Internal quality assessment of tomato fruits using image color analysis

AbdelGawad Saad*, Ayman Ibrahim, Nazeer El-Bialee

(Department of Agricultural Bio-Engineering, Agricultural Engineering Research Institute (AEnRI), Agricultural Research Center (ARC), Dokki, Giza, Egypt)

Abstract: Nondestructive optical methods based on image analysis have been used for determining quality of tomato fruit. It is rapid and requires less sample preparation. A samples of fresh tomatoes were picked at different maturity stages, and determining chromaticity values (L*,a*,b*,a*/b*,h°and ΔE) by image analysis and colorimeter. Total soluble solids (TSS), were measured by refractometer, lycopene extracting and expressed as mg/kg fresh tomato (FW). Results indicated that, during ripening both L*, b*, h°, and ΔE tendency to decline, opposite tendency was determined with a*, a*/b* ratio, TSS and lycopene content. Chromaticity values have an important impact in internal quality parameters. Where, avg. of TSS, entire class and lycopene content had a positive linear correlation with a*/b* ratio. Contrary correlation was determined between avg. of TSS, entire class and both h° and ΔE. Meanwhile, h° and ΔE, had a negative logarithmic correlation with lycopene content. On the other hand, there were positive correlation between chromaticity values performed by image analysis technology and colorimeter. Where, on determining avg. of TSS, entire class, and lycopene content, correlations were linear with a*/b* ratio, and logarithmic with ΔE. Meanwhile, h° had alogarithmic correlation on determining avg. of TSS, entire class, and exponential correlation on determining lycopene content.

Keywords: tomato, image color analysis, chromaticity values, internal quality, TSS, lycopene content

Citation: Saad, AbdelGawad, Ayman Ibrahim, and Nazeer El-Bialee. 2016. Internal quality assessment of tomato fruits using image color analysis. Agric Eng Int: CIGR Journal, 18(1):339-352.

1 Introduction

Fruits and vegetables (F&V) play an important role in the human diet. Tomato (*Lycopersicon esculentum*) is known as one of the most popular fruit worldwide. It is a rich source of fiber, vitamins A & C, lycopene and an excellent source of healthy nutrients. Consumption of tomato has been associated with decreased risk of some cancers, cardiovascular, osteoporosis and chronic disease. (Takeoka, et al., 2001; Chang et al., 2006; Beckles, 2012; Bhowmik et al., 2012).

Egypt is the fifth largest tomato producer in the world followed by China, USA, Turkey and India. Whereat, it occupy about 212,946 hectares with an annual production, about 6,5Tg ≈ 5.21% of global production (FAOSTAT, 2015).

F&V quality is very important to the consumer, as well as, the producer. Whilst, There is ample evidence indicating that flavor and skin color are the two most important attributes of tomato for customer evaluation (Domis and Papadopoulos, 2002; Batu, 2004). Rather, total soluble solids 'TSS' plays a role to the overall flavor of tomatoes (Lenucci et al., 2008), and lycopene (C40H56) is a pigment imparts deep red color of a ripe tomato (Wold, 2004; Olives-Barba et al., 2006; Ibitoye et al., 2009; Garg and Cheema, 2011). Thus, TSS and lycopene contents are widely used as a maturity index and assessing tomato quality (Anthon et al., 2011).

On the basis of external visual color, USDA established six ripening stages of tomato which are reflecting human ability to discriminate ripeness. Where, the green stage, which fruit skins are completely green; breaker, less than 10% of fruit skins in red color; turning,

Received date: 2015-09-21 **Accepted date:** 2015-11-23

***Corresponding author: AbdelGawad Saad,** Department of Agricultural Bio-Engineering, Agricultural Engineering Research Institute (AEnRI), Agricultural Research Center (ARC), 12311 Dokki, Giza, Egypt, en_gawad2000@yahoo.com

more than 10% but less than 30% of fruit skins in red color; light red, more than 60% but not over 90% red color in fruit skins; and red, over 90% of fruit skins in red color (CFR,1991).

On the other hand, the colorimeters are used to measuring L*, a* and b* values. Where, value L* (Lightness) indicates the ratio of white to black color, value a* (color index) - the ratio of red to green color, value b* (yellowness index)- the ratio of yellow to blue color (LópezCamelo and Gómez, 2004; Radzevičius et al., 2009). Otherwise, lycopene content, correlated with the fruit color, L* and a*, producing the best regression, it had inverse and direct relations with them, respectively (Arias et al., 2000; Polder et al., 2003; Helyes et al., 2006; Chen, 2008). Furthermore, color changes in tomato are commonly recorded as a*/b* ratio (Gómez et al., 2001). Likewise, Hue angle is another indicator that has been widely used to express tomato color changes, because it is more simplicity detected than variations in chroma or lightness (Choi et al., 1995; López Camelo and Gómez, 2004). Recently, color difference (ΔE), has been used in tomato (Yang et al., 1990), and in many ISO procedures such as 12647-2 for process control in the production of halftone color separations (Habekost, 2013).

Analytical quantification of quality parameters is based on complex processing of samples, destructive, include a considerable amount of expensive chemical reagents, labour and time consuming and so on (Szuvandzsie, et al., 2014). In recent years, nondestructive optical methods based on image analysis have been developed for determining quality of F&V, since it requires less sample preparation, do not disturb the product, cost effective and rapid technique (Shao et al., 2007). Wherever, nondestructive methods 'NDM' depending on predicting internal quality parameters based on external properties "visual color skin" (Peirs et al., 2005; Xie et al., 2008; Makino et al., 2010; Yang, 2011; Ecarnot et al., 2013).

In the last decade, image processing and machine vision techniques have been found, increasingly used in the F&V industry, especially in quality inspection, grading and sorting applications. The main objective of image processing is to enhance the appearance of images and to increase specific details that will be utilized for further interpretation (LópezCamelo and Gómez, 2004). It has been used to objectively measure the color of different foods (Scanlon et al., 1994; Segnini et al., 1999; Papadakis et al., 2000; Chen et al., 2002; Brosnan and Sun, 2004; Mendoza and Aguilera, 2004; Pedreschi et al.,2004; Bennedsen and Peterson, 2005; Ibrahim, 2012). Also, image processing techniques employed to estimate the yields of fruits such as citrus fruits (Hannan et al., 2009; Kurtulmus et al., 2011), apples (Wang et al., 2012; Zhou et al., 2012), peaches (Teixidó et al., 2012; Kurtulmus et al., 2014), mangoes (Payne et al., 2013; and 2014) and grapes (Nuske et al., 2011; Diago et al., 2012). In addition, a computer vision system based on image processing for sorting and classifying dates fruit according to color, Ibrahim et al., (2014) recommended that, appearance of dates can be linked to sugar content, moisture and acidity of dates fruit through the color tone and saturation.

Therefore, the aim of the present study is to determine whether, chromacity values could be useful for estimating tomato TSS and lycopene contents to an acceptable degree of accuracy. Also, establish relation between chromaticity values performed by image and colorimeter, and classify tomato according to maturity stage by estimate the color degree of tomato fruit.

2 Materials and methods

2.1 Materials

A sample of 155 fresh tomatoes (Master 100 hybrid variety), were picked at different maturity stages during summer season 2014, from open field farm at 35℃ ± 5℃, located in El-Noubareya region, El-Behiara governorate, Egypt. At 30° 40'N latitude and 30° 04'E longitudes and at an altitude of 12m above sea level, and brought quickly to the laboratory of National Research Center (NRC).

2.2 Methods

Color parameters (L*, a*, b*, a*/b*, h°, and ΔE) and quality (TSS and lycopene) were measured and determined immediately after picking. Samples with uniform size and free from damage and fungal infection were rinsed using fresh water, then dried by tissue paper, and equilibrated at room temperature (25–27°C, RH ≈70%) approximately two hours before data acquisitions.

