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RESEARCH ARTICLE

Quantifying quality changes in dark purple eggplant as affected by fluctuating storage conditions and wrapping materials

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ABSTRACT

Produce quality can be irreversibly damaged by exposure to fluctuating temperature and light when moving along the supply chain. Quality loss of fresh fruits and vegetables is of considerable interest due to its omnipresent occurrence, which exceeds 50% in some developing countries. In this work, different storage scenarios and their effect on eggplant quality were investigated. Under isothermal conditions, two temperatures were chosen under partial and complete absence of light. Under non-isothermal storage, four different combinations of temperatures and light were studied. These combinations represented all segments of the supply chain of fresh fruits and vegetables (from the producer to the consumer). At the end of the entire storage duration, the measured quality loss for unwrapped samples were 75.62% for firmness, 11.02% for weight loss, 10.19% for color and 61.11% for quality index. These losses were reduced significantly ($P < 0.05$) through wrapping the fresh produce during storage and the percent quality loss were as follows: 19.43% for firmness, 0.84% for weight loss, 7.31% for color and 22.22% for quality index. Kinetic models were used to provide a structural framework for quantitatively describing and predicting those losses.

Keywords: Quality changes, quantification, eggplant, storage conditions, wrapping materials

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INTRODUCTION

Fresh fruits and vegetables are an essential part of human's daily diet (Florkowski *et al.,* 2014). The environmental conditions under which fresh horticultural commodities are produced, transported and displayed have a major effect on the keeping quality of the foods and the amount that is lost. Such losses are minimised by proper temperature and light management at every link within the supply chain (Hodges *et al.,* 2011; Hoogerwerf *et al.,* 1994). Moreover, storing the crop at fluctuating temperatures was demonstrated to be the driver behind accelerated respiration and transpiration rates, which can cause further deterioration of the postharvest quality of the produce (Florkowski *et al.,* 2014). Consequently, the rate of water loss from the fresh produce increases causing irreversible weight loss that cannot be regained when placed back into a cold environment (Moretti *et al.* 2010). Other studies carried out by Sanz *et al.* (2009), showed that light was also a major cause for the deterioration of fresh commodities (like asparagus) due to acceleration in the physiological activities. According to other

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researchers (Ayala *et al*., 2009; Cervera *et al*., 2007), lighting exposure caused an increase in respiration rate and changes in the overall appearance of minimally processed green vegetables.

Eggplant (*Solanum melongena* L.), commonly known also as aubergine, is considered to be among the 30 commonly produced and consumed horticultural crops worldwide (Concellón *et al*., 2007; Florkowski *et al*., 2014). It is best grown in tropical and sub-tropical areas (Concellón *et al*., 2012; Loose *et al*., 2014) and has high economic and nutritional values worldwide (FAO, 2013; Okmen *et al*., 2009). Beside its medicinal properties including the inhibition of the formation of blood vessels responsible for tumour growth and metastasis (Matsubara *et al*., 2005), eggplant contains a large amount of polyphenols, vitamins and minerals (Boulekbache-Makhlouf *et al*., 2013). In many countries in Asia and Latin America, the majority of eggplant fruits are cultivated and harvested by small-holder farmers and are considered as a vital source of income for them (Hanson *et al*., 2006). Eggplant, like many other fresh plant produce, is highly perishable and continues to be metabolically active even after harvesting (Kader *et al*., 2004). Usually eggplants are egg-shaped or globular and have dark green calix, firm texture and dark purple skin (Gross *et al*., 2014). At the international level, the dark purple eggplant is the most commercially consumed fruit among the eggplant varieties (Zaro *et al*., 2014).

Quality perception is very complex (Luning *et al*., 2009). A commonly accepted definition by the International Standard Organisation (ISO, 2014) is that "*quality is a desirable characteristic that a product or service must have*". In the case of fresh fruits and vegetables, the consumer's quality perception is generally focused on quality attributes such appearance, color, size, shape, firmness and freshness (Florkowski *et al*., 2014). Appearance is the first quality attribute assessed by the consumer and a key factor in buying or rejecting the fresh produce (Florkowski *et al*., 2014). Color is also a determining parameter when purchasing fruits and vegetables. In the case of eggplant, the dark purple color reflects the antioxidant content (anthocyanin) in the fruit (Mishra *et al*., 2012). When evaluating the texture of a fresh commodity, firmness is equivalent to the maturity stage or the degree of freshness of that commodity (Kader *et al*., 2002). For crops like eggplant, tomato and cucumber, consumers have an expectation of a firm quality product that could last longer before consumption. However, crops such as string beans for example; should be harvested at their early maturity stages in order to assure a soft product because firmer string beans would not be consumable as they become fibrous and hard to digest.

Numerous authors have shown that using wrapping films could play a major role in reducing postharvest losses of fresh produce during storage and therefore, extending their shelf-life (Janave *et al*., 2005; Xiao *et al*., 2014b). In research on mango fruits, Janave *et al*. (2005) stated that food grade films created certain barriers between the food system and their surroundings, therefore, the fruits retained around 40% of their chlorophyll content and a 50% reduction of their weight loss was observed compared to unwrapped fruits. Consequently, the shelf life of wrapped mangoes was extended by 15 days and the ripening process was slowed down. Other studies conducted by Bouzo *et al*. (2012) revealed that wrapping films decreased respiration and transpiration rates of fresh fig fruits and hence prolonged the storage life and quality appearance.

Postharvest storage conditions can foster many chemical composition changes in fresh eggplant (Florkowski *et al*., 2014; Matsubara *et al*., 2005). The measurement of appropriate kinetic parameters, such as reaction rate constant and activation energy for these changes, enables the estimation of the magnitude of change in a given food component during storage and prior to final consumption (Heldman, 2011). The kinetic analysis of quality attributes has been extensively investigated in a wide variety of fresh commodities. Nourian *et al*. (2003) documented that first-order prediction models for physical (color and firmness) and chemical (ascorbic acid, total soluble solids and pH) quality attributes were a good fit for the experimental data of potato when stored at different temperatures. Other authors (Cruz *et al*. 2009) reported that zero order models best described the color data obtained during cold storage of watercress. It is often very difficult to ensure constant environmental factors during postharvest handling of fruits and vegetables, therefore, the continuous exposure of fresh horticultural crops to fluctuating temperature and light during handling is the challenge facing stakeholders in many countries that lack refrigeration and other supporting postharvest technologies.

