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REVIEW

Changes in quality parameters of tomatoes during storage: a review

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Abstract

The quality of tomatoes drastically changes according to storage conditions, such as temperature, humidity, and air composition. High storage temperatures result in the degradation of the firmness and color of tomatoes and in decay by bacteria, whereas chilling injury and softening can be caused by storage at low temperatures. The gas composition in the storage and packaging are other parameters that influence the quality and shelf life of tomatoes by preventing excessive transpiration and respiration. In addition, tomato quality is dependent on the degree of maturity and harvest season. Because there are many quality parameters, it is necessary to systemically establish an optimal standard, and this approach requires collecting and reviewing various data on storage conditions. The aim of this review was to provide basic information by comparing and analyzing studies on the changes in tomato quality (firmness, color, lycopene content, and acidity of tomatoes) during storage and to describe a few models that can assess the quality parameters. Many studies have provided results from experiments on the effects of postharvest control (e.g., storage temperature, packaging film, and gas treatment, as reviewed above) on tomato quality including firmness, soluble solids content, and lycopene content. However, it is still necessary to conduct an overall analysis of the published conditions and to determine the best method for preserving the quality of tomatoes as well as other fruits.

Keywords: quality assessment model, quality parameter, storage conditions, tomato

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Introduction

Tomato is considered to be one of healthy foods, which is beneficial for body water regulation, and strength of capillary vessels. In addition, tomato is reported that it can prevent artery hardening owing to the abundant nutrients such as lycopene, phenolic compounds, and vitamins E and C (Choi et al., 2013b). In particular, lycopene, a pigment of

tomato, has been intensively studied to elucidate its positive effects on human health (Ahrens and Hubber, 1990); its effectiveness at prevention of cancer (Stahl and Sies, 1996; Hong et al., 2003), and adult diseases including diabetes (Hong et al., 2003; Kim et al., 2010) has been reported. Hence, tomato is increasingly recognized as a valuable fruit, and its consumption is expected to keep increasing due to the recent trend in the demand for functional foods. Tomato, which is composed of over 90% of water, is easily damaged by septicity and via softening by physical shock and has a breathing pattern of climacteric type causing rapid quality changes due to high ethylene production after harvest (Choi et al., 2013c). These researches suggested that maintaining quality of tomato after harvest is difficult, and thus careful postharvest management is required (Bae et al., 2018).

There are some postharvest factors affecting consumption of agricultural products including tomatoes, such as flavor, appearance, color, and texture (Schuch and Bird, 1993; Malundo et al., 1995). To supply high-quality agricultural products during postharvest management, many studies have suggested environmental control (Kwon and Park, 2017; Kim et al., 2018; Kwon et al., 2018), nondestructive detection of disease (Lim et al., 2017; Qin et al., 2017; Hong et al., 2018) and cold storage (Gong et al., 2016; Shim et al., 2016). Among the postharvest management, cold storage is the most common and important process widely used for agricultural product and it determines quality of tomato. To meet the consumers' needs by keeping high postharvest quality, controlled atmosphere (CA) storage has been suggested to be effective for tomato, but modified atmosphere (MA) storage is widely used because of a technical standard, economic affordability, and distribution conditions (Lee et al., 2004). A few studies addressed the effects of MA storage on fruits such as paprika (Choi et al., 2012), apple (Park et al., 2004), kiwi (Choi et al., 2013a), and tomato (Choi et al., 2014; Islam et al., 2014). In these studies, the quality parameters were firmness, soluble solids, titratable acidity, chromaticity, and decay rate. As for tomato, Choi et al. (2013b) studied changes in quality parameters of tomato during low-temperature storage after harvesting at various degrees of maturity. In addition, the effect of storage temperature on the precocity of tomatoes was reported (Kim et al., 2010). The main cause of tomato quality changes is the respiratory rate, which affects the after-ripening process. Kader et al. (1989) determined the optimal concentration of carbon dioxide for MA storage to be ~ 2%, and reported that softening, maturation inhibition, and faulty insertion could be observed at > 2% and mature-green and turning tomatoes at > 5% (Morris and Kader, 1977). In addition, the optimal gas composition ratio of oxygen and carbon dioxide in packing film was found to be 3 - 5%, for keeping freshness of fruits in the study of MAP (modified atmosphere packaging) by Farber (1991). To maintain quality, the optimal control for keeping a desired gas composition is necessary. A study showed a beneficial effect of antimicrobial microperforated (AMP) film packaging on quality and storage of cherry tomato (Lee et al., 2011). Furthermore, low-density polyethylene film (LDPE) (Park et al., 1999) and polyethylene (PE) film (Moon et al., 1992) have been studied to maintain quality of tomato based on the degree of respiration. Recently, the effect of gas treatment on tomato quality has been assessed: 1-methylcyclopropene (1-MCP) (Cho et al., 2007), ClO_2 (Choi et al., 2013c), or CO_2 (Lee et al., 2014).