Fruits sorted into three main classes '*mature green-intermediate* and *advanced*' includes six ripeness stages based on their external visual color, designated *green - breaker*, *turning – pink* and *light red – deepred*.

Color parameters of tomatoes in terms of L*, a*, b* values were measured using HunterLab mini Scan XE Plus colorimeter (Model 45/0-L, USA), previously standardized using a black and white calibration tiles provided with the instrument. Hue angle (h°), calculated according to the equations as seen below (Anonymous, 2006).

$$h^{\circ} = \arctan\left(\frac{b}{a}\right) \quad \text{.....(1)}$$

Meanwhile, by using true red color as a reference color (coordinate: L* = 50, a*= 60 and b* = 0), color difference (ΔE) calculated according to the following equation (LópezCamelo and Gómez, 2004).

$$\Delta E = \sqrt{(L-50)^2 + (a^*-60)^2 + (b^*)^2} \quad \text{.....(2)}$$

The volumes L*, a*, and b* are measured in NBS units. It is a unit of the USA National Standard Bureau and equivalent to one threshold of color distinction power, i.e. the least distinction in color, which the trained human eye can notice (HunterLab, 1996). Where, hue angle (h°) measured in degrees from 0 to 360°. Each color record was an average of four measurements of every tomato fruit (two at the distal area and two under equatorial zone in different fruit directions).

For acquiring images, the vision system based upon a calibrated digital camera was used and designed by Ibrahim (2012). It consists of an illumination box contain with two parallel lamps (two fluorescent tubes in each lamp, Natural Daylight, 20W/965, Toshiba), and color temperature of 6500K (D65, standard light source). The digital camera (Model SXY-I30 equipped with 25 mm lens 2/3″ Mega-Pixel) was situated vertically at 40 cm above tomato sample with 45°(angle between the camera lens and lighting source axis). In order to, image analysis, all the algorithms of acquired images, preprocessing of full images, segmentation from the background (binary image), and color analysis were written in MATLAB 2013 (The MathWorks, Inc., USA).

To determine quality parameters (TSS and lycopene), after measurements of color and imaging, each tomato fruit was cut into two equal pieces and extracted juice from every piece by using manual stainless steel squeezer. The resultant of tomato slurry was filtered through muslin fabric and then used to determine TSS and lycopene.

TSS expressed in °Brix, was measured using portable digital refractometer (ERMA, Japan), with a scale of 0–32 °Brix (least count 0.2 °Brix) at room temperature (≈25°C), by placing 1 to 2 drops of juice on the prism. Between samples, the prism was washed with distilled water and dried by blotting paper before reuse.

Lycopene extraction was performed as in Ranveer et al., (2013), by using 4± 0.01g of filtered tomato juice deposited into a 200ml, flask wrapped with aluminum foil to keep out light. A 100 ml., mixture of hexane-acetone-ethanol, 2:1:1(v:v:v), was added to the flask and agitated continuously for 10 min, on a orbital shaking incubator, after that, 15 ml of water was added followed by another 5 min of agitation. The solution was then left to separate into distinct polar and non-polar layers and filtered using filter paper (Whatman grade 42). The absorbance of filtered hexane (upper) layer, was measured in a 1 cm path length quartz cuvette, at 503nm by UV/VIS Spectrophotometer (SHIMADZU, Japan, Model UV-1800), versus a blank of hexane. lycopene concentration expressed as mg/kg fresh tomato (FW), and calculated by the following equation.(Kumar et al., 2013)

Lycopene (mg/kg FW) =

$$A_{503} \times \frac{(536.9 \times 10^3)}{(17.2 \times 10^4)} \times \frac{(100) \times (0.55)}{(4)} \approx$$

$A_{503} \times 42.9\ldots$ ….(3)

Where:

A_{503} : absorbance value of the sample extract at 503nm;

536.9×10^3 : molecular weight of lycopene (mg/mole);

100 : volume of mixed solvent (ml);

0.55 : volume ratio of the upper layer to the mixed solvents;

4 : mass of tomato added (g);

17.2×10^4 : Molar extinction coefficient (i.e., the theoretical absorbance of a $E_{1cm}^{1\%}$ -1% solution in a 1-cm path) of lycopene, M^{-1}.cm, (peak = 3120 in hexane, at 50 nm.) (Choudhari and Ananthanarayan, 2007; Strati and Oreopoulou, 2011).

Each sample of fresh tomato was extracted twice in triplicate analysis, yielding six results for each fresh tomato.

Measures of dispersion (range, Min., Max., SD and CV), central tendency (average), predicted equations and correlation coefficients were calculated and graphically using MS Excel (version 11).

3 Results and discussion

Samples divided into three main classes, includes six ripeness stages based on their external visual color, according to the USDA standards. The definitions of them are described pictorially in Table 1.

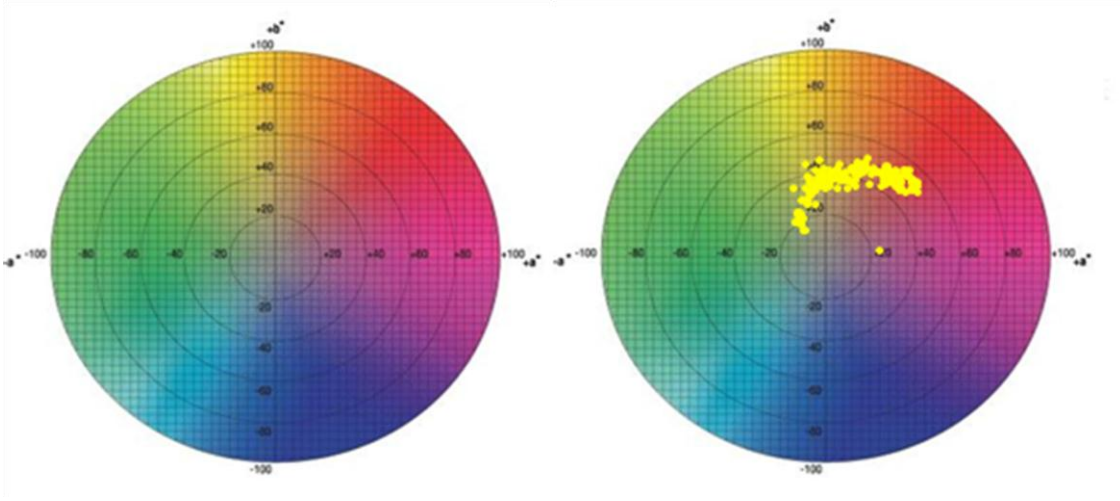
Table 1. Samples classes and maturity stages definition based on their external visual color

Stage	Green	Breaker	Turning	Pink	Light red	Deep red
Class	Mature green		Intermediate		Advanced	

Color index (a*) and yellowness index (b*) value, by colorimeter ranged from -6.66 to 39.36 and 20.86 to 50.82, respectively. Meanwhile, by image ranged from -14.09 to 37.91 and 10.24 to 48.90., respectively. They were presented on model CIE L*a* b* color space model (Figure1 A and B). While, other color indexes (L*, h°, and ΔE) and lycopene content (mg/kg FW) values of tomato fruit, and statistical details (e.g Min., Max., SD and CV), at different stages, were presented in Table 2 and Figure 2.

Major changes in L*, a*, and b* were occurred between stages 2, 3, and 4 of tomato ripening. Also, color index (a*) and a*/b* ratio increased with a higher percentage of red color. L* decreased slightly during ripening stages, reflects darkening of tomatoes with carotenoid synthesis and the loss of greenness.