The objective of this research was to study the effect of temperature and light fluctuations and wrapping materials during postharvest storage on quality attributes in dark purple eggplant. The specific objectives were to: (1) assess postharvest losses over time during storage under several temperature and light combinations and wrapping materials, (2) quantify these losses using kinetic models, and (3) study the dependence of temperature and light on quality degradation.

MATERIALS AND METHODS

Plant material preparation

Fresh eggplants were obtained from a local, year-round, greenhouse supplier (Lufa farms, Montreal, Canada). Right after harvesting, the samples were labeled and separated into experimental units of similar quantity for further analysis. These crops were then divided into two groups, namely "with wrapping film" and "without wrapping film" (Thermo Fisher Scientific Inc, Montreal, Canada).

Experimental set-up

Controlled environment chambers (Conviron Inc., PGR15, Manitoba, Canada) were used in the study. With an internal capacity of 78 ft^3, the chambers were fully programmable to monitor set factors (temperature and light). The chamber was capable of maintaining temperatures in the range between 10 and 45^oC. Airflow inside the unit was distributed uniformly upward using an air distribution plenum (Conviron, 2014) that allowed up to 20 ft^3/min of air exchange. Light intensity in the chamber was maintained up to 875 micromoles/m^2/s or 64,750 lux using fluorescent and incandescent lamps. This is the typical average of light intensity during a sunny day.

Under constant storage conditions (SC), samples of eggplant were stored at 10 and 30^oC for 10 days with 90±5% RH with two different light scenarios, namely "complete darkness" and an "interval of 12 hours of direct light per day" for each temperature setting. A total of four different storage combinations of temperature and light were conducted as follow: SC1 = 10ºC (with light); SC2 = 30ºC (with light); SC3 = 10ºC (without light); SC4 = 30ºC (without light).

Under fluctuating conditions, the storage of eggplant was simulated based on real situations occurring during the handling process of fresh produce in many countries around the world (Figure 1). After harvesting, the eggplant samples were stored at 25ºC for 2 hours with no light exposure (S1). This step was similar to the activity carried out by farmers in the field, where they place their crop under shade after harvesting. The following step (S2) was to store the eggplant for 3 hours under light, which simulated the transportation of the fresh produce to the market using open trucks. Step 3 corresponded to the marketing stage of the harvested commodity for a typical duration of three consecutive days under fluctuating conditions of temperature and light between day and night. Therefore, the eggplant samples were stored at 30ºC with light for 12 hours and at 20ºC with no light for another 12 hours. This step (S3) lasted for 72 hours. The final step (S4) illustrated conditions similar to what happened at the consumption level where the produce was stored at low temperature (10ºC) in the absence of light for a maximum duration of 6 days (144 hours). The entire experiment was conducted in triplicate.

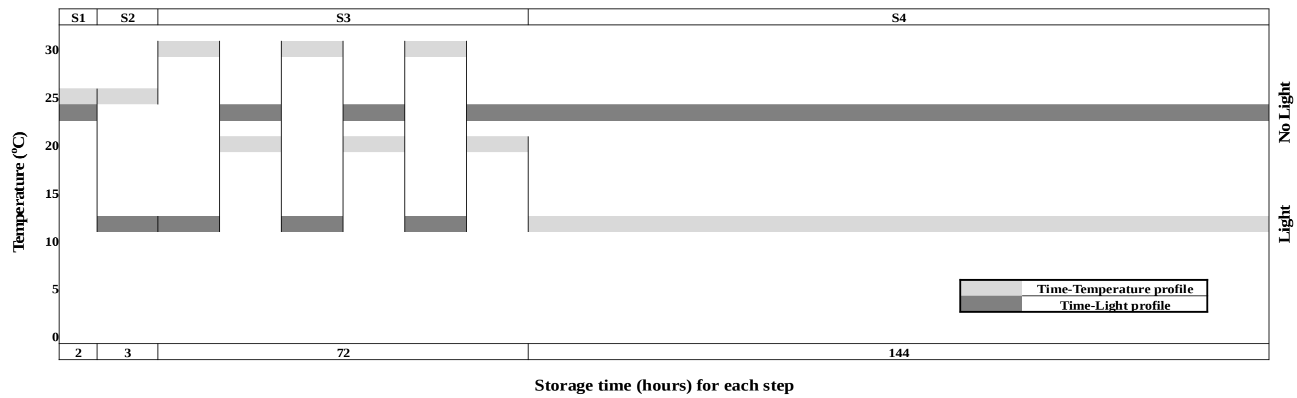

Figure 1. Schematic diagram of fluctuating environmental conditions during storage

Color measurement

The color of studied samples was expressed in CIELAB color space using a Minolta Spectrophotometer (CM-3500d, Japan) where L* defines lightness, a* describes the red/green coordinate and b* the yellow/blue value. The equipment was calibrated against standard ceramic white and black tiles. The total color difference (ΔE) was stated as a single value using the following equation:

$$\Delta E = \sqrt{(\Delta L^2) + (\Delta a^2) + (\Delta b^2)} \qquad (1)$$

where $\Delta L = L^* - L^*_{standard}$; $\Delta a = a^* - a^*_{standard}$; $\Delta b = b^* - b^*_{standard}$; and the standard $L^*a^*b^*$ values were defined as the initial color values of the freshly harvested produce. Triplicate readings were taken for individual samples to obtain a better representation of its actual color.

Texture analysis

Firmness or texture evaluation was measured using the Instron Universal Testing Machine (Model 4502, Instron, Canton, MA, USA). A compression test was carried out with 5 mm diameter probe, a crosshead speed of 5 mm/min and a maximum load cell of 50N. For the purpose of this study, the firmness was defined in terms of applied force (F) or load on the surface of the commodity and was expressed in Newton (N). Load-displacement plots were then obtained and firmness corresponding to maximum load (N) was calculated. A total of three readings were acquired for each crop and an average firmness was registered.

Weight loss evaluation

Loss of weight in fresh eggplant during postharvest handling was measured using the formula:

$$WL = 100 * \left(W_i - W_f\right) / W_i \qquad (2)$$

where WL was the weight loss (%), Wi and Wf were the initial (t = 0) and the final weight of the produce calculated before and after treatment.

Quality index rating

Quality index (QI) was assessed for individual produce using a nine point hedonic scale for the subsequent parameters: symptoms of deterioration and limits of marketability. A quality index for eggplant summarizing all these parameters was determined (Table 1) and a score for each sample was given.