Although tomato has been addressed as a healthy food, studies on quality change of tomato are quite limited. To establish a standard of postharvest management of tomatoes, it is necessary to obtain basic information collected from various studies. In addition, analysis of existing data allows us developing a quality assessment model which can be effectively used for predicting changes in quality parameters and identifying optimal

postharvest conditions (Kim et al., 2016). The aim of this review, therefore, is to provide baseline information for setting up optimal postharvest quality maintenance of tomato by reviewing various studies on quality parameters such as firmness, chromaticity, lycopene content and structure, respiration, and acidity, and by analyzing quality parameters in the existing quality assessment models.

Contents of a literature review

The quality of tomato is affected by the storage conditions, such as temperature, humidity, and composition of air. In general, a temperature rise results in degradation of firmness and color of tomato. In contrast, low-temperature storage can lead to chilling injury including a lack of juiciness as well as softening (Crisosto et al., 1999; Choi et al., 2013b). Additionally, tomato quality is affected by the degree of maturity in harvesting. For this reason, proposing an optimal postharvest condition to maintain the quality of tomato requires a comprehensive review of existing studies because all possible conditions cannot be tested because of cost, labor, and time limitations. Herein, we selected four postharvest conditions and reviewed some notable studies to comprehensively evaluate the effects of selected conditions on tomato quality, and additionally reviewed some models developed for effectively assessing quality parameters of tomato (Table 1):

1) Storage temperature
2) Type of packaging film
3) Pretreatment by gas
4) Degree of maturity and harvest season
5) Models for assessment of quality parameters

Effects of storage temperature

Choi et al. (2013b) studied changes in quality parameters of tomatoes harvested at different maturity stages (turning, pink, and red) during storage. As reported by them, pink tomatoes stored at 10℃ soften more quickly than at storage temperature of 5℃, while turning tomatoes at 10℃ storage temperature maintain high firmness for 2 weeks. In addition, they showed that red tomatoes rapidly soften regardless of storage temperature. As for soluble solids content, it is not increased during ripening (from turning to pink stage), but it is high in red tomatoes. Soluble solids content did not change with maturity stages for 3 weeks during storage at 5℃, whereas soluble solids in turning and pink tomatoes reach the same levels as those in red tomatoes after 2-weeks storage at 10℃. When harvesting pink tomatoes, it is possible to increase soluble solids content by storage at 10℃, which allows for better flavor. Titratable acidity drastically changes from the turning stage to pink stage, but it is not significantly different between pink and red tomatoes. Choi et al. (2013b) measured chromaticity of tomatoes and expressed it using Hunter L*, a*, and b* values. Hunter L* of turning and pink tomatoes was found to decrease during storage, but the value does not change in red tomatoes. Hunter a* of turning and pink tomatoes decreases faster at 10℃ than at 5℃, while changes of Hunter b* are not affected by storage temperature. Lycopene content of pink tomatoes stored at 5℃ decreases with storage time but increases in turning tomatoes during the first week of storage. During storage at 10℃, lycopene content is not changed in red tomatoes with

time, but it increases in turning and pink tomatoes with time and reaches the same level as in red tomatoes after 2 weeks of storage. As expected, the decay rate during storage is significantly higher at 10℃ than at 5℃. In 5℃ storage, decay rates of turning, pink, and red tomatoes were found to be 5, 5, and 12%, respectively. However,

Table 1. Storage conditions and references.

References	Ripening stage	Type of film or gas	Storage time	Storage temperature
Choi et al. (2013b)	1. Turning	-	21 days	5℃
	2. Pink		10 days	10℃
	3. Red			
Kim et al. (2010)	1. Turning	-	5 days	10℃
				20℃
				25 ± 2℃
				30℃
Park et al. (1999)	1. Red	LP 40 (LDPE film, 40 μm)	28 days	4℃
		CE 40 (Ceramic film + antifogging agent, 40 μm)		10℃
		LP 20 (LDPE film, 20 μm)		
		CE 20 (Ceramic film + antifogging agent, 20 μm)		
Lee et al. (2011)	1. Red	Oriented polypropyle ne (OPP) film	9 days	15 ± 1℃ and
		Microperfor ated (MP) film (10 μm)		RH 45 ± 5%
		Microperfor ated (MP) film (30 μm)		
		Antimicrobi al microperfor ated (AMP) film (10 μm)		
		Antimicrobi al microperfor ated (AMP) film (30 μm)		
Moon et al. (1992)	1. Breaker	No film	21 days	15 ± 1℃ and
		Polyethylen e film (PE) film (2 μm)		RH 85 ± 3%
		Polyethylen e film (PE) film (4 μm)		
		Polyethylen e film (PE) film (6 μm)		
Cho et al. (2007)	1. Pink–light red	1-Methylcyc lopropene	41 days	20℃ and RH 85 - 95%
	2. Light red–red			
Choi et al. (2013c)	1. Red	No treatment	7 days	5℃
		ClO_2 5 ppm (10 minutes)		23℃
		ClO_2 10 ppm (3 minutes)		
		ClO_2 1 ppm (1 day)		
Hong and Lee (1996)	1. Immature green (normal, *rin*)	-	-	Room temperature
	2. Mature green (normal, *rin*)			
	3. Breaker (normal, *rin*)			
	4. Pink (normal, *rin*)			
	5. Red and yellow (normal, *rin*)			
	6. Over-ripe and over-yellow (normal, *rin*)			
Park et al. (2005)	1. Breaker	-	4 weeks	Break: 5, 10, 15℃ and room temperature
	2. Pink			Pink: 1, 5, 10℃ and room temperature

chilling injury is well pronounced at 5℃, affecting 45% of tomatoes. In contrast, at storage temperature of 10℃, decay rate is over 80% regardless of maturity, and chilling injury is not observed.

