 ± 2	5.54 ± 0.22	6.29 ± 0.18	21.41 ± 1.97	19.26 ± 2.07
Ma-Br	15 ± 2	13 ± 2	2.64 ± 0.07	3.11 ± 0.08	22.04 ± 2.11	24.50 ± 2.77
Ma-Tn	13 ± 2	12 ± 2	2.52 ± 0.17	2.68 ± 0.03	23.67 ± 1.87	23.97 ± 1.92
Ma-Pk	10 ± 2	07 ± 1	2.15 ± 0.08	2.81 ± 0.04	26.73 ± 2.07	24.77 ± 2.10
Ma-LR	08 ± 1	06 ± 1	2.26 ± 0.06	2.35 ± 0.11	26.43 ± 1.77	26.85 ± 2.14
Ma-Rd**					27.10 ± 1.72	
Thi-MG	15 ± 2	14 ± 2	2.49 ± 0.15	3.65 ± 0.17	23.87 ± 1.92	23.50 ± 1.97
Thi-Br	15 ± 2	12 ± 2	2.62 ± 0.10	3.34 ± 0.07	23.03 ± 1.17	24.00 ± 1.92
Thi-Tn	14 ± 2	07 ± 1	2.60 ± 0.10	1.26 ± 0.08	23.73 ± 2.11	26.40 ± 1.77
Thi-Pk	10 ± 1	06 ± 1	2.12 ± 0.09	1.48 ± 0.08	26.90 ± 2.57	27.33 ± 2.07
Thi-LR	07 ± 1	05 ± 1	1.96 ± 0.07	1.70 ± 0.07	29.63 ± 1.99	29.57 ± 2.37
Thi-Rd**					32.05 ± 2.17	
LS-MG	20 ± 1	12 ± 1	4.63 ± 0.11	4.82 ± 0.11	16.37 ± 1.97	16.40 ± 2.77
LS-Br	19 ± 1	11 ± 1	4.25 ± 0.13	4.60 ± 0.07	17.70 ± 1.92	19.10 ± 1.87
LS-Tn	13 ± 1	10 ± 1	4.36 ± 0.12	4.16 ± 0.14	18.70 ± 2.07	18.67± 1.17
LS-Pk	09 ± 1	07 ± 1	1.05 ± 0.14	2.74 ± 0.11	18.97 ± 2.11	16.33 ± 1.97
LS-LR	06 ± 1	04 ± 1	1.32 ± 0.17	2.17 ± 0.13	17.73 ± 1.97	16.87 ± 1.81
LS-Rd**					31.17 ± 1.92	

Variety and maturity	No Days*		Weight loss (%)		Firmness (N)	
	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)
Ra-MG	22 ± 2	17 ± 2	5.67 ± 0.24	5.40 ± 0.18	20.57 ± 2.07	21.04 ± 1.87
Ra-Br	15 ± 1	13 ± 1	3.48 ± 0.21	3.31 ± 0.07	20.33 ± 1.77	21.43 ± 2.77
Ra-Tn	13 ± 1	11 ± 1	2.47 ± 0.08	3.74 ± 0.09	25.17 ± 1.17	25.53 ± 2.07
Ra-Pk	09 ± 1	10 ± 1	2.31 ± 0.07	3.65 ± 0.07	25.10 ± 1.92	23.82 ± 1.97
Ra-LR	08 ± 1	05 ± 1	1.32 ± 0.12	1.54 ± 0.10	28.40 ± 2.47	24.07 ± 2.11
Ra-Rd**					24.50 ± 1.44	
T245-MG	20 ± 2	12 ± 2	6.07 ± 0.17	5.91 ± 0.21	19.67 ± 2.07	20.20 ± 1.97
T245-Br	19 ± 1	10 ± 1	3.58 ± 0.17	3.59 ± 0.22	20.33 ± 1.94	21.60 ± 1.11
T245-Tn	13 ± 1	07 ± 1	3.22 ± 0.11	3.88 ± 0.06	20.50 ± 1.99	23.67 ± 1.77
T245-Pk	10 ± 1	05 ± 1	2.68 ± 0.08	3.28 ± 0.11	26.23 ± 1.97	24.83 ± 1.92
T245-LR	07 ± 1	04 ± 1	1.83 ± 0.04	2.03 ± 0.07	27.63 ± 1.67	27.17 ± 2.07
T245-Rd**					27.00 ± 1.23	

**Number of days until fruits reach red-ripe after harvest, **vine red-ripe*
Ba- Bathiya, Ma- Maheshi, Thi- Thilina, LS- Lanka Sour, Ra- Rashmi, MG- mature green; Br-breaker; Tn-turning; Pk- pink; LR- light red; Rd –red; Amb- ambient