Kinetic modeling and data analysis

Under isothermal storage conditions, zero and first order kinetic equations are expressed as follows:

$$C_t = C_0 - kt \tag{3}$$

$$\frac{C_t}{C_0} = \exp^{-kt} \tag{4}$$

where C_t is the measured quality parameter (color, firmness, quality index and weight loss) at time *t*, C_0 is the initial quality before any storage, *t* is the storage time and *k* is the rate constant at temperature *T*.

Equations 3 and 4 were fitted to experimental data. Appropriate model was chosen based on the highest R^2. The temperature-dependence of the rate constant *k* was assumed to follow the Arrhenius equation (Eq. 5):

$$k = k_{ref} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T_i} - \frac{1}{T_{ref}}\right)\right] \tag{5}$$

where k_{ref} is the reaction rate at reference temperature (T_{ref}), E_a is the activation energy of the reaction (J/mol), R is the universal gas constant (8.314 J/mol.K) and T_i is the absolute temperature (K). The reference temperature used was 30^{o}C.

Under non-isothermal conditions, the quality attributes can be predicted for a given time by equation 6 and 7:

$$C_t = C_0 - k_{ref} \int_0^t \exp\left[\frac{-E_a}{R}\left(\frac{1}{T_i} - \frac{1}{T_{ref}}\right)\right] dt \tag{6}$$

$$\frac{C_t}{C_0} = \exp^{k_{ref} \int_0^t \exp\left[\frac{-E_a}{R}\left(\frac{1}{T_i} - \frac{1}{T_{ref}}\right)\right] dt} \tag{7}$$

By introducing effective temperature (T_{eff}) term as demonstrated by Giannakourou *et al*. (2003) and defined as the constant temperature at which the same quality change resulted from the same time duration as the temperature fluctuated along the storage, the quality changes for the entire storage duration of studied crops as influenced by fluctuating temperature and light can then be predicted using equations 8 and 9:

$$C_{t_{total}} = C_0 - k_{eff} t_{total} \tag{8}$$

$$\frac{C_{t_{total}}}{C_0} = \exp^{-k_{eff} t_{total}} \qquad (9)$$

where k_{eff} is the value of the rate constant at the effective temperature. Therefore, $k_{eff}\, t_{total}$ was calculated using equation 10:

$$k_{eff} t_{total} = k_{ref} \sum_i \left(\exp\left[\frac{-E_a}{R} \left(\frac{1}{T_i} - \frac{1}{T_{ref}} \right) \right] t_i \right) \qquad (10)$$

An analysis of ANOVA followed by a Tukey-Kramer HSD test for comparison of means was conducted using JMP version 11 software.

RESULTS AND DISCUSSION

Effect of environmental factors on quality parameters

In this study, the storage at 10^{o}C represented the optimum conditions for commercial storage recommended for eggplant (Gross *et al*., 2014); whereas, the storage at 30^{o}C corresponded to the average annual temperature that best characterize tropical countries where temperature abuse during postharvest handling is more frequent. The results showed that quality parameters of eggplants were influenced by temperature and light during postharvest storage.

At complete darkness, there was a consistent degradation of firmness with softer samples ($P > 0.05$) stored at 30^{o}C compared to 10^{o}C (Figure 2a). These results are in agreement with other studies, which demonstrated that storage at higher temperature further decreased the firmness in fresh vegetables (Liu *et al*., 2014; Lopez *et al*., 2010). Numerous studies concluded that the extent of firmness degradation during postharvest storage varied between crops. Pyrotis *et al*. (2011) showed that the loss of firmness in stored strawberry increased by 0.6 N with 1^{o}C increase in temperature. Other studies demonstrated that the firmness of tomato fruits decreased exponentially during storage at higher temperatures (Lana *et al*., 2005). Similarly, the percent weight loss of eggplant was higher ($P > 0.05$) when stored at 30^{o}C under the absence of light (Figure 2b). During this storage period, eggplant samples lost between 9 to 14.5% of their initial weight (at harvest). Storage at lower temperature (10^{o}C) in the absence of light slowed down the weight loss to the initial weight and could be recommended for eggplant storage while maintaining higher quality and longer shelf life.

Weight loss is both a quantitative and a qualitative loss and is usually associated with moisture loss that causes wilting, shrivelling and softening of the external texture of the crop (FAO, 2007; Hung *et al*., 2011). Preserving the color during the postharvest handling of eggplant is an important practice in quality management. Anthocyanin compounds in eggplant are responsible for providing the dark purple color on the outside peel of the eggplant fruit (Sun *et al*., 1990). Therefore, reducing the loss of those color pigments is crucial during storage. Figure 2c showed the results of total color difference (ΔE) compared to the initial color value (at time 0). Storage in complete darkness at both temperatures caused some color loss in eggplants, however, the color difference was not significant ($P > 0.05$). A similar trend was observed for quality index degradation during storage (Figure 2d). In the absence of light, storage at lower temperature resulted in slower rate of quality deterioration ($P > 0.05$) and a better quality index was registered compared to higher temperature.