Kim et al. (2010) reported the effect of storage temperature on the quality of immature tomatoes. The firmness is not changed during storage at 10℃ but rapidly decreases above 20℃ after 5 days of storage. Soluble solids content does not significantly change with storage time, showing a slight decrease and minimal changes at room temperature (25℃). Titratable acidity does not show a significant change until ripening. Regarding titratable acidity, the results of Kim et al. (2010) are a little bit different from those of Choi et al. (2013b). This discrepancy may be observed because they used different varieties and maturity stages. Kim et al. (2010) reported that chromaticity represented by Hunter L*, a*, and b* was significantly changed by storage temperature and duration. Hunter L* strongly decreases at 20℃ and at room temperature after 5 days of storage, while Hunter a* greatly increases at 30℃ during the same storage period. In contrast, the value of Hunter b* is not significantly affected by storage temperature. Besides chromaticity, they showed that the concentration of lycopene increases with time at all the storage temperatures. The higher storage temperature leads to a larger increase in lycopene content and shows the least change at 10℃ as compared to other storage temperatures.

In summary, firmness of tomatoes at 10℃ is not changed, but storage temperature higher than 20℃ results in softening regardless of the repining stage. Hence, it is likely that low storage temperature about 10℃ is suitable for keeping firmness of tomatoes. In particular, tomatoes at the red stage need to be rapidly distributed because the softening will be completed within 7 days regardless of storage temperature.

Effects of type of packaging film

Packaging materials control the respiration rate and water loss of harvested fruits, thus allowing the fruits to maintain hardness. For this reason, an optimal type of packaging material and its optimal thickness should be determined depending on the species of fruits.

Park et al. (1999) compared several types of packaging films in terms of quality parameters of tomatoes. They reported that the ceramic 20 μm film (CE 20) shows the lowest amount of ethylene gas, which catalyzes the process of softening of tomatoes, and maintains the highest hardness. As for films CE 20 and, low-density polyethylene 40 μm film (LP 40), the weight loss appeared to be greater at 10℃ than at 4℃ storage temperature. In a comparison of the weight loss among the types of packaging film, LP 40 resulted in the lowest weight loss, while CE 20 led to the largest weight loss. However, the weight loss is less than 2%, and thus satisfies the weight loss standard of 7%, suggesting that CE 20 film may prevent marketability loss (Burton, 1982). In the 4 and 10℃ of storage temperature, LP 40 yields carbon dioxide concentration greater than 5%, whereas CE 40 and low-density polyethylene 20 μm film (LP 20) show carbon dioxide concentrations 2 - 4%. In all ranges of temperatures, CE 20 showed the best performance and yielded the lowest concentration of CO_2 (less than 1%). The ethylene gas concentration is not significantly affected by types of film (LP 40, LP 20, and CE 40 [ceramic 40 μm film]). On the last day of storage, the concentrations were recorded and found to be 3 and 7 ppm at 4 and 10℃, respectively. In CE 20, ethylene gas concentration was below 1 ppm at both 4 and 10℃ for all the storage periods. The soluble solids in various packaging do not show any statistically significant or noticeable difference.

As for titratable acidity, CE 20 yields the largest reduction in acidity, but this reduction is the smallest with LP 40.

Lee et al. (2011) studied postharvest quality changes in fruits among various types of films such as oriented polypropylene (OPP) film, microperforated (MP) film, and Antimicrobial microperforated (AMP) film. They reported that hardness is greatly decreased (by 33.6%) after 9 days of storage when packaging consists of OPP film. They also demonstrated that MP 30 μm and AMP 30 μm are more effective at maintaining initial hardness of the fruit than MP 10 μm and AMP 10 μm are. The weight loss appeared to be ~ 1% for all types of film, and there were no significant differences among the films.

For the OPP film, oxygen concentration is low in the package because the oxygen consumption rate as a result of respiration activity is greater than the oxygen input rate through the film. For MP and AMP films, the oxygen concentration inside the package gradually increases, causing the MA effect to positively influences the product quality (Fonseca et al., 2002; Opiyo and Ying, 2005; Montanez et al., 2010). The gas composition ratio observed for MP 30 μm and AMP 30 μm packaging is very similar to the suggested gas composition ratio reported in the MAP application study by Farber (1991), who proposed the optimal oxygen and carbon dioxide concentration in the package at 3 - 5%. The soluble solids content slightly increased for AMP 30 μm, but other films did not show any differences. When packaging consists of AMP 30 μm, the total number of bacterial cells was 0.15 log $CFU \cdot g^{-1}$, meaning the best antibacterial performance. The spoil rates were 49.5, 9.4, 5.6, 3.2, and 0% for films OPP, MP 10, MP 30, AMP 10, and AMP 30 μm, respectively.