The a* component showed the most obvious change. Slender changes were observed when fruits were still predominately green (mature green to breaker) or red (light red to deep red), but there was a sharp increase between stages 2 and 5 (breaker to light red) with a* changing from negative (green color) to positive (red color) values, as a consequence of both, chlorophyll degradation and lycopene synthesis.



(A) (B)

Figure1 Samples coloridentity. A) by colorimeter and B) by image

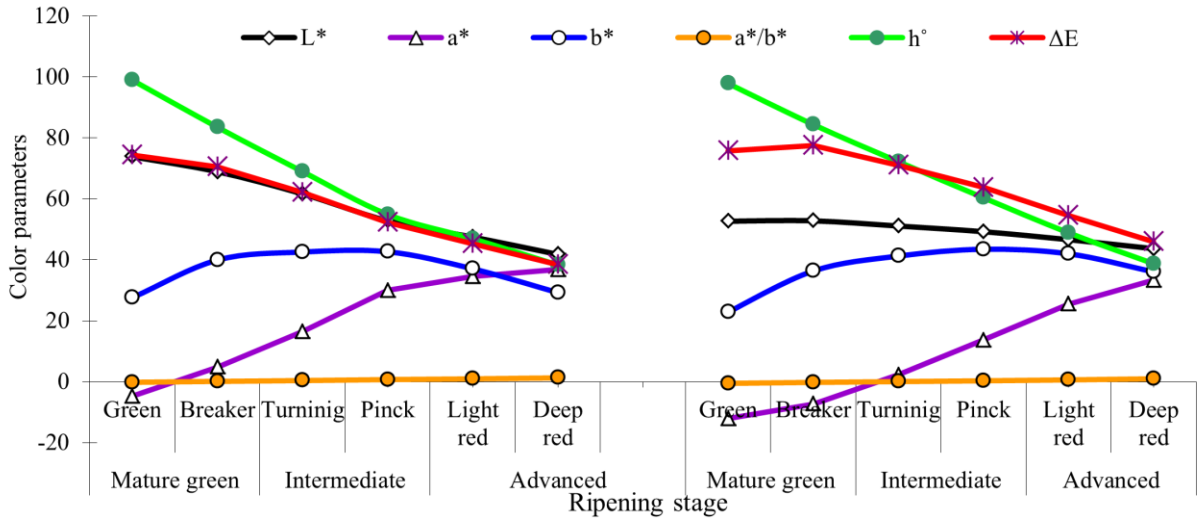


Figure 2 Mean values of chromaticity values L*, a*, b*, a*/b*, h° and ΔE at different ripening stages, A) by colorimeter and B) by image

The b* values increased through the first three maturity stages of the tomatoes and after the four maturity stage decreased, the values were higher at the pink-light red stage. This may be related to the fact that ζ-carotenes (pale-yellow color) reach their highest concentration before full ripening, where lycopene (red color) and *β*-carotene (orange color) achieve their peaks. The a*/b* ratio is often used as an indicator of color development in tomatoes. It increased with a higher percentage of red color, and produced a good linear regression with the maturity stages of the tomatoes. Similar behavior was observed by Arias et al.,(2000); Polder et al.,(2000); LópezCamelo and Gómez, (2004); Periago et al.,(2009); Vazquez-Cruz et al.,(2013). Analysis of calculating ripening indexes indicated that h°and ΔE were essentially expressing the same. In all these cases, differences between visual ripening stages were significant, showing h° a higher range of values and, like ΔE, a negative trend (Radzevičius et al., 2008).

Table 2 Color index value of tomato fruit at different stages, performed by colorimeter and image, and lycopene content (mg/kg FW)

Class			Mature green		Intermediate		Advanced	
Stage			Green	Breaker	Turning	Pink	Light red	Deep red
Colorimeter	L*	Min.	71.09	62.2	55.52	46.95	31.42	37.52
		Max.	76.63	74.48	67.99	57.08	55.17	45.73
		SD	1.56	2.86	2.78	5.42	4.55	2.13
		CV	2.12	4.15	4.51	4.59	9.58	5.098
	h°	Min.	90.33	78.37	59.69	48.14	37.09	33.59
		Max.	103.24	93.30	77.19	59.13	56.38	44.12
		SD	3.33	4.56	5.13	2.86	4.76	3.25
		CV	3.36	5.46	7.44	5.21	10.15	8.47
	ΔE	Min.	73.06	67.44	54.49	45.99	37.29	35.07
		Max.	75.43	76.14	68.69	55.75	54.41	42.74
		SD	0.72	2.67	3.73	2.53	4.16	2.14
		CV	0.96	3.79	6.00	4.84	9.18	5.57
Image	L*	Min.	49.22	46.90	46.09	43.15	41.84	37.29
		Max.	56.00	56.94	55.24	53.33	52.75	49.53
		SD	2.27	2.50	2.00	2.75	2.01	2.60
		CV	4.31	4.74	3.91	5.58	4.30	5.96
	h°	Min.	94.56	77.24	62.05	52.02	42.09	20.17
		Max.	101.22	97.13	81.39	65.33	59.08	42.77
		SD	1.67	4.59	5.04	3.13	4.30	5.16
		CV	1.71	5.44	6.98	5.19	8.81	13.33
	ΔE	Min.	72.34	75.12	63.67	57.45	49.12	41.60
		Max.	77.69	82.95	76.48	67.21	65.43	49.03
		SD	1.74	2.31	3.29	2.32	3.74	2.26
		CV	2.29	2.98	4.63	3.64	6.85	4.90
Lycopene content (mg/kg FW)		Min.	0.51	2.46	5.42	8.77	10.95	26.84
		Max.	8.99	22.02	29.42	33.93	36.18	40.99
		SD	2.21	3.78	5.93	2.73	5.30	4.19
		CV	87.97	44.64	37.21	11.95	19.54	12.03

The study showed that, generally, there were two important invents. First, that TSS tends to increase as the ripening proceeds. The average of TSS was 4.28 ˚Brix, for the green stage, and the concentration reached at the final ripening stage (red) was 4.58 ˚Brix. Thatchange was a natural phenomenon occurring during ripening and correlated with hydrolytic changes of starch concentration during ripening. Also, increasing concentrations of macro elements, resulting in the increased TSS of tomato fruits. Over and above, average value of TSS (˚Brix) entire class had a linear positive correlation with repining stages, with correlation coefficient value (R) ≈ 0.99. These results could agree with Kays, (1997); Lin and Glass (1997); Sammi and Masud (2007). These obvious facts were illustrated in Figure 3.