SSC, TA, and pH

The variety basically governed the SSC, TA, and pH of PR fruits (Table 4) (Tilahun *et al*., 2019; Alenazi *et al*., 2020). In each variety, the SSC and TA were not noticeably different among the fruits harvested from LR to Bk, however, lower when the MG fruits reached Rd-ripe stage. Tao *et al*. (2021) showed that starch/carbohydrate are higher in MG fruits than in red mature fruits. However, the MG fruits take more time to reach red, during which the starch could be hydrolyzed into soluble carbohydrates without replacement. Besides, lower SSC and TA cause loss of typical tomato taste (El-Anany *et al*., 2009) and may not be acceptable for processing.

The PR fruits (harvested from LR to MG) showed higher pH than the VR fruits (Table 4). The pH of the PR fruits also varied depending on the variety and harvesting maturity. An increasing trend in pH was observed from LR to Bk, and a considerably higher pH was observed, when MG fruits reached Rd-ripe.

Previous studies have shown that an increase in pH with pronged storage of fruits was probably due to the degradation of organic acids (Barragán-Iglesias *et al*., 2018). Thus, pH is a good index for shelf life studies.

Lycopene content

A major change seen during tomato ripening is a sharp increase in lycopene, resulting in a progressive shift from green to orange/red on the surface of the fruit (Helyes *et al*., 2006). The fruits harvested from LR to MG developed full redness, however, the time taken to reach peak concentration was different depending on the variety, maturity, and postharvest environmental conditions.

Table 4. The combined effect of variety, level of maturity, and postharvest ripening environmental condition on TSS, TA, pH, and lycopene content of the postharvest red-ripened fruits compared with vine red-ripe fruits

Variety and maturity	SSC (%)		TA (%)		pH		Lycopene content (µg g^{-1})	
	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)
HTH3-MG	6.4 ± 0.3	6.1 ± 0.2	0.58 ± 0.01	0.60 ± 0.01	4.43 ± 0.02	4.52 ± 0.03	14.3 ± 0.3	14.0 ± 0.4
HTH3-Br	6.7 ± 0.1	6.5 ± 0.2	0.61 ± 0.02	0.63 ± 0.02	4.45 ± 0.01	4.44 ± 0.02	14.7 ± 0.6	15.3 ± 0.6
HTH3-Tn	6.8 ± 0.2	6.8 ± 0.1	0.64 ± 0.01	0.65 ± 0.01	4.40 ± 0.02	4.50 ± 0.01	15.0 ± 0.4	15.3 ± 0.4
HTH3-Pk	7.0 ± 0.1	6.8 ± 0.1	0.60 ± 0.02	0.64 ± 0.01	4.45 ± 0.03	4.49 ± 0.04	15.6 ± 0.3	15.8 ± 0.5
HTH3-LR	7.0 ± 0.2	6.8 ± 0.2	0.64 ± 0.01	0.65 ± 0.02	4.44 ± 0.01	4.52 ± 0.02	15.9 ± 0.4	16.0 ± 0.5
HTH3-Rd*	7.0 ± 0.1		0.64 ± 0.01		4.37 ± 0.2		14.6 ± 0.5	
Ba-MG	6.2 ± 0.1	6.0 ± 0.2	0.55 ± 0.02	0.54 ± 0.03	4.56 ± 0.03	4.59 ± 0.02	13.0 ± 0.4	12.5 ± 0.2
Ba-Br	6.8 ± 0.2	6.6 ± 0.2	0.60 ± 0.01	0.60 ± 0.01	4.48 ± 0.03	4.43 ± 0.04	13.5 ± 0.6	13.0 ± 0.5
Ba-Tn	7.0 ± 0.1	7.0 ± 0.2	0.60 ± 0.02	0.64 ± 0.01	4.46 ± 0.04	4.51 ± 0.02	13.2 ± 0.3	13.3 ± 0.5
Ba-Pk	7.0 ± 0.1	6.7 ± 0.1	0.63 ± 0.01	0.64 ± 0.02	4.42 ± 0.02	4.45 ± 0.04	14.7 ± 0.5	14.8 ± 0.6
Ba-LR	6.9 ± 0.2	6.8 ± 0.1	0.64 ± 0.01	0.66 ± 0.03	4.38 ± 0.02	4.35 ± 0.03	14.4 ± 0.4	14.2 ± 0.5
Ba-Rd*	6.9 ± 0.0		0.64 ± 0.01		4.19 ± 0.04		14.0 ± 0.3	
Ma-MG	5.0 ± 0.2	4.8 ± 0.2	0.51 ± 0.03	0.55 ± 0.01	4.53 ± 0.02	4.58 ± 0.03	10.5 ± 0.5	10.3 ± 0.5
Ma-Br	5.4 ± 0.2	5.3 ± 0.2	0.57 ± 0.02	0.58 ± 0.01	4.42 ± 0.01	4.52 ± 0.04	10.6 ± 0.6	10.4 ± 0.4
Ma-Tn	5.6 ± 0.1	5.4 ± 0.1	0.58 ± 0.02	0.57 ± 0.02	4.37 ± 0.02	4.43 ± 0.02	10.9 ± 0.4	10.6 ± 0.3
Ma-Pk	5.5 ± 0.1	5.6 ± 0.2	0.60 ± 0.01	0.57 ± 0.03	4.39 ± 0.05	4.46 ± 0.04	11.4 ± 0.4	11.6 ± 0.6
Ma-LR	5.7 ± 0.2	5.8 ± 0.2	0.60 ± 0.02	0.59 ± 0.01	4.31 ± 0.03	3.34 ± 0.03	11.2 ± 0.5	11.0 ± 0.4
Ma-Rd*	5.8 ± 0.0		0.61 ± 0.02		4.31 ± 0.04		10.8 ± 0.3	
Thi-MG	6.3 ± 0.2	6.4 ± 0.2	0.61 ± 0.02	0.62 ± 0.02	4.58 ± 0.02	4.56 ± 0.02	13.5 ± 0.5	13.5 ± 0.6
Thi-Br	6.7 ± 0.2	6.7 ± 0.2	0.63 ± 0.01	0.65 ± 0.03	4.42 ± 0.02	4.46 ± 0.02	13.9 ± 0.4	14.1 ± 0.3
Thi-Tn	6.9 ± 0.2	6.8 ± 0.1	0.64 ± 0.02	0.60 ± 0.02	4.46 ± 0.01	4.44 ± 0.01	13.6 ± 0.6	13.8 ± 0.5
Thi-Pk	6.9 ± 0.1	6.8 ± 0.2	0.64 ± 0.03	0.61 ± 0.02	4.46 ± 0.02	4.38 ± 0.02	13.4 ± 0.5	13.9 ± 0.4