Moon et al. (1992) reported the effect of PE film on tomato quality by comparing PE film-packaged and unpackaged tomatoes, and demonstrated a 40% reduction of hardness in unfilmed tomatoes after 3 days of storage. In addition, they showed a protective effect of PE film against softening of tomatoes, and the hardness reduction rate also decreased as the film thickness increased. The weight loss was found to significantly increase for tomatoes stored without film, leading to more than 4% weight loss at the end of storage. PE film generally lowers the weight loss rate as compared to unfilmed storage, and the weight loss slows with the increasing film thickness. For instance, the weight loss rate was 1% at 6-μm thickness and 4% in the unpacked group. Furthermore, the weight loss rate was ~ 2% and 1.5% at 2- and 4-μm thickness, respectively. This phenomenon might be explained as follows: Film packaging increases relative humidity in the package, and consequently prevents the water loss in tomatoes by preventing transpiration (Moon et al., 1992). However, all the experimental groups (Table 1) showed all that the weight loss rates were less than the tolerance range of 7% (Burton, 1982). Hence, even though thicker film is more effective at preventing weight loss, we should consider the optimal thickness of a film on the basis of other quality parameters as well as economic evaluation. The carbon dioxide concentration in all the groups rapidly increased at the beginning of storage, and the highest concentration was observed after 24 h. The concentration gradually decreased for the next 7 days and stayed at a constant level. Even though the trend of changes in carbon dioxide was similar in the all the groups, higher carbon dioxide concentration was observed with the thicker film. In contrast, oxygen concentration rapidly decreased at the beginning stage, and the lowest concentration was recorded after 24 h. The concentration gradually increased for the next 7 days, and then remained at a constant level. The thicker film resulted in a lower oxygen concentration; this trend is exactly opposite to that of carbon dioxide concentration, as expected.

The increase in carbon dioxide concentration and a decrease in oxygen concentration results from the

respiration activity of tomato (Moon et al., 1992). The concentration differences among the films with different thickness is caused by the penetrability of the films. PE 6-μm film contains 4 - 6% of carbon dioxide and oxygen concentrations that are close to the optimal ranges (4 - 6%) of carbon dioxide and oxygen concentrations for tomatoes in MA storage (Geeson, 1989). The ethylene gas concentration tends to first increase, and then slightly decreases, and the increase is slowed by a thicker film. Soluble solids and titratable acidity show no differences among groups with different film types. The color generally changes less on film-packaged tomatoes than on unfilmed tomatoes, with smaller changes in the Hunter a* value in a thicker film. In addition, the Hunter L* value changes less with storage time but shows a slight tendency for a decrease. However, the Hunter b* value does not show any changes with film thickness.

Effect of pretreatment by gas

The pretreatment with gas enables technologists to maintain the quality of tomatoes by reducing respiration and by delaying postmaturity (Wills and Ku, 2002; Cho et al., 2007; Choi et al., 2013c). Cho et al. (2007) reported that 1-MCP treatment delays the softening of cherry tomatoes and maintains the hardness at maturity of both pink-light red (P-LR) and light red-red (LR-R) tomatoes. The weight loss of light red-red (LR-R) tomatoes without 1-MCP treatment increases in comparison with 1-MCP treatment at 14 days of storage. The reason for the higher rate of weight loss observed in untreated tomatoes is that rates of ethylene generation and respiration are higher than in other groups, and the faster ripening leads to rapid moisture evaporation along with the fast softening. As for untreated tomatoes, the early respiration rate is 90.62 $mL \cdot kg^{-1} \cdot h^{-1}$ in LR-R tomatoes. Those rates are higher than the respiration rate of 1-MCP-treated tomatoes (52 - 54 $mL \cdot kg^{-1} \cdot h^{-1}$ until 7 days of storage. Moreover, the 1-MCP treatment groups showed an increase in the respiration after 8 to 15 days of storage, suggesting that optimal shelf life had to be identified even in the case of pretreatment. Soluble solids content and titratable acidity were not different between 1-MCP-treated and untreated groups. Titratable acidity was assessed by means of citric acid content and 0.1 N NaOH:

$$\%TA = Used\ for\ titration\ NaOH \times 0.1(normality\ NaOH) \times 0.064 \times 100/6\ g \quad (1)$$

In early storage, titratable acidity in LR-R tomatoes was 0.869%, which was higher than that of P-LR tomatoes: 0.716%. Titratable acidity of 1-MCP-treated LR-R tomatoes rapidly decreased until 5 days of storage, and then it stayed at 0.7%. In addition, P-LR tomatoes showed the same constant titratable acidity at 0.7% until the late period of storage. In a comparison of the effects of 1-MCP treatment, titratable acidity of untreated LR-R tomatoes decreased faster than that of 1-MCP-treated tomatoes, and stayed at ~ 0.6% after 10 days of storage, whereas in P-LR tomatoes it decreased to ~ 0.5% during the late periods of storage. This finding suggests that pretreatment with gas is effective at maintaining titratable acidity of tomatoes.