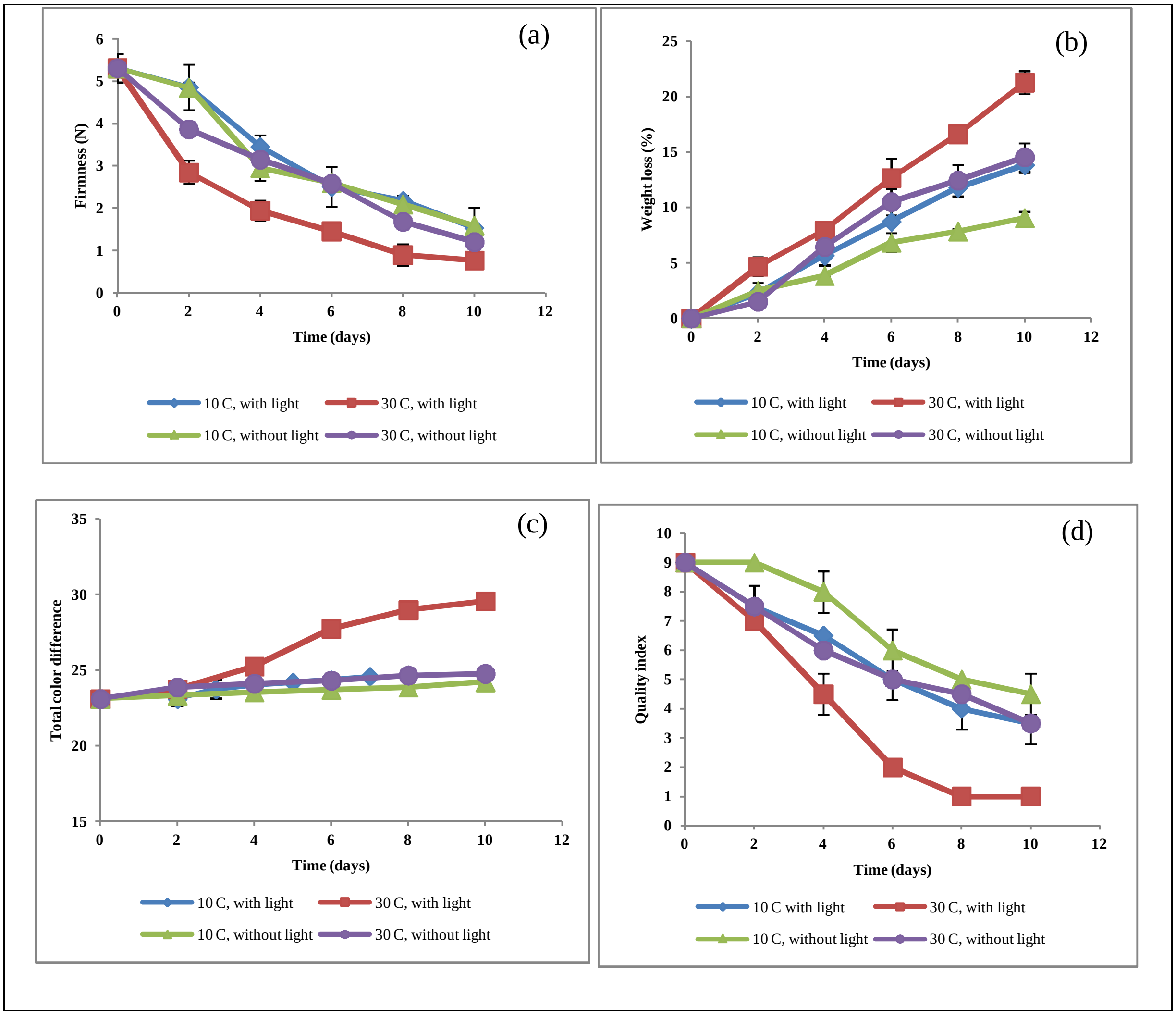

Figure 2. Quality attribute responses during storage of unwrapped eggplants.

Under light conditions, there was a higher rate of quality deterioration of eggplant over time. The firmness of eggplant samples decreased from 5.31 N to 0.77 N (85.5% loss). These results in Figure 2a revealed that light, combined with elevated temperatures, had accelerated ($P > 0.05$) the softening process of stored eggplant. As mentioned previously, light could speed-up the metabolic and physiological activities of the plant cells. Similar results on the influence of light were demonstrated by Martinez-Sanchez *et al.* (2011), where they stored fresh Romaine lettuce under complete darkness and partial light conditions. As seen in Figure 2b, storing the eggplants at light with 30^{o}C has further increased the weight loss up to 21% ($P > 0.05$). A plausible explanation is that during storage, light exposure is responsible for stomata opening which increases further the weight loss of the produce through transpiration (Martinez-Sanchez *et al*. 2011). In terms of color, a significant difference ($P < 0.05$) in color was observed after 10 days of storage at 30^{o}C in the presence of light (Figure 2c). Studies conducted by Fennema *et al.* (1996) revealed that anthocyanin is very susceptible to high temperature and direct light exposure. Other studies performed by Xiao *et al*. (2014a) stated that lycopene, anthocyanin and carotenoid were very unstable when exposed to solar radiation and showed higher stability in the dark. The loss of color in fresh fruits and vegetables is mainly due to the occurrence of oxidation during storage (Sanz *et al*., 2009). In the presence of light, this oxidation process is called photo-oxidation (Tiwari *et al.*, 2013). In terms of quality index (Figure 2d), the eggplant samples have lost their overall quality (P > 0.05) only after 6 days of storage at 30°C with light and became unmarketable at day 8 (QI = 1). These results are in agreement with the recommended conditions of 10°C in dark conditions for the commercial storage of eggplant (Gross *et al.*, 2014).