Variety and maturity	SSC (%)		TA (%)		pH		Lycopene content (μg g^{-1})	
	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)	(Cold)	(Amb)
Thi-LR	6.6 ± 0.1	6.7 ± 0.2	0.64 ± 0.02	0.61 ± 0.01	4.42 ± 0.02	4.33 ± 0.01	13.8 ± 0.4	13.8 ± 0.3
Thi-Rd*	6.9 ± 0.1		0.64 ± 0.02		4.35 ± 0.02		13.8 ± 0.4	
LS-MG	4.8 ± 0.3	5.0 ± 0.3	0.75 ± 0.01	0.77 ± 0.01	4.39 ± 0.02	4.42 ± 0.01	15.5 ± 0.6	15.9 ± 0.5
LS-Br	5.9 ± 0.2	6.0 ± 0.1	0.87 ± 0.01	0.85 ± 0.02	4.29 ± 0.02	4.36 ± 0.02	16.3 ± 0.7	16.1 ± 0.5
LS-Tn	5.7 ± 0.2	5.9 ± 0.2	0.88 ± 0.01	0.86 ± 0.01	4.33 ± 0.04	4.35 ± 0.03	16.3 ± 0.4	16.1 ± 0.6
LS-Pk	5.8 ± 0.2	5.9 ± 0.2	0.89 ± 0.01	0.88 ± 0.02	4.34 ± 0.03	4.35 ± 0.03	16.5 ± 0.7	16.4 ± 0.7
LS-LR	5.9 ± 0.3	5.8 ± 0.2	0.91 ± 0.01	0.89 ± 0.02	4.31 ± 0.01	4.33 ± 0.03	17.0 ± 0.7	16.8 ± 0.6
LS-Rd*	6.0 ± 0.1		0.90 ± 0.02		4.27 ± 0.02		16.8 ± 0.8	
Ra-MG	5.4 ± 0.2	5.2 ± 0.2	0.51 ± 0.03	0.48 ± 0.03	4.45 ± 0.02	4.47 ± 0.03	9.1 ± 0.4	9.5 ± 0.4
Ra-Br	5.8 ± 0.3	5.6 ± 0.2	0.51 ± 0.01	0.51 ± 0.01	4.34 ± 0.04	4.32 ± 0.04	9.5 ± 0.5	9.6 ± 0.5
Ra-Tn	6.0 ± 0.2	5.8 ± 0.1	0.51 ± 0.02	0.51 ± 0.02	4.37± 0.02	4.34 ± 0.02	10.0 ± 0.6	9.9 ± 0.6
Ra-Pk	5.9 ± 0.2	5.7 ± 0.1	0.54 ± 0.02	0.51 ± 0.02	4.30 ± 0.03	4.34 ± 0.04	9.6 ± 0.4	9.9 ± 0.3
Ra-LR	6.0 ± 0.2	5.8 ± 0.2	0.58 ± 0.02	0.61 ± 0.02	4.27 ± 0.01	4.31 ± 0.03	9.6 ± 0.5	9.7 ± 0.4
Ra-Rd*	6.0 ± 0.0		0.64 ± 0.01		4.16 ± 0.02		9.9 ± 0.5	
T245-MG	5.9 ± 0.1	6.0 ± 0.3	0.77 ± 0.02	0.77 ± 0.02	4.41 ± 0.03	4.50 ± 0.03	12.8 ± 0.6	13.1 ± 0.5
T245-Br	6.9 ± 0.2	6.9 ± 0.2	0.90 ± 0.01	0.91 ± 0.01	4.34 ± 0.02	4.24 ± 0.04	13.6 ± 0.4	13.3 ± 0.3
T245-Tn	6.7 ± 0.1	6.8 ± 0.1	0.92 ± 0.01	0.83 ± 0.02	4.38 ± 0.02	4.42 ± 0.03	14.1 ± 0.5	13.6 ± 0.4
T245-Pk	7.0 ± 0.2	6.9 ± 0.2	0.90 ± 0.01	0.86 ± 0.01	4.24 ± 0.04	4.21 ± 0.02	13.7 ± 0.6	13.6 ± 0.5
T245-LR	6.9 ± 0.2	6.8 ± 0.2	0.88 ± 0.02	0.90 ± 0.03	4.15 ± 0.03	4.20 ± 0.04	13.5 ± 0.4	13.6 ± 0.4
T245-Rd*	6.9 ± 0.1		0.90 ± 0.03		4.07 ± 0.02		13.7 ± 0.6	