To determine chromaticity measures, the values of lightness, chroma, and Hunter a* and b* were measured, and the estimated values were converted to the values of Hue angle (h°):

$$\text{When } a^* > 0, b^* > 0, Hue\ angle\ (^\circ) = Arc\ tan\ (b^*/a^*) \quad (2)$$

$$\text{When } a^* < 0, b^* > 0, Hue\ angle\ (^\circ) = 180 + Arc\ tan\ (b^*/a^*) \quad (3)$$

The change of chromaticity (hue angle, chroma, and lightness) in all the 1-MCP-treated tomatoes was delayed because the ethylene generation rate and respiration rate after 5 days were low. The Hue angle in untreated P-LR tomatoes decreased more rapidly from 87° to 52° than from 88° to 78° in 1-MCP-treated groups on day 5. This means that the ethylene generation rate and respiration rate are higher in the untreated group. Tomatoes treated with 1-MCP showed a delay in changes of chromaticity at every maturity stage, whereas the delaying effect was greater in P-LR tomatoes than in LR-R tomatoes. Regardless of the maturity, chroma increased with storage time during treatment with 1-MCP, thus prolonging shelf life of tomatoes. Changes in lightness showed a trend similar to that of Hue angle. When 1-MCP was applied to P-LR tomatoes, higher lightness was observed as compared to untreated groups.

Choi et al. (2013c) studied the effects of various chlorine dioxide (ClO_2) treatments (Table 1) on the quality parameters of tomatoes, such as firmness, weight loss, gas concentration, color, and decay rate, during storage at low temperature (5℃) and room temperature (23℃). The untreated group showed 7.03-N firmness for storage at 5℃, whereas the group treated with a low concentration for a long period (low-concentration-long-treatment group: ClO_2 1 ppm 1 day) at the same storage temperature showed firmness of 7.90 N. For storage temperature of 23℃, the untreated and low-concentration-long-treatment group (ClO_2 1 ppm, 1 day) showed firmness 2.87 and 7.73 N, respectively. This result suggests that firmness can be maintained in low-temperature storage, and ClO_2 treatment can reduce the softening at room temperature. Treatment with a high concentration of ClO_2 for a short period (ClO_2 10 ppm, 3 min) was more effective during storage at room temperature because the briefly treated group (ClO_2 10 ppm, 3 min) did not show a difference from the untreated group at storage temperature 5℃. There was significant dependence of weight loss on storage temperature, in line with other studies (Park et al., 2005), but it did not differ among ClO_2 treatments. The concentration of oxygen at 5℃ showed the biggest reduction, from 21.01 to 11.20% in the untreated group, whereas the smallest decrease in oxygen concentration (14.23%) was observed in the low-concentration-long-treatment group (ClO_2 1 ppm, 1 day). In contrast to oxygen, the carbon dioxide in the untreated group showed the largest increase (up to 9.43%) than in any other groups, also showing the lowest concentration in low-concentration-long-treatment group (ClO_2 1 ppm, 1 day; 7.43%). A similar observation was reported for samples stored at 23℃: the largest decrease in oxygen (0.32% concentration) and increase of carbon dioxide (31.9% concentration) were observed in the untreated group, whereas carbon dioxide in the low-concentration-long-treatment group (ClO_2 1 ppm, 1 day) increased by the smallest value. From this review, it is clear that ClO_2 treatment can reduce the respiration rate, and lengthy treatment at a low concentration is more effective than a high-concentration short treatment, suggesting that an optimal treatment in terms of concentration and time should be chosen based on the storage period.

The pH and chromaticity were not affected by ClO_2. In particular, because ClO_2 treatment did not cause any changes in chromaticity including discoloration, it seems to be a suitable treatment for maintaining chromaticity: one of quality parameters in tomatoes. Choi et al. (2013c) also experimented with the decay rate. During treatment with 10 ppm ClO_2 for 3 min at 5℃, the decay rate was 18.33%, which was not different from that in the untreated group: 21.67%. Nonetheless, ClO_2 treatment at 5 ppm for 10 min was effective at reducing the decay rate, in particular, showing the lowest rate: 1.67%. A similar trend was observed at room temperature. The decay rate was more than 50% in no-treatment and in high-concentration-long-treatment (3 min at 10

ppm) groups but was the lowest (11.67%) in the low-concentration-long-treatment group. Besides the effect of treatment in this study, we can again confirm that the decay rate is drastically affected by storage temperature, and low-temperature storage is much more suitable for long-term storage (Choi et al., 2013b).