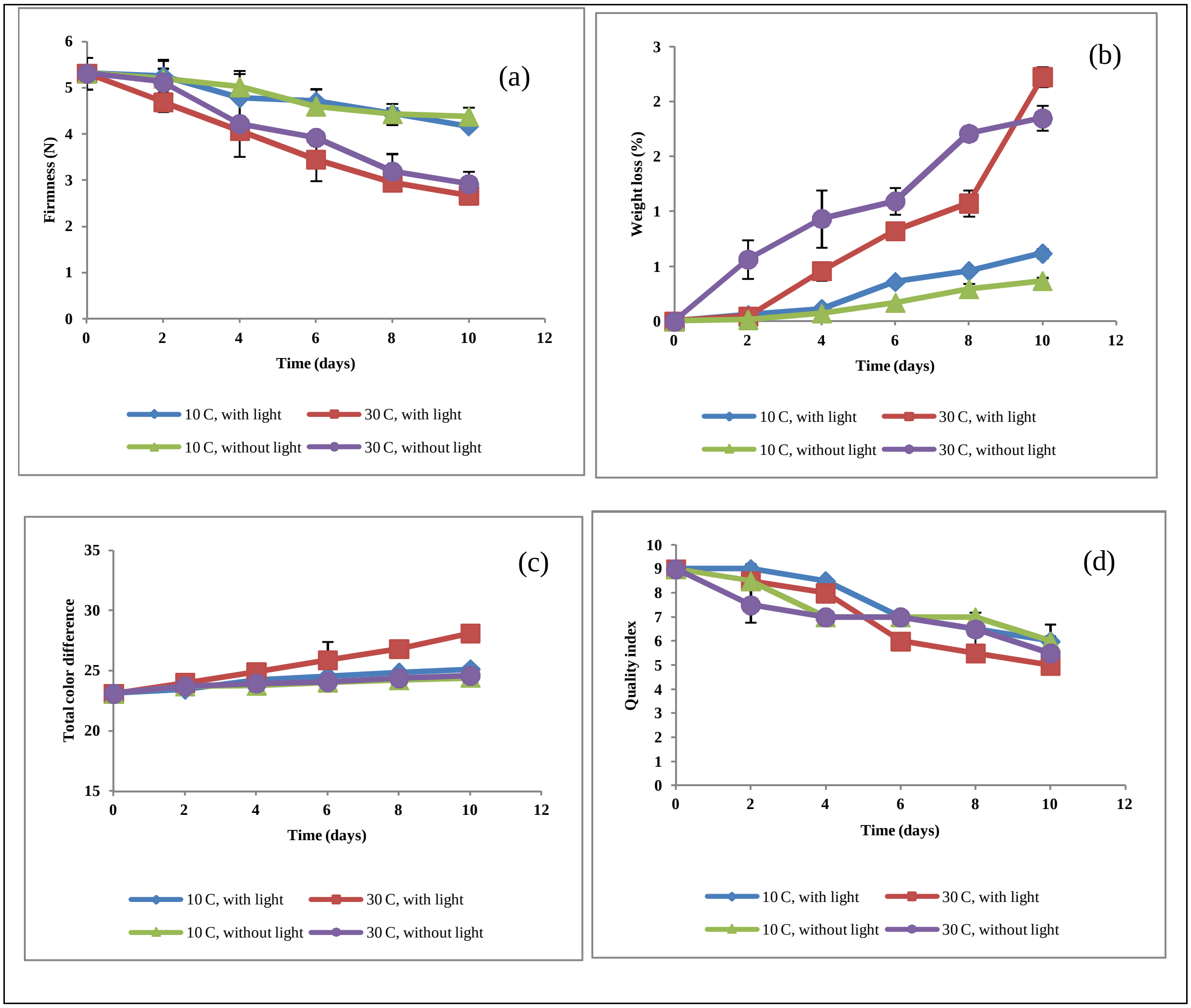

Figure 3. Quality attribute responses during storage of wrapped eggplants.

Effect of wrapping material on keeping quality

Analysis of variance showed that wrapping influenced the quality of eggplants during storage. Wrapping film behaved as a barrier between the surface of the plant produce and the surrounding environment. Quality losses were reduced significantly (P < 0.05) when the crops were wrapped with the exception of color. In case of unwrapped eggplants, these losses during 10-day storage at 30°C with light, were as follows: 85.5 % for firmness, 21 % for weight loss, 27.96 % for color and 89 % for visual quality index. Under the same storage conditions (SC2 = 30°C with light), quality losses for wrapped produce were 49.7 % for firmness, 2.23 % for weight loss, 21.69 % for color and 44.44 % for quality index (Figure 3). Food grade polyethylene film helped in maintaining the firmness quality under all storage conditions with firmer produce at lower temperature (Figure 3a). Similar results were published by Maftoonazad *et al.*, (2008), where they showed the beneficial effect of wrappers on firmness retention of avocado stored at various temperatures. Similarly, little weight loss was observed with wrapped eggplant due to the barrier effect to water vapor movement caused by the wrapping film (Bouzo et al., 2012; Mebratie et al., 2016).

Table 1. Full description of quality index scales of eggplant.

Quality Index	Quality	Description
9	Excellent	Calyx of freshly dark green color, turgid appearance. Glossy skin and dark black in color. Firm in texture. Absence of major handling defects. Absence of decay.
7	Good	Green calyx, slightly wilting appearance. Skin reasonably glossy and black in color. Slight loss of firmness. Presence of minor handling defects. Absence of decay.
5	Average	Pale green calyx, wilted or slightly dry and brownish in color at its end. Dull skin and lightly browning. Slight softness in texture. Presence of decay and major handling defects.
3	Poor	Very pale calyx and brown in color, severe wilting or partly drying. Major browning in skin. Soft in texture. Presence of remarkable decay and major handling defects.
1	Unmarketable	Brown calyx, complete wilting or drying. Skin very brown in color. Very soft in texture. Presence of complete decay and severe handling defects.

The crop turgor was maintained during the entire duration of the storage as shown in Figure 3b. From Figure 3c, the difference in color between wrapped and unwrapped samples was not significant ($P > 0.05$). This finding is in accordance with a previous study carried out by Olarte *et al.* (2009) on broccoli and cauliflower where the packaging film did not influence the retention or degradation of the color coordinates. Conversely, a study conducted by Maftoonazad *et al*. (2008), stated a significant reduction in color difference between wrapped and unwrapped avocado. Figure 3d also revealed that the overall visual quality of studied eggplants was significantly maintained during the entire storage period. At the 10-day storage period, a score of 5 was registered at 30°C under light exposure compared to a score of 1 for unwrapped produce under the same storage conditions (SC2).

For all quality attributes, the wrapping effect was equivalent to storing the unwrapped eggplant samples at 10°C in complete darkness. Therefore, food grade polyethylene film could be a promising solution to reduce postharvest losses and maintaining the quality of fresh produce among the supply chain segments especially in countries where controlling the temperature and light effect is difficult to address during the handling practices.

Changes of quality attributes during storage

Firmness and quality index changes

Changes in texture and visual quality of unwrapped and wrapped eggplant during storage at constant conditions are presented in Tables 2 and 3. The experimental data fitted the first order reaction model (Eq. 4) well for all four storage conditions. During storage, both firmness and quality index attributes decreased over time at a rate that depended on temperature and light exposure. Among all storage conditions, the quality degradation was faster at 30^oC in the presence of light for both unwrapped and wrapped eggplants. However, the food grade polyethylene film slowed down the firmness deterioration by threefold ($k_{unwrapped}$ = 0.191/day and $k_{wrapped}$ = 0.071/day) and the quality index by fourfold ($k_{unwrapped}$ = 0.252/day and $k_{wrapped}$ = 0.064/day) during the 10-day storage. Using Arrhenius formula (Eq. 5) with $T_{30}{^o}_C$ as reference temperature, the activation energy was calculated. In the study, two different "Ea" were obtained considering the light factor. In theory, a chemical reaction occurs within the food system when sufficient energy is available.

Table 2. Kinetic parameters of unwrapped eggplant at constant storage conditions.

Quality attributes	Storage Conditions	C_0	C_{eq}	Kinetic parameters		
				k(day^{-1})	R^2	Ea (KJ/mol)
Firmness	SC1	5.31	1.53	0.127	0.98	14.56
	SC2	5.31	0.77	0.191	0.97	
	SC3	5.31	1.59	0.124	0.97	15.41
	SC4	5.31	1.20	0.144	0.98	
Weight loss	SC1	0.00	13.81	1.459	0.99	12.91
	SC2	0.00	21.27	2.095	0.99	
	SC3	0.00	9.06	0.854	0.96	32.02
	SC4	0.00	14.53	1.601	0.95	
Total color difference	SC1	23.10	24.57	0.106	0.99	33.12
	SC2	23.10	29.56	0.766	0.95	
	SC3	23.10	24.22	0.099	0.98	60.06
	SC4	23.10	24.77	0.117	0.98	
Quality index	SC1	9.00	3.50	0.098	0.99	12.57
	SC2	9.00	1.00	0.252	0.95	
	SC3	9.00	4.50	0.078	0.94	19.55
	SC4	9.00	3.50	0.092	0.99	

SC1 = 10^{0}C (with light); SC2 = 30^{0}C (with light); SC3 = 10^{0}C (without light); SC4 = 30^{0}C (without light).