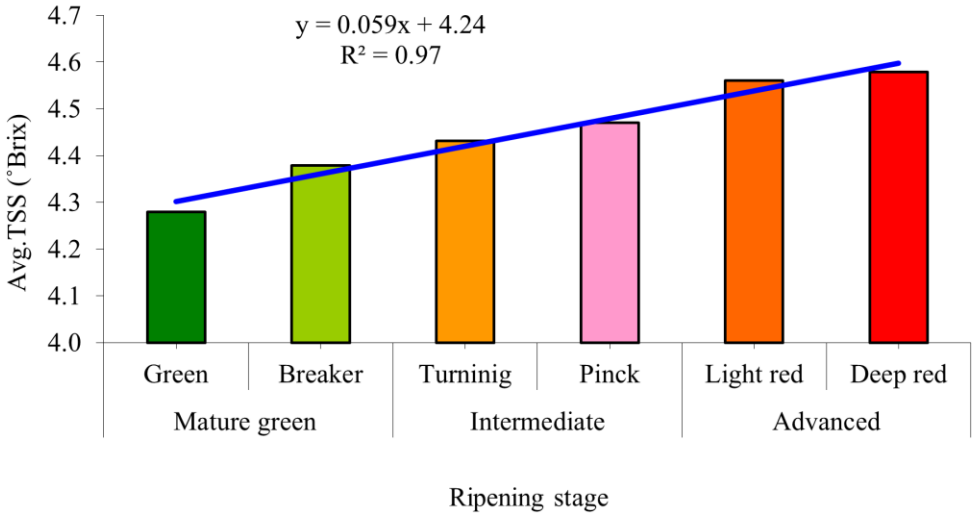
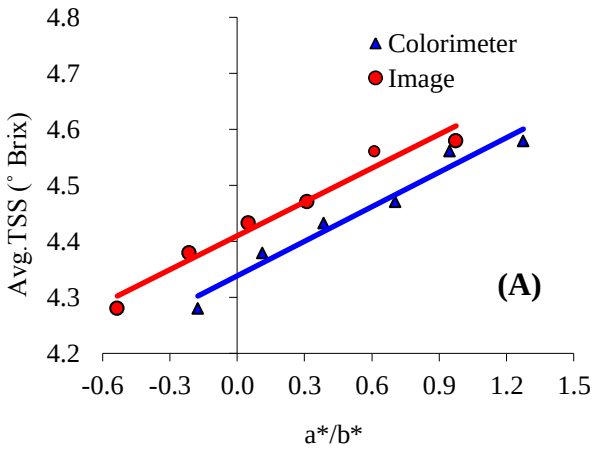
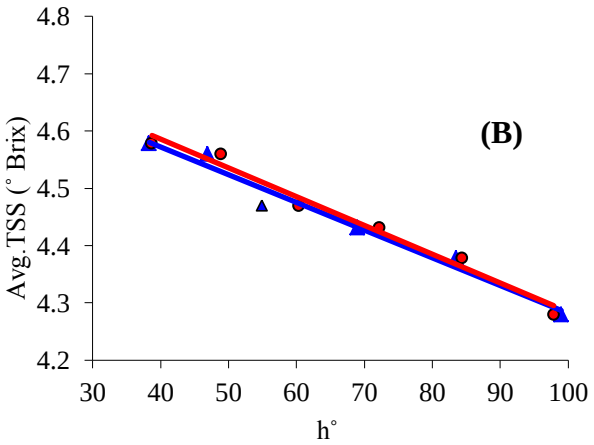


Figure 3 Relation between repining stages and avg.TSS (˚Brix) entire class

Second, there were not any correlated relation between avg.TSS, and any chromaticity values of raw data. These results contrary to Ibrahim et al., (2014). Where, they found that, color analysis of date fruit can be linked to the sugar content through the color tone and saturation for date fruit.

Meanwhile, after classified samples into six classes, several correlations were found between avg. TSS (˚Brix) entire class, with the color parameters a*/b*, h˚, and ΔE., performed with the colorimeter and image as seen below Figure 4 A, B and C. On the other hand, Figures 5D, E and F, show the correlation between each color parameter performed by colorimeter and image. As well as, previous relations were fitted to the following equations;





Equation	R^2
Avg. TSS (˚Brix) ≈ 0.205 ($a^*/b^*_{Colorimeter}$) + 4.34	0.981
Avg. TSS (˚Brix) ≈ 0.201 (a^*/b^*_{Image}) + 4.41	0.982
Avg. TSS (˚Brix) ≈ - 0.0048 $\left(h^{\circ}_{Colorimeter}\right)$ + 4.76	0.986
Avg. TSS (˚Brix) ≈ - 0.005 $\left(h^{\circ}_{Image}\right)$ + 4.79	0.989
Avg. TSS (˚Brix) ≈ - 0.0077 ($\Delta E_{Colorimeter}$) + 4.89	0.970
Avg. TSS (˚Brix) ≈ - 0.0083 (ΔE_{Image}) + 4.99	0.916
a^*/b^*_{Image} ≈ 1.02 ($a^*/b^*_{Colorimeter}$) - 0.35	0.998
h°_{Image} ≈ 61.67 Ln $\left(h^{\circ}_{Colorimeter}\right)$ - 187.35	0.998
ΔE_{Image} ≈ 47.72 Ln($\Delta E_{Colorimeter}$) - 127.01	0.989

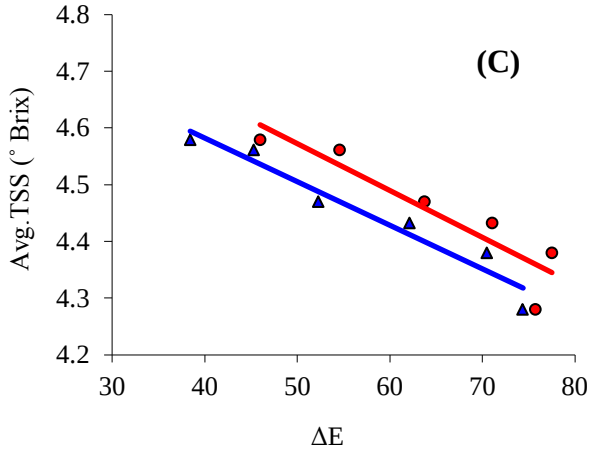


Figure 4. Relation between avg. TSS (˚Brix) entire class and color parameters, were A) a*/b* ratio, B) h˚, and C) ΔE

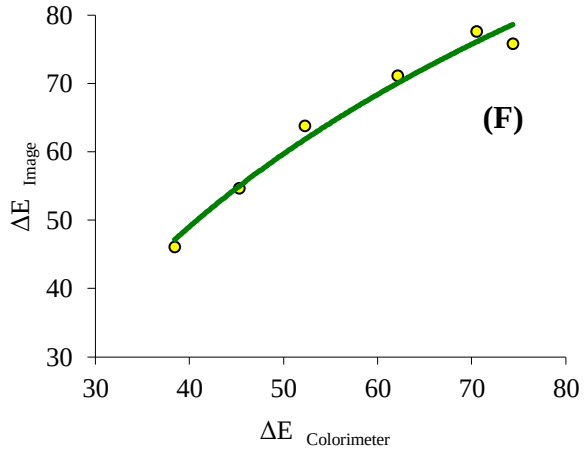
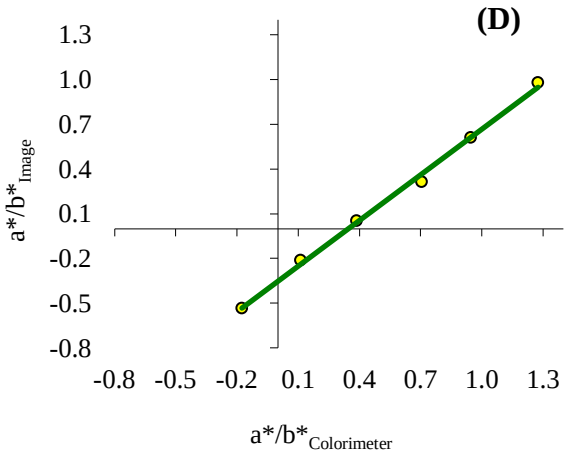
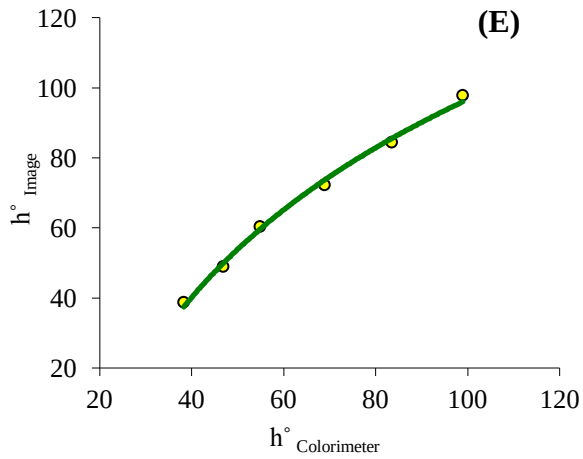


Figure 5. Correlation between color parameters performed with colorimeter and image, where, D) a*/b* ratio, E) h˚, F) ΔE





The results of our investigation established that lycopene content (mg/kg FW) during fruit ripening significantly increased. The lowest concentration of lycopene ≈ 0.51 mg/kg FW., found in green fruit at mature green class. Meanwhile, The highest concentration of lycopene ≈ 40.99 mg/kg FW., found in deep red fruit at advanced. Otherwise, average value of lycopene content entire class had a linear positive correlation with repining stages with R ≈ 0.99. These obvious facts were illustrated in Figure 6. This result was superior with Radzevičius et al., (2009); Saad et al., (2014); Saad et al., (2015).