Effect of harvest at different maturity stages

Hong and Lee (1996) studied physiological characteristics of tomatoes harvested at each maturity stage and in after-ripened tomatoes harvested green-mature. They also compared the physiological characteristics of normal tomatoes, maturation-arrested (mutant) tomatoes, and ripening inhibitor (*rin*)-tomatoes which genetically modified to prevent ripening phenomena (Vrebalov et al., 2002). Color, respiration, and ethylene were the not different between after-ripened tomatoes and tomatoes at other maturity stages. As tomatoes became mature and aged, *rin*-tomatoes showed no change in the ethylene yield and in the respiration rate. Hong and Lee (1996) confirmed that *rin*-tomatoes are nonclimacteric fruit. Park et al. (2005) compared the quality of tomatoes at the breaker stage (stored at 5, 10, 15℃, or room temperature), a commonly harvested stage, with those at the pink stage (stored at 1, 5, 10℃, or room temperature) to identify the optimal conditions for room temperature and low-temperature tomato distribution. The concentration of soluble solids is not different among the maturity stages and storage temperatures according to Park et al. (2005). It is not different between low and room temperatures; this finding is not consistent with another study, which showed that 10℃ storage temperature can increase soluble solids content whereas 5℃ cannot (Choi et al., 2013b). In addition, Javanmardi and Kubota (2006) reported that soluble solids content shows no significant differences between low temperature (5℃) and room temperature (25 - 27℃); the observed range is 5.0 - 5.1%. de León-Sánchez et al. (2009) found that soluble solids content is not different up to day 14 between 10 and 20℃. In addition, many reports have indicated that soluble solids content remains unchanged after chilling and reconditioning (Kader et al., 1978; Stern et al., 1994; Maul et al., 1998; Maul et al., 2000; de León-Sánchez et al., 2009; Gómez et al., 2009; Beckles, 2012). However, Getinet et al. (2008) reported that soluble solids content rapidly increases during the first week of storage under ambient conditions and then quickly declines thereafter.

The soluble solids content stays constant at low temperature, but at high temperature, is retained or changed depending on the species. Concentrations of glucose and fructose (the major sugars of tomato) were 8.1 - 8.9 mg · g^{-1} fresh weight (FW) and 8.2 - 8.7 mg · g^{-1} FW, respectively, showing no statistically significant difference between the breaker stage and pink stage. At the breaker stage after 2 weeks of storage, soluble sugar contents of glucose and fructose in tomatoes stored at 10 - 15℃ were maintained at 16.62 mg · g^{-1} FW (10℃) and 17.07 mg · g^{-1} FW (15℃) in comparison with 13.23 mg · g^{-1} FW (5℃), whereas temperature 1 - 5℃ was optimal for soluble sugar contents of glucose and fructose: 17.9 mg · g^{-1} FW (1℃) and 17.29 mg · g^{-1} FW (5℃) in comparison with 13.7 mg · g^{-1} FW (10℃) at the pink stage after 1 week of storage. The concentration of citric acid is higher at the pink stage compared to breaker stage, but malic acid content is higher at the turning stage than at the pink stage. Concentrations of these two organic acids gradually decrease during storage, and the degree of the decrease increases with storage temperature. The largest decrease was observed at room temperature for the breaker stage, while the down regulation of organic acids at the pink stage was the largest

at both 10℃ and room temperature. Changes in weight during storage were large at the breaker stage, and the rate of weight loss accelerated at higher storage temperature. The Hunter L* and a* values of tomatoes changed rapidly at the higher storage temperatures, especially in the tomatoes at the breaker stage. In the tomatoes at the breaker stage stored at 5℃ and those at the pink stage stored at 1 and 5℃, chilling injuries including water pillows, late coloring, and poor coloring occurred. Overall, the best temperature for storing the breaker stage tomatoes until the red stage is 10℃. Regarding the least degradation of quality, approximately 7, 11, and 18 days are the limits of preservation at 20, 15, and 10℃, respectively. When considering maturity stages, for tomatoes at the pink stage, the proper temperature is 5 - 10℃. Nevertheless, if a technologist wants to store pink stage tomatoes at 20 or 10℃, the storage periods have to be 4 and 7 days, respectively.

Predictive models of quality change of tomatoes

Modeling is a powerful tool that can reduce experimental labor and cost, and its applications are extended to various fields including food processing. For instance, there are some notable models used for predicting shelf life of foods (Fu and Labuza, 1993; Polderdijk et al., 1993; Dalgaard, 1995; McMeekin and Ross, 1996). Nevertheless, modeling has been hardly used for assessing the quality of tomatoes. Herein, we introduce and review of a few models of interest to promote their active application to the field of food quality evaluation.

Color is the quality parameter that is first seen by consumers, indicating its importance for marketability. In addition, color is easy to measure. For this reason, many investigators have developed a model for estimating color as a measurable quality index. Most of such studies have used a Hunter value (which measures color by the values of L, a, and b) to develop a model for tomato color. The L value represents lightness, with L = 0 meaning black and L = 100 indicating white. The value has a range from green (negative) to red (positive), whereas the b value measures blue (negative) and yellow (positive) indices. Because the optically measured color is known to be strongly related to the Hunter a value, which also has a numeric form, it is reasonable to use the Hunter value as an easily accessible quality index for both researchers and consumers (Tijskens and Evelo, 1994). In particular, the Hunter a, b, and a/b values have been frequently used with statistical analysis because they can account for frequently observed colors in tomatoes under the influence of physiological changes (Hunter, 1948, 1958; Tijskens and Evelo, 1994). For example, β-carotene is accumulated, and the synthesis of lycopene is limited at temperatures higher than 30℃ in storage, and the color of tomatoes turns orange-yellow under these conditions (Tijskens and Evelo, 1994). On the contrary, when temperature falls below 12℃, chlorophyll is broken down and lycopene is not accumulated, resulting in a yellowish green color of tomatoes (Shewfelt et al., 1988; Tijskens and Evelo, 1994). In addition, during exposure to long-term low-temperature injury, the function of after-ripening is disabled and tomatoes turn yellowish green (Shewfelt et al., 1988; Tijskens and Evelo, 1994).