The results in Tables 2 and 3 revealed that the energy needed to start the firmness degradation in the presence of light were Ea = 14.56 and 38.70 KJ/mol for unwrapped and wrapped eggplants, respectively. Similarly, for overall quality index, the activation energy were Ea = 12.57 and Ea = 33.70 KJ/mol, respectively. In the absence of light, higher Ea values for firmness (15.41 KJ/mol for unwrapped samples and 41.80 KJ/mol for wrapped samples) and quality index (19.55 KJ/mol for unwrapped samples and 41.84 KJ/mol for wrapped samples) were recorded, respectively. From the results, it could be concluded that exposure to light has a negative influence on maintaining firmer and high quality produce and should be carefully considered during postharvest quality management of fresh fruits and vegetables. Once again, the wrapping material used in the study proved to be highly efficient in maintaining the quality during storage, since it slowed down the rate of the deterioration process.

Under non-isothermal conditions, the effective reaction rates "k_{eff}" multiplied by the cumulative storage time "t_{total}" at each storage period, as illustrated in Figure 1, was calculated from Eq. 10 and presented in Tables 4 and 5. At time = 2 hours, the firmness and quality index loss occurred at slower rates. At time = 5 hours, the loss continued in an increasing rate due to light effect. At the end of step 3 (77 hours), the quality degradation was much faster due to the effect of fluctuating temperature and light during every 12-hour period. During the last storage period (221 hours), the loss occurred at a slower rate at 10^0C in complete darkness. It is important to mention that wrapping film was beneficial to slow down the degradation rate throughout the entire storage duration.

Table 3. Kinetic parameters of wrapped eggplant at constant storage conditions.

Quality attributes	Storage Conditions	C_0	C_{eq}	Kinetic parameters		
				k(day^{-1})	R^2	Ea (KJ/mol)
Firmness	SC1	5.31	4.17	0.024	0.96	38.70
	SC2	5.31	2.67	0.071	0.99	
	SC3	5.31	4.37	0.022	0.95	41.80
	SC4	5.31	2.91	0.064	0.97	
Weight loss	SC1	0.00	0.62	0.073	0.97	43.64
	SC2	0.00	2.22	0.248	0.91	
	SC3	0.00	0.37	0.046	0.98	60.11
	SC4	0.00	1.85	0.167	0.96	
Total color difference	SC1	23.10	25.13	0.200	0.94	70.57
	SC2	23.10	28.11	0.506	0.99	
	SC3	23.10	24.42	0.094	0.97	73.01
	SC4	23.10	24.60	0.111	0.98	
Quality index	SC1	9.00	6.00	0.045	0.93	33.70
	SC2	9.00	5.00	0.064	0.94	
	SC3	9.00	6.00	0.037	0.88	41.84
	SC4	9.00	5.50	0.041	0.90	

SC1 = 10^0C (with light); SC2 = 30^0C (with light); SC3 = 10^0C (without light); SC4 = 30^0C (without light).

Weight loss and color changes

Under constant storage conditions, the experimental data fit a zero order model (Eq. 3) well as shown in Tables 2 and 3. Weight loss and color difference increased over time at different rates based on storage conditions. Maximum loss was observed with unwrapped samples stored at higher temperature with light exposure (k_{WL} = 2.095/day and k_{TCD} = 0.766/day).

As mentioned earlier, combining these two environmental factors together will irreversibly damage the fresh produce, hence, increasing its quality loss. When wrapping the eggplant, the rate of weight loss was reduced by eightfold compared to unwrapped samples ($k_{unwrapped}$ = 2.095/day and $k_{wrapped}$ = 0.248/day).

Table 4. Kinetic parameters of unwrapped eggplant at fluctuating storage conditions.

Quality attributes	Storage period (hours)	C_0	C_{eq}	Kinetic parameters
				$k_{eff}\ t_{total}$
Firmness	2	5.66	5.50	0.014
	5	5.66	5.32	0.035
	77	5.66	3.20	0.553
	221	5.66	1.38	1.297
Weight loss	2	0.00	0.30	0.141
	5	0.00	0.42	0.381
	77	0.00	5.03	5.560
	221	0.00	11.02	10.684
Total color difference	2	23.10	23.14	0.039
	5	23.10	23.20	0.098
	77	23.10	24.86	1.675
	221	23.10	25.46	2.268
Quality index	2	9.00	9.00	0.016
	5	9.00	8.50	0.041
	77	9.00	5.00	0.633
	221	9.00	3.50	1.101

The minimum rate for weight loss (k = 0.046/day) was registered with wrapped produce and storage at 10^{o}C in the dark. In contrast, wrapping material did not have any major effect on color attribute and the results revealed a slight reduction in the deterioration rate (at SC2) compared to unwrapping ($k_{unwrapped}$ = 0.766/day and $k_{wrapped}$ = 0.506/day). Using a similar calculation with other quality attributes, the activation energy for weight loss during light exposure were Ea = 12.91 and 43.64 KJ/mol for unwrapped and wrapped eggplant, respectively, whereas during the storage in darkness, Ea = 32.02 and 60.11 KJ/mol were needed to start the reactions within the food system. In terms of total color difference, Ea = 33.12 and 70.57 KJ/mol for unwrapped and wrapped samples, respectively, were obtained in the presence of light (Tables 2 and 3), however, in complete darkness, the activation energy needed was lower, with Ea = 60.06 and 73.01 KJ/mol, respectively. It could also be concluded that higher temperature and exposure to direct light accelerated the quality degradation, while lower temperature with the absence of light and wrapping the produce maintained better quality during storage.

Table 5. Kinetic parameters of wrapped eggplant at fluctuating storage conditions.