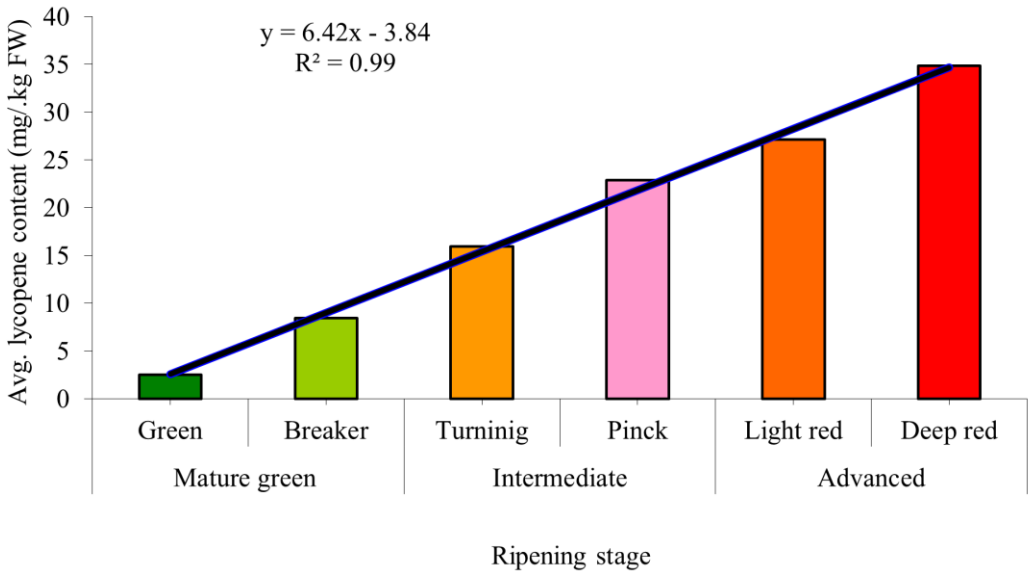


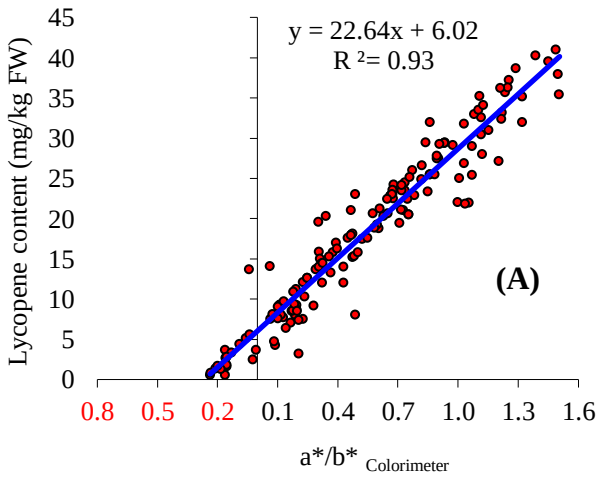
Figure 6. Relation between repining stages and avg. lycopene content (mg/kg FW) entire class.

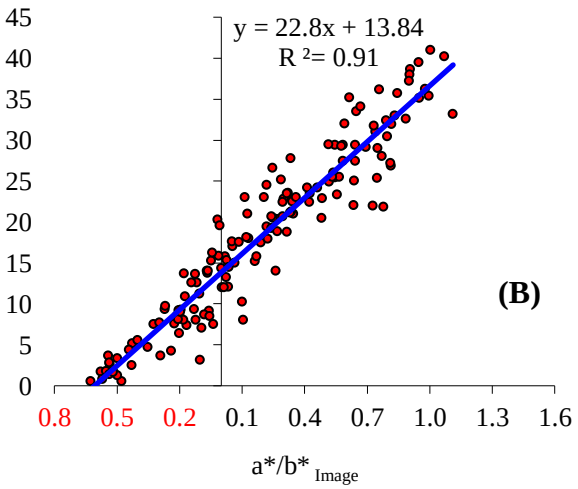
Obtained results show clearly that, with exclusion mature green class (green and breaker stage), there were a roughly linear positive correlation between lycopene content (mg/kg FW) and a*/b* ratio for both colorimeter and image. Rather, lycopene ≈ 22.649 ($a^*/b^*_{Colorimeter}$) + 6.0232 ≈ 22.809 (a^*/b^*_{Image}) + 13.846, with R ≈ 0.965, and 0.954, respectively. Figures7A and B.

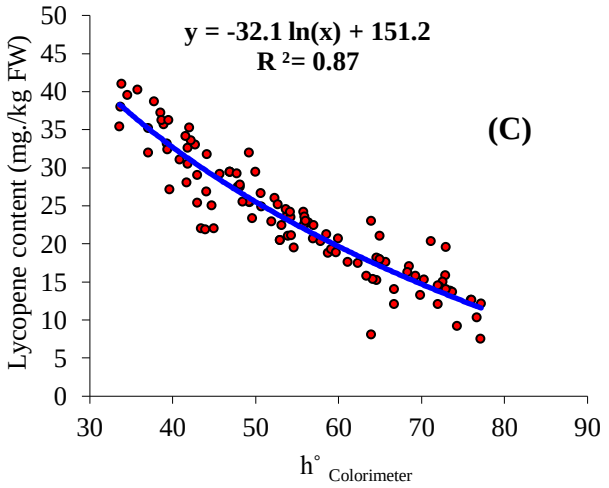
The results show clearly that, not all relationships between lycopene content and other chromaticity values (h° and ΔE) were positive and linear. Contrary to the former relation, there was a negative correlation between lycopene and h°. Where, external color was expressed in terms of h°. It is an angular measurement in the quadrant between the a* and b* axes. Results recorded that, there was a logarithmic correlation between lycopene content (mg/kgFW) and both $h^\circ_{Colorimeter}$ and h°_{Image}. Where, lycopene ≈ -32.149 Ln $\left(h^\circ_{Colorimeter}\right)$ +151.29, with R≈ 0.9328, Figure 7C.

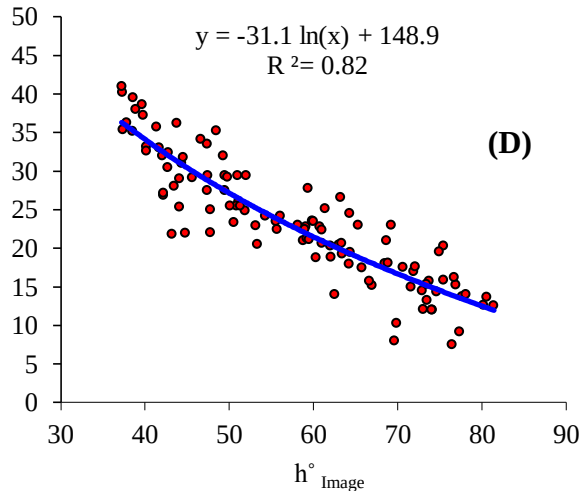
Moreover, correlation coefficient increased from 0.579 to 0.878 during coloring and transition from turning and pink stages to maturity (light red, and deep red).