Thorne and Alvarez (1982) developed a statistics-based (the least square method) color change model for the time-temperature-tolerance (TTT) hypothesis, and proved additivity and commutativity (Vanarsdel, 1957) and confirmed changes in the surface color (Hunter a/b) and firmness of tomatoes with time at constant temperature between 13℃ and 21℃ (see the equation (4) and (5)).

$$\ln\left(\frac{\frac{a}{b}-\left(\frac{a}{b}\right)_{mg}}{\left(\frac{a}{b}\right)_{rr}-\left(\frac{a}{b}\right)}\right)=4.54+\frac{6.14*t}{27.5-T} \quad (4)$$

where a = Hunter a value, b = Hunter b value, rr = repining red, mg = mature green, t = time, and T = temperature.

$$d=1.5+9.7\frac{t}{27.0-T}\times10^{-2} \quad (5)$$

where d = Penetration depth of a penetrometer probe (cm), t = time, and T = temperature.

According to that study, the TTT hypothesis, a method for predicting the effect of irregular temperature on stored agricultural products, is valid when the change of quality including firmness and color in stored agricultural products is additive and commutative. Thorne and Alvarez (1982) compared estimated values and actual measurements (Hunter values) using irregular temperature over time. They showed that the assumption of additivity and commutativity was valid when applied to the TTT hypothesis within the designated range (12 - 27℃) based on the model predicted the changes in surface color (Hunter a/b) and firmness.

Hardness is one of the quality parameters that generally depends on consumers' subjective methods (e.g., finger testing). In addition, at an auction of tomatoes, their quality maintenance period is calculated based on the hardness of tomatoes measured right after harvesting. Nevertheless, this method can lead consumers to purchase low-quality tomatoes and sellers to have difficulty in with maintaining quality if hardness is not adequately measured. Thus, this parameter requires systematic, standardized, and objective evaluation. Moreover, most of laboratory measurements of hardness are destructive. Hence, the use of a predictive model for the period of tomato quality maintenance based on hardness is effective at providing some objective guidelines. Polderdijk et al. (1993) analyzed the relation between quality and hardness of tomatoes and developed a model for predicting a quality maintenance period as a function of hardness of tomatoes represented by compression distance:

$$\text{Maintenance of quality (days)} = 12.6\left(\frac{\text{day}}{\text{mm}}\right)\text{compression distance (mm)} + \text{intercept (days)} \quad (6)$$

Besides tomatoes as a fruit, there are processed tomatoes; e.g., ketchup, spaghetti source. In the relevant manufacturing process, tomatoes are powdered or dried at high pressure and temperature, and internal quality factors drastically change (Cole and Kapur, 1957; Lee and Chen, 2002; Goula et al., 2006). Miki and Akatsu (1970) reported that lycopene loss in juice is 1 - 2% when juice is heated at 100℃ for 7 min. Noble (1975) observed degradation of tomato pulp up to 57% with concentration to 20% of soluble solids at 121℃. In addition, Sharma and Maguer (1996) studied kinetics of lycopene degradation in heated tomato pulp at 100℃. Zanoni et al. (1998) found that lycopene content decreases at most by 10% at 110℃, but is not changed at 88℃ during the drying process. Heat treatment causes degradation of lycopene in tomatoes but increases the amount of bioavailable lycopene, such as *sis*-lycopene. Dewanto et al. (2002) reported that *sis*-lycopene content increases

by 54, 171, and 164% after 2, 15, and 30 min during thermal processing at 88℃, respectively. In particular, the apparent amount of lycopene in processed tomatoes is higher than that in raw tomatoes because of the release of lycopene from the cellular matrix and isomerization to *cis*-lycopene (Stahl and Sies, 1992; Gärtner et al., 1997; Sies and Stahl, 1998; Shi and Maguer, 2000; Agarwal et al., 2001; Dewanto et al., 2002). *Cis*-lycopene mainly present in heat-processed juice (Stahl and Sies, 1992), tomato puree (Shi et al., 2008), and tomato paste (Gärtner et al., 1997) is absorbed more easily than *trans*-lycopene (raw tomato) because total lycopene in human serum and tissues consists of more than 50% of *cis*-isomers. Because the amount of lycopene varies among studies, it is necessary to develop a mathematical model. The general equation of total lycopene degradation was developed for assessing the concentration of total lycopene as a function of time by Goula et al. (2006):

$$C = C_0 * \exp(-k*t) \quad (7)$$

where C = concentration of lycopene, C_0 = initial concentration of lycopene, k = reaction rate constant, and t = time.