Quality attributes	Storage period (hours)	C_0	C_{eq}	Kinetic parameters $k_{eff}\ t_{total}$
Firmness	2	5.66	5.54	0.004
	5	5.66	5.48	0.011
	77	5.66	5.03	0.177
	221	5.66	4.56	0.309
Weight loss	2	0.00	0.02	0.014
	5	0.00	0.03	0.038
	77	0.00	0.63	0.575
	221	0.00	0.84	0.851
Total color difference	2	23.10	23.13	0.028
	5	23.10	23.18	0.078
	77	23.10	24.33	1.173
	221	23.10	24.79	1.737
Quality index	2	9.00	9.00	0.004
	5	9.00	9.00	0.011
	77	9.00	8.00	0.180
	221	9.00	7.00	0.402

Tables 4 and 5 showed the changes in quality of eggplant as affected by fluctuating environmental factors during handling. For both weight loss and color difference, the degradation process was much faster during the third storage period (77 hours) where most of temperature and light fluctuation occurred. Applying wrapping films reduced the weight loss during storage but did not change the deterioration rate in terms of color.

Prediction of quality loss

Studying kinetics was necessary to predict the changes in postharvest quality attributes and the influence of temperature and light on the studied crop during storage. Table 6 presented the cumulative percent quality loss of predicted versus measured values of different quality parameters obtained at fluctuating conditions. The majority of losses happened during the 77-hour period of storage. At the end of the entire storage duration, the observed quality loss for unwrapped samples were 75.62% for firmness, 11.02% for weight loss, 10.19% for color and 61.11% for quality index. These losses were reduced significantly ($P < 0.05$) through wrapping the fresh produce during storage. The percent quality losses were as follows: 19.43% for firmness, 0.84% for weight loss, 7.31% for color and 22.22% for quality index. The experimental data obtained at fluctuating conditions were plotted against the prediction model values (Eq. 8 and 9). Predicted quality loss was in line with observed data for studied eggplant. These results confirmed the validation of the predictive models in response to variable environmental factors used in the study.

Table 6. Cumulative percent quality loss of predicted against observed values obtained under fluctuating conditions.

Quality attributes	Storage period (hours)	Percent quality loss (Unwrapped)		Percent quality loss (Wrapped)	
		Observed	Predicted	Observed	Predicted
Firmness	2	2.92	1.39	2.12	0.40
	5	6.01	3.44	3.18	1.09
	77	43.55	42.48	11.13	16.22
	221	75.62	72.66	19.43	26.58
Weight loss	2	0.30	0.14	0.02	0.01
	5	0.42	0.38	0.03	0.04
	77	5.03	5.56	0.63	0.58
	221	11.02	10.68	0.84	0.85
Total color difference	2	0.15	0.27	0.13	0.09
	5	0.44	0.41	0.36	0.27
	77	7.59	6.46	5.32	4.67
	221	10.19	11.62	7.31	8.74
Quality index	2	0.00	1.59	0.00	0.40
	5	5.56	4.02	0.00	1.09
	77	44.44	46.90	11.11	16.47
	221	61.11	66.75	22.22	33.10

Conclusion

In this study, the quantification of postharvest losses of the quality attributes in dark purple eggplant as affected by constant and fluctuating storage temperature and light was presented. Higher losses occurred at 30ºC under light exposure during a 10-day period. Storage at higher temperatures further decreased the quality in fresh vegetables. The lower storage temperature (10ºC) delayed the quality changes over time. Similarly, light has a great influence on degrading quality, which was the same as high temperature under complete darkness. The utilization of wrapping material extended shelf life and maintained the quality of studied samples during the entire storage duration. Kinetic models were very useful for measuring and predicting the magnitude of change in quality attributes during constant and fluctuating storage. This study presented an important tool that allowed the closing up of major data gaps in the knowledge of quantifying postharvest quality changes of fresh eggplant as affected by temperature and light abuse during handling practices, aiming to recommend best strategies to reduce postharvest losses of fruits and vegetables.

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REFERENCES

Ayala, F., Echavarri, J. F., Olarte, C. and Sanz, S. 2009. Quality characteristics of minimally processed leek packaged using different films and stored in lighting conditions. International Journal of Food Science and Technology, 44(7): 1333-1343.

Boulekbache-Makhlouf, L., Medouni, L., Medouni-Adrar, S., Arkoub, L. and Madani, K. 2013. Effect of solvents extraction on phenolic content and antioxidant activity of the byproduct of eggplant. Industrial Crops and Products, 49: 668-674.

Bouzo, C. A., Travadelo, M. and Gariglio, N. F. 2012. Effect of Different Packaging Materials on Postharvest Quality of Fresh Fig Fruit. International Journal of Agriculture and Biology, 14(5): 821-825.

Cervera, S. S., Olarte, C., Echavarri, J. and Ayala, F. 2007. Influence of exposure to light on the sensorial quality of minimally processed cauliflower. Journal of Food Science, 72(1): S12-S18.

Concellón, A., Anon, M. C. and Chaves, A. R. 2007. Effect of low temperature storage on physical and physiological characteristics of eggplant fruit (Solanum melongena L.). Lwt-Food Science and Technology, 40(3): 389-396.

Concellón, A., Zaro, M. J., Chaves, A. R. and Vicente, A. R. 2012. Changes in quality and phenolic antioxidants in dark purple American eggplant (Solanum melongena L. cv. Lucía) as affected by storage at 0°C and 10°C. Postharvest Biology and Technology, 66(0): 35-41.

Conviron. 2014. http://www.conviron.com.

Cruz, R. M. S., Vieira, M. C. and Silva, C. L. M. 2009. Effect of cold chain temperature abuses on the quality of frozen watercress (Nasturtium officinale R. Br.). Journal of Food Engineering, 94(1): 90-97.

FAO. 2007. Safety and quality of fresh fruit and vegetables: a training manual for trainers. New York and Geneva: United Nations.

FAO. 2013. FAO Statistical Yearbook: World Food and Agriculture (S. division, Trans.). Rome: Food and Agriculture Organization of the United Nations.

Fennema, O. R. and Tannenbaum, S. R. 1996. Introduction to food chemistry. New York: Marcel Dekker, Inc.

Florkowski, W. J., Shewfelt, R. L., Brueckner, B. and Prussia, S. E. 2014. Postharvest Handling: A Systems Approach (Third ed.): Elsevier Science Publishing Co Inc.

Giannakourou, M. C. and Taoukis, P. S. 2003. Kinetic modelling of vitamin C loss in frozen green vegetables under variable storage conditions. Food Chemistry, 83(1): 33-41.

Gross, K. C., Yi Wang, C. and Saltveit, M. 2014. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks: USDA, Agriculture Handbook Number 66.

Hanson, P. M., Yang, R. Y., Tsou, S. C. S., Ledesma, D., Engle, L. and Lee, T. C. 2006. Diversity in eggplant (Solanum melongena) for superoxide scavenging activity, total phenolics, and ascorbic acid. Journal of Food Composition and Analysis, 19(6-7): 594-600.