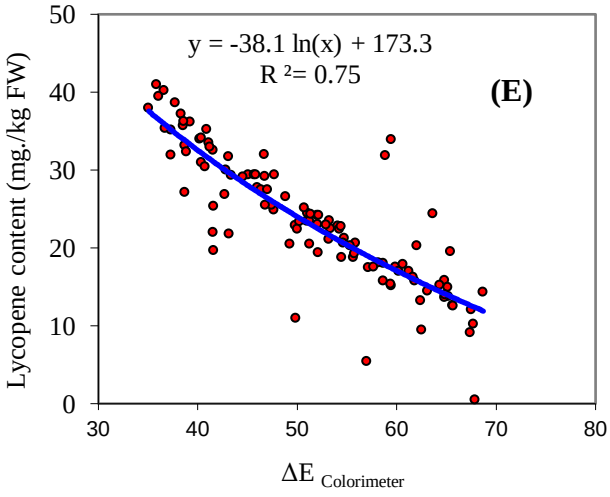
Meanwhile, Figure 7D illustrated that, lycopene ≈ -31.139Ln $\left(h^\circ_{Image}\right)$ + 148.96, with R ≈ 0.903. Anywhere, R increased from 0.579 to 0.887 during the transition from turning and pink stage to full ripeness. Also, results presented in Figures 7E and F show that, there were negative logarithmic correlations between lycopene content and both $\Delta E_{Colorimeter}$ and ΔE_{Image}, with (R) ≈ 0.8664 and 0.8254, respectively. Where, lycopene ≈ -38.17 Ln ($\Delta E_{Colorimeter}$) + 173.36 ≈ -41.322 Ln (ΔE_{Image}) + 192.79.











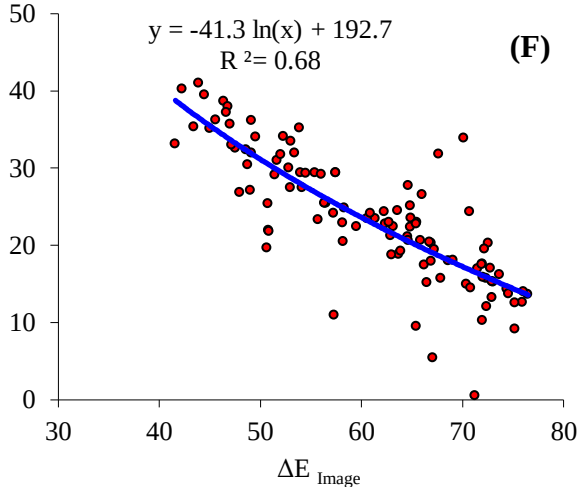
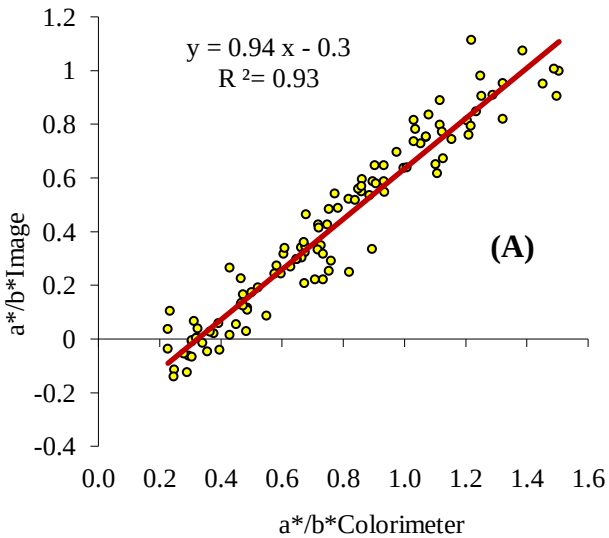


Figure 7. Relationship between lycopene content (mg/kg FW) and; A) a*/b* $_{Colorimeter}$ ratio, B)a*/b* $_{Image}$ ratio, C) $h^{\circ}_{Colorimeter}$, D) h°_{Image}, E) $\Delta E_{Colorimeter}$, F) ΔE_{Image}

These previous essentials resulted in different positive correlations between chromaticity values (a*/b* ratio, h° and ΔE) performed by colorimeter and image, respectively. This correlation was a linear correlation between a*/b*$_{Image}$ ratio and a*/b*$_{Colorimeter}$ ratio. Where, a*/b*$_{Image}$ = 0.9365 (a*/b*$_{Colorimeter}$)- 0.3027, with R ≈ 0.966. Meanwhile, it was an exponential correlation between h°_{Image} and $h^{\circ}_{Colorimeter}$. Where, h°_{Image} = 1.1903 $\left(h^{\circ}_{Colorimeter}\right)^{0.9698}$, with R ≈ 0.97. Finally, it was a logarithmic correlation between ΔE_{Image} and $\Delta E_{Colorimeter}$. Where, ΔE_{Image} =49.794 ln ($\Delta E_{colorimeter}$) – 134.58, with R ≈ 0.937, as described below in Figure 8 A, B, and C.



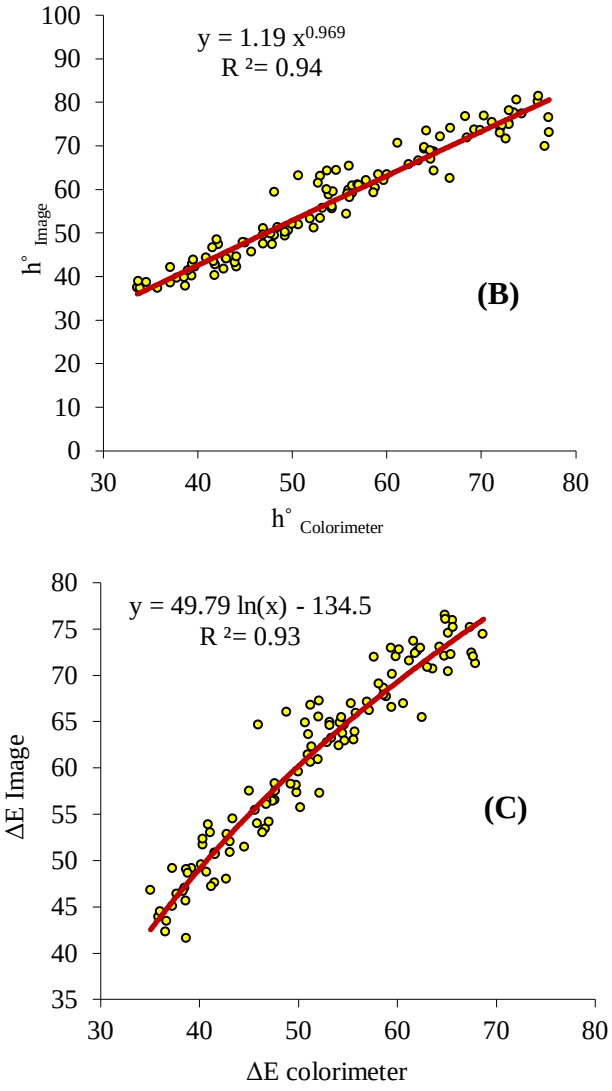


Figure 8. Correlation between chromaticity values performed by colorimeter and image where; A) a*/b* ratio, (B) h°, and C) ΔE

4 Conclusions

Chromaticity values and internal quality parameters were changed during ripening. L*, b*, h°, and ΔE tendency to decline. Opposite tendency was determined with a*, a*/b* ratio, TSS and lycopene content. In this work, chromaticity values showed to have an important impact in internal quality parameters (TSS and lycopene content). Further, it can be concluded that there was a good correlation between chromaticity values performed by image and colorimeter, and can estimate lycopene content during tomato maturity stage by them.