Discussion

It has been known that CA storage is more effective at maintaining postharvest quality of fruits than MA storage. However, MA storage has been frequently used for economic and technical reasons. To identify the optimal conditions for MA storage, information on changes in quality parameters is important. An optimal shelf life of tomatoes is 2 weeks for minimization of damage by decay and chilling injury. For red tomatoes, storage temperature of 5℃ is better than the others, whereas immature tomatoes require storage temperature higher than 10℃ because it leads to postmaturity (Kim et al., 2010; Choi et al., 2013b).

Quality of tomatoes depends on the thickness of packaging film and storage temperature, suggesting that an optimal standard is necessary involving a target quality index after harvest. Weight of tomatoes is effectively maintained at 4℃ with packaging in 40-μm film, while the concentration of carbon dioxide and ethylene, which guarantee better firmness and vitamin C amount at a lower concentration, are the lowest at 4℃ when packaging consists of the CE 20 film (Park et al., 1999). In addition, the concentration of vitamin C and titratable acidity are higher with packaging in the CE 20 film than in LP 40 film. Collectively, these data suggest that storage temperature of 4℃ and CE 20 film are the optimal choice for storing ripening-red tomatoes in order to preserve weight, firmness, and nutritional components. In one study, an AMP film (30 μm) was found to be the best at preventing decay and maintaining firmness and weight in comparison with general films (Lee et al., 2011). In particular, this approach may be effective where tomatoes can be exposed to bacteria. To maintain the optimal carbon dioxide and oxygen concentrations (4 - 6% gas ratio), PE film of 6 μm is desirable (Moon et al., 1992). This packaging thickness and type also show the ability to prevent weight loss as compared to unpackaged tomatoes. Consequently, we can conclude that 6 μm is the optimal thickness for a PE film. Pretreatment with gas also affects quality indices of tomatoes. Treatment with 1-MCP decreases ethylene emission and respiration during the initial storage and preserves (or slows the loss of) weight, color, firmness, titratable acidity, and soluble solids content (Cho et al., 2007). Furthermore, 1-MCP treatment is effective at maintaining quality at any

maturity stages and works best for immature tomatoes. ClO_2 treatment is effective in maintaining firmness and soluble solids content because it decreases respiration, the total number of bacterial cells, and rate of decay (Choi et al., 2013c). It was also shown that low-concentration lengthy treatment is better than high-concentration brief treatment, indicating the necessity of adequate concentration and time for treatment.

When comprehensively evaluating existing studies, optimal postharvest conditions should be determined by considering maturity of tomatoes. For example, the optimal storage temperature is different among maturity stages. Additionally, adequate thickness of packaging is necessary because the respiration rate and consequent ethylene and carbon dioxide contents are suppressed by a thick film, whereas a thin film may lose its functionality. Pretreatment with a gas is also effective at preserving quality parameters in tomatoes by controlling respiration. Finally, it should be noted that all the relevant conditions have been analyzed in independent experiments. Hence, response surface methodology or at least a meta-analysis are necessary to determine the optimal postharvest conditions. Through this condition, we can preserve tomato quality instead of attempting to control all the conditions. Further research comparing control conditions is required. The optimal storage conditions were summarized by factors affecting tomato quality reviewed in this study (Table 2).

Table 2. Optimal conditions for tomato storage in previous studies.

Treatment	Ripening stage	Optimal treatment	Firmness	Soluble solids	Lycopene	Weight loss	Concentration of CO_2	Decay
Temp.	Turning	2-weeks at 5°C	10	10	20	-	-	5
	Pink	2-weeks at 5°C	5	10	20	-	-	5
	Red	1-week at 5 - 10°C	No difference	No difference	No difference	-	-	5
Films	Red	CE 20 at 4°C AMP 30	CE 20 MP 30 AMP 30	No difference	AMP 30	LP 40 CE 40 OPP AMP 30	CE20 MP 30 AMP 30	AMP 30
	Breaker	PE 6	PE 6	No difference	-	PE 6	PE 2	-
Gas	Red	ClO_2 1 ppm (1 day)	ClO_2 1 ppm (1 day)	ClO_2 5 ppm (10 minutes)		no difference	-	ClO_2 1 ppm (1 day)

LP, low-density polyethylene; CE, ceramic; OPP, oriented polypropylene; AMP, antimicrobial microperforated; PE, polyethylene.

Conclusion

On the market, consumers mainly select tomatoes depending on their quality, such as taste, appearance, color, and texture. Most of recent reports suggest that CA storage is the best, but its application is quite limited in many countries because of high cost and technical requirements. Accordingly, many studies continuously have provided results of experiments on the effects of postharvest control (e.g., storage temperature, packaging film, and gas treatment, as reviewed above) on tomato quality including firmness, soluble solids content, lycopene content and structure, color, and maturity. However, it is still necessary to conduct an overall analysis of published conditions and to determine the best method for preserving the quality of tomatoes.

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