**vine red-ripe*

Ba- Bathiya, Ma- Maheshi, Thi- Thilina, LS- Lanka Sour, Ra- Rashmi, MG- mature green; Br- breaker; Tn- turning; Pk- pink; LR- light red; Rd- red; Amb- ambient

The PR fruits of *HTH3, Bathiya*, and *Maheshi* varieties harvested at Pk and LR had higher levels of lycopene than those harvested at MG, Bk, and Tn (Table 4). Meanwhile, the lycopene content of *LS, Rashmi*, and *T245* varieties (that were harvested from LR to Bk) exhibited a slight decreasing trend as the ripening proceeded and the fruits harvested at MG stage showed the lowest lycopene content. However, lycopene content was not much different in all the maturities of Thilina. The postharvest ripening environmental conditions did not show a clear effect on lycopene content at Rd-ripe stage, however, there were few exceptions; for instance, the lycopene development of MG and Bk fruits of hybrids were found to be slightly favored by cold conditions.

In summary, postharvest ripening under both CCs and ACs could produce similar contents of soluble carbohydrates, acidity, and lycopene as in vine ripening, nevertheless, pH increased to unacceptable higher levels exceeding appropriate levels for processing tomato. Besides, maturity and postharvest environmental conditions determined time taken to reach red and consequently, the weight and firmness decreased with time to reach the red-ripe stage is reduced. On top, variety has a pronounced effect on final quality in taste, color and firmness, thus careful selection of variety and maturity is required for achieving the best tomato for processing.

Conclusions

Morphological, physicochemical, and biochemical characteristics pertinent to processing were diverse among the tomato varieties/cultivar. *HTH3, Bathiya*, and *Thilina* varieties could be suggested as suitable for long-distance transportation and processing. Moreover, morphological characteristics such as shape index, number of locules, and pericarp thickness could be used to predict important chemical and functional properties of tomato.

Variety, harvesting maturity, and postharvest ripening environmental conditions determined time taken to reach red, and directly influenced weight loss and firmness. *Thilina, Lanka Sour, Rashmi*, and *T245* varieties reached red faster at ambient conditions, while *HTH3, Maheshi*, and *Bathiya* varieties showed less sensitivity to postharvest ripening environmental conditions. Harvesting at later ripeness resulted in an optimum redness with a less reduction in fruit weight, firmness, and SSC. Overall, the variety is the key aspect in selecting tomato for processing, however, harvesting maturity and ripening environmental conditions should be well-managed. Thus, this provides guidance to growers and processors in selecting variety, maturity, and postharvest environmental conditions.

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