5 Acknowledgment

Authors are thankful to the Agricultural Engineering Research Institute (AEnRI), Department of Agric. Bioengineering, for harnessing all infrastructure facilities to carry out research activities.

References

Anonymous. 2006. Hunter Lab Users Manuel. Hunter Associates Laboratory.

Anthon, G. E., M. Le Strange, and D.M. Barrett. 2011. Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. *Journal of the Science of Food and Agriculture*, 91(7):1175–1181.

Arias, R., T.C. Lee, L. Logendra, and H. Janes. 2000. Correlation of lycopene measured by HPLC with the L*, a*, b* color readings of a hydroponic tomato and the relationship of maturity with color and lycopene content. *Journal of Agricultural and Food Chemistry*, 48(5): 1697–1702.

Batu, A. 2004. Determination of acceptable firmness and color values of tomatoes. *Journal of Food Engineering*, 61(3): 471–475.

Beckles, D. M. 2012. Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanumlycopersicum* L.) fruit. *Postharvest Biology and Technology*, 63(1): 129–140.

Bennedsen, B.S. and D.L. Peterson.2005. Identification of apple stem and calyx using unsupervised feature extraction. *Transactions of the ASAE*., 47(3): 889-894.

Bhowmik, D., K.P. Kumar, S. Paswan, and S. Srivastava. 2012. Tomato a natural medicine and its health benefits. *Journal of Pharmacognosy and Phytochemistry*, 1(1): 33-43.

Brosnan, T. and D.W. Sun. 2004. Improving quality inspection of food products by computer vision - a review. *Journal of Food Engineering*, 61(1): 3-16.

CFR. 1991. Code of Federal Regulations (CFR). United States Standards for Grades of Fresh Tomatoes. USDA Agricultural Marketing Service, Washington, DC.

Chang, C. H., L. Hsing-Yu, C. Chi-Yue, and L. Yung-Chuan. 2006.Comparisons on the antioxidant properties of fresh, freeze-dried and hot-air-dried tomatoes. *Journal of Food Engineering*, 77(3): 478-485.

Chen, Y.R., K. Chao, and M.S. Kim. 2002. Machine vision technology for agricultural applications. *Computers and electronics in Agriculture*, 36(2): 173-191.

Chen, L. 2008. Non-destructive measurement of tomato quality using visible and Near-infrared reflectance spectroscopy. M.Sc. Thesis. Bioresource Engineering Dept., McGill University Sainte Anne-de-Bellevue, Quebec, Canada.

Choi, K., G. Lee, Y.J. Han, and J.M. Bunn. 1995. Tomato maturity evaluation using color image analysis. *Transactions of the ASAE*., 38 (1): 171-176.

Choudhari, S.M. and L. Ananthanarayan.2007. Enzyme aided extraction of lycopene from tomato tissues. *Food chemistry*, 102(1):77–81.

Diago, M.P., C. Correa, B. Millán, P. Barreiro, C. Valero, and J. Tardaguila. 2012. Grapevine yield and leaf area estimation using supervised classification methodology on RGB images taken under field conditions. *Sensors*, 12(12):16988–17006.

Domis, M., and A. P. Papadopoulos. 2002. Greenhouse tomato fruit quality. *Horticultural reviews*, 26, p.239.

Ecarnot, M., P. Baogonekczyk, L. Tessarotto, and C. Chervin. 2013. Rapid phenotyping of the tomato fruit model. Micro-Tom. with a portable VIS-NIR spectrometer. *Plant Physiol. Biochemistry*, 70: 159-163.

FAOSTAT. 2015. Production crops: Tomatoes. FAOSTAT Agricultural production database. http://faostat.fao.org. Accessed on 12th August 2015.

Garg, N. and D. S. Cheema. 2011. Assessment of fruit quality attributes of tomato hybrids involving ripening mutants under high temperature conditions. *Scientia Horticulturae*, 131: 29–38.

Gómez, R., J .Costa, M. Amo, A. Alvarruiz, M. Picazo, and J.E. Pardo. 2001. Physicochemical and colorimetric evaluation of local varieties of tomato grown in SE Spain. *Journal of the Science of Food and Agriculture*, 81(11): 1101–1105.

Habekost, M. 2013. Which color differencing equation should be used. *Int Circular Graphic Educat Res*, 6: 20-33.

Hannan, M.W., T.F. Burks, and D.M. Bulanon. 2009. A machine vision algorithm combining adaptive segmentation and shape analysis for Orange fruit detection. *Agricultural Engineering International: CIGR Journal*, Manuscript 1281. Vol. XI.

Helyes, L., J. Dimény, Z. Pék, and A. Lugasi. 2006. Effect of maturity stage on content, color and quality of tomato (*Lycopersicon lycopersicum* (L.) Karsten). *International Journal of Horticultural Science*, 12: 41–44.

Hunterr Lab. 1996. CIE L*a*b* Color Scale: Applications, Note 8(7): 1–4.

Ibitoye, D.O., P.E. Akin-Idowu, and O.T. Ademoyegu. 2009. Agronomic and lycopene evaluation in tomato (*Lycopersiconlycopersicum* Mill.) as a function of genotype.*World Journal of Agricultural Sciences*, 5 (S): 892-895.

Ibrahim, A.A. 2012. Using a mechanical vision system in sorting of some agricultural products. Ph. D., Thesis. Agric. Eng. Dept., Fac. Agric., Minoufiya Univ., Egypt.

Ibrahim, A.A., A.H. Eisa, and A.O. Alghannam.2014. Image processing system for automated classification date fruit. *International Journal of Advanced Research*, 2(1):702-715.

Kays, S.J. 1997. Post-harvest physiology of perishable plant products. Van Nostrand Rein Hold Book, AVI Publishing Company, New York. pp.149 316.

Kumar, S.R., S.S. Sundar, A. Afandi, and S. Rahman. 2013. Optimization of lycopene from malaysian all season colored fleshy fruits. *International Journal of Biology, Pharmacy and Allied Sciences*, 2(7):1455-1467.

Kurtulmus, F., W.S. Lee, and A. Vardar. 2011. Green citrus detection using "eigenfruit", color and circular Gabor texture features under natural outdoor conditions. *Computers and electronics in agriculture*, 78(2): 140–149.

Kurtulmus, F.; W. S. Lee, and A. Vardar. 2014. Immature peach detection in colour images acquired in natural illumination conditions using statistical classifiers and neural network. *Precision agriculture*, 15(1): 57-79.

Lenucci, M.S., M.R. Leucci, G. Piro, and G. Dalessandro. 2008. Variability in the content of soluble sugars and cell wall polysaccharides in red-ripe cherry and high-pigment tomato cultivars. *Journal of the Science of Food and Agriculture*, 88(10):1837-1844.

Lin, W.C. and A.D.M. Glass. 1997. The effects of NaCl addition and macronutrient concentration on fruit quality and flavor volatiles of green house tomatoes. *In International Symposium on Growing Media and Hydroponics* 481, pp. 487-494.

López Camelo, A. F. and P. A. Gómez. 2004.Comparison of color indexes for tomato ripening. *Horticultura Brasileira*, 22 (3): 534-537.

Makino, Y., M. Ichimura, S. Oshita, Y. Kawagoe, and H. Yamanaka. 2010. Estimation of oxygen uptake rate of tomato (*Lycopersicon esculentum* Mill.) fruits by artificial neural networks modeled using near-infrared spectral absorbance and fruit mass. *Food Chemistry*, 121(2): 533-539.

Mendoza, F. and J.M. Aguilera. 2004. Application of image analysis for classification of ripening bananas. *Journal of Food Science*, 69(9): 471–477.

Nuske, S., S. Achar, T. Bates, S. Narasimhan, and S. Singh. 2011. Yield estimation in vineyards by visual grape detection. In Proceedings of 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), San Francisco, CA, USA, 25–30 September 2011., 2353–2358.

Olives-Barba, A.I., M. Camara-Hurtado, M.C. Sanchez-Mata, V. Fernandez-Ruiz, and M. Lopez-Saenz de Tejada. 2006. Application of a UV– vis detection- HPLC method for a rapid determination of lycopene and β-carotene in vegetables. *Food Chemistry*, 95(2): 328–336.

Papadakis, S. E., S. Abdul-Malek, R. E. Kamdem, and K. L. Yam. 2000. A versatile and inexpensive technique for measuring color of foods. *Food Technology*, 54(12): 48–51.

Payne, A.B., K.B. Walsh, P.P. Subedi, and D. Jarvis. 2013. Estimation of mango crop yield using image analysis-Segmentation method. *Computers and electronics in agriculture*, 91:57–64.

Payne, A.B., K.B. Walsh, P.P. Subedi, and D. Jarvis. 2014. Estimating mango crop yield using image analysis using fruit at "stone hardening" stage and night time imaging. *Computers and electronics in agriculture*, 100(): 160–167.

Pedreschi, F., D. Mery, F. Mendoza, and J.M. Aguilera. 2004. Classification of potato chips using pattern recognition. *Journal of Food Science*, 69(6): E264–E270.

Peirs, A., A. Schenk and B.M. Nicolai. 2005. Effect of natural variability among apples on the accuracy of VIS-NIR calibration models for optimal harvest date predictions. *Postharvest Biology and Technology*, 35(1):1-13.

Periago, M.J., J. Garcia-Alonso, K. Jacob, A.B. Olivares, M.J. Bernal, M.D. Iniesta, C. Mar-tinez, and G. Ros. 2009. Bioactive compounds folates and antioxidant properties of tomatoes (*Lycopersicum esculentum*) during vine ripening. *International Journal of Food Sciences and Nutrition*, 60(8): 694–708.

Polder, G., G. W. A. M. Van der Heijden,and I.T. Young. 2000. Hyperspectral image analysis for measuring ripeness of tomatoes. In: ASAE International Meeting, 2000, Milwaukee. Proceedings. Milwaukee: ASAE, Paper No 003089.

Polder, G., G. W. A. M. Van Der Heijden, and I.T. Young. 2003.Tomato sorting using independent component analysis on spectral images. *Real-Time Imaging*, 9(4): 253- 259.

Radzevičius, A., P. Viškelis, and Č. Bobinas. 2008. Quality and physiological parameters of tomato (*Lycopersicon esculentum* Mill.) fruits of Lithuanian selection. *biologija*, 54 (2): 108–111.

Radzevičius, A., R. Karklelienė, P. Viškelis, Č. Bobinas, R. Bobinaitė, and S. Sakalauskienė. 2009. Tomato (*Lycopersicon esculentum* Mill.) fruit quality and physiological parameters at different ripening stages of Lithuanian cultivars. *Agronomy Research*, 7 (Special issue II): 712–718,

Ranveer, R. C., S. N. Patil, and A. K. Sahoo. 2013. Effect of different parameters on enzyme-assisted extraction of lycopene from tomato processing waste. *Food and Bioproducts Processing*, 91(4): 370–375.

Saad, A.M., J. Pranita, and S.N. Jha. 2014. Non-destructive quality evaluation of intact tomato using VIS-NIR spectroscopy. *International Journal of Advanced Research*, 2 (12): 632-639.

Saad, A., S. N. Jha, P. Jaiswal, N. Srivastava, and L. Helyes. 2015. Non-destructive quality monitoring of stored tomatoes using VIS-NIR spectroscopy. *Engineering in Agriculture, Environment and Food*, doi:10.1016/j.eaef.2015.10.004.

Sammi, S. and T. Masud. 2007. Effect of different packaging systems on storage life and quality of tomato (*Lycopersicon esculentum* var. Rio Grande) during different ripening stages. *Journal of Food Safety*, 9:37–44.

Scanlon, M. G., R. Roller, G. Mazza, and M.K. Pritchard. 1994. Computerized video image analysis to quantify color of potato chips. *American Potato Journal*, 71(11): 717–733.

Segnini, S., P. Dejmek, and R. Öste. 1999. A low cost video technique for color measurement of potato chips. *Food Science and Technology*, 32(4): 216–222.

Shao, Y., Y. He, A. H. Gómez, A. G. Pereir, Z. Qiu, and Y. Zhang. 2007. Visible/near infrared spectrometric technique for nondestructive assessment of tomato 'Heatwave' (*Lycopersicum esculentum*) quality characteristics. *Journal of Food Engineering*, 81(4): 672–678.

Strati, I.F. and V. Oreopoulou. 2011. Effect of extraction parameterson thecarotenoid recovery from tomato waste. *International Journal of Food Science & Technology*, 46(1):23–29.

Szuvandzsiev. P., L. Helyes, A. Lugasi, C. Szántó, P. Baranowski, and Z.Pék. 2014.Estimation of antioxidant components of tomato using VIS-NIR reflectance data by handheld portable spectrometer. *International Agrophysics*, 28(4):521-527.

Takeoka, G. R., L. Dao, S. Flessa, D. M. Gillespie, W.T. Jewell, and B. Huebner. 2001. Processing effects on lycopene content and antioxidant activity of tomatoes. *Journal of Agricultural and Food Chemistry*, 49(8): 3713–3717.

Teixidó, M., D. Font, T. Pallejà, M. Tresanchez, M. Nogués, and J. Palacín. 2012. Definition of linear color models in the RGB vector color space to detect red peaches in orchard images taken under natural illumination. *Sensors*, 12(6): 7701–7718.

Vazquez-Cruz, M.A., S.N. Jimenez-Garcia, R. Luna-Rubio, L.M. Contreras-Medina, E. Vazquez-Barrios, E. Mercado-Silva, I. Torres-Pacheco, and R.G. Guevara-Gonzalez. 2013. Application of neural networks to estimate carotenoid content during ripening in tomato fruits (*Solanum lycopersicum*). *Scientia Horticulturae*, 162: 165–171.

Wang, Q., S. Nuske, M. Bergerman, and S. Singh. 2012. Automated crop yield estimation for Apple orchards. In Proceedings of the 13th International Symposium on Experimental Robotics, Quebec, QC, Canada, 18–21 June 2012., 745–758.

Wold, A. B., H. J. Rosenfeld, K. Holte, H. Baugerød, R. Blomhoff, and K. Haffner. 2004. Color of post-harvest ripened and vine ripened tomatoes (*Lycopersicon esculentum* Mill.) as related to total antioxidant capacity and chemical composition. *International Journal of Food Science and Technology*, 39(3): 295–302.

Xie, L., Y. Ying, H. Lin, Y. Zhou, and X. Niu. 2008. Nondestructive determination of soluble solids content and pH in tomato juice using NIR transmittance spectroscopy. *Sensing and Instrumentation Food Quality Safety*, 2(2):111-115.

Yang, R.F., T.S. Cheng, and R.L. Shewfelt. 1990. The effect of high temperature and ethylene treatment on the ripening of tomatoes. *Journal of Plant Physiology*, 136(3):368-372.

Yang, H. 2011. Nondestructive prediction of optimal harvest time of cherry tomatoes using VIS-NIR spectroscopy and PLSR calibration. *Advanced Engineering Forum*, 1: 92-96.

Zhou, R., L. Damerow, Y. Sun, and M.M. Blanke. 2012. Using color features of cv. "Gala" apple fruits in an orchard in image processing to predict yield. *Precision agriculture*, 13(5): 568–580.