Heldman, R. D. 2011. Food preservation process design: Elsevier Inc.

Hodges, R. J., Buzby, J. C. and Bennett, B. 2011. Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. Journal of Agricultural Science, 149: 37-45.

Hoogerwerf, A., Simons, A. E. and Reinders, M. P. 1994. A systems view on horticultural distribution applied to the postharvest chain of cut flowers. Agricultural Systems, 44(2): 163-180.

Hung, D. V., Tong, S., Tanaka, F., Yasunaga, E., Hamanaka, D., Hiruma, N. and Uchino, T. 2011. Controlling the weight loss of fresh produce during postharvest storage under a nano-size mist environment. Journal of Food Engineering, 106(4): 325-330.

ISO. 2014. International Standard Organization. from http://www.iso.org

Janave, M. T. and Sharma, A. 2005. Extended storage of gamma-irradiated mango at tropical ambient temperature by film wrap packaging. Journal of Food Science and Technology-Mysore, 42(3): 230-233.

Kader, A. A. 2002. Postharvest Technology of Horticutlural Crops.

Kader, A. A. and Rolle, S. R. 2004. The role of post-harvest management in assuring the quality and safety of horticultural produce (Vol. 152). Rome: Food and Agriculture Organization of the United Nations.

Lana, M. M., Tijskens, L. M. M. and van Kooten, O. 2005. Effects of storage temperature and fruit ripening on firmness of fresh cut tomatoes. Postharvest Biology and Technology, 35(1): 87-95.

Liu, C. H. and Liu, Y. 2014. Effects of Elevated Temperature Postharvest on Color Aspect, Physiochemical Characteristics, and Aroma Components of Pineapple Fruits. Journal of Food Science, 79(12): C2409-C2414.

Loose, L. H., Maldaner, I. C., Heldwein, A. B., Lucas, D. D. P. and Righi, E. Z. 2014. Maximum evapotranspiration and crop coefficient of eggplant cultivated in plastic greenhouse. Revista Brasileira De Engenharia Agricola E Ambiental, 18(3): 250-257.

Lopez, J., Uribe, E., Vega-Galvez, A., Miranda, M., Vergara, J., Gonzalez, E. and Di Scala, K. 2010. Effect of Air Temperature on Drying Kinetics, Vitamin C, Antioxidant Activity, Total Phenolic Content, Non-enzymatic Browning and Firmness of Blueberries Variety OA ' Neil. Food and Bioprocess Technology, 3(5): 772-777.

Luning, A. P. and Marcelis, J. W. 2009. Food quality management: Technicological and managerial principles and practices: Wageningen Academic Publishers.

Maftoonazad, N. and Ramaswamy, H. S. 2008. Effect of pectin-based coating on the kinetics of quality change associated with stored avocados. Journal of Food Processing and Preservation, 32(4): 621-643.

Martinez-Sanchez, A., Tudela, J. A., Luna, C., Allende, A. and Gil, M. I. 2011. Low oxygen levels and light exposure affect quality of fresh-cut Romaine lettuce. Postharvest Biology and Technology, 59(1): 34-42.

Matsubara, K., Kaneyuki, T., Miyake, T. and Mori, M. 2005. Antiangiogenic activity of nasunin, an antioxidant anthocyanin, in eggplant peels. Journal of Agricultural and Food Chemistry, 53(16): 6272-6275.

Mebratie, M. A., Woldetsadik K., Ayalew, A. and Haji, J. 2016. Influence of Packaged Transportation on Shelf Life and Quality of Banana (*Musa* spp) Fruits. Journal of Postharvest Technology, 04 (01): 006-015.

Mishra, B. B., Gautam, S. and Sharma, A. 2012. Browning of fresh-cut eggplant: Impact of cutting and storage. Postharvest Biology and Technology, 67: 44-51.

Moretti, C. L., Mattos, L. M., Calbo, A. G. and Sargent, S. A. 2010. Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: A review. Food Research International, 43(7): 1824-1832.

Nourian, F., Ramaswamy, H. S. and Kushalappa, A. C. 2003. Kinetics of quality change associated with potatoes stored at different temperatures. Lebensmittel-Wissenschaft Und-Technologie-Food Science and Technology, 36(1), 49-65.

Okmen, B., Sigva, H. O., Mutlu, S., Doganlar, S., Yemenicioglu, A. and Frary, A. 2009. Total Antioxidant Activity and Total Phenolic Contents in Different Turkish Eggplant (*Solanum Melongena* L.) Cultivars. International Journal of Food Properties, 12(3): 616-624.

Olarte, C., Sanz, S., Echavarri, J. F. and Ayala, F. 2009. Effect of plastic permeability and exposure to light during storage on the quality of minimally processed broccoli and cauliflower. Lwt-Food Science and Technology, 42(1): 402-411.

Pyrotis, S., Abayomi, L., Rees, D. and Orchard, J. 2011. Effect of Temperature and Humidity on Strawberry Firmness at Two Different Sites in the Huelva Region of Spain. XXVIII International Horticultural Congress on Science and Horticulture for People (Ihc2010): International Symposium on Berries: From Genomics to Sustainable Production, Quality and Health, 926: 567-570.

Sanz, S., Olarte, C., Ayala, F. and Echavarri, J. F. 2009. Evolution of Quality Characteristics of Minimally Processed Asparagus During Storage in Different Lighting Conditions. Journal of Food Science, 74(6): S296-S302.

Sun, W. Q., Wang, D. B., Wu, Z. Z. and Zhi, J. R. 1990. Seasonal Change of Fruit Setting in Eggplants (*Solanum melongena* L) Caused by Different Climatic Conditions. Scientia Horticulturae, 44(1-2): 55-59.

Tiwari, B. K., Brunton, N. P. and Brennan, C. S. 2013. Handbook of plant food phytochemicals: sources, stability and extraction. Oxford, UK: Wiley-Blackwell.

Xiao, Z. L., Lester, G. E., Luo, Y. G., Xie, Z. H., Yu, L. L. and Wang, Q. 2014a. Effect of light exposure on sensorial quality, concentrations of bioactive compounds and antioxidant capacity of radish microgreens during low temperature storage. Food Chemistry, 151: 472-479.

Xiao, Z. L., Luo, Y. G., Lester, G. E., Kou, L. P., Yang, T. B. and Wang, Q. 2014b. Postharvest quality and shelf life of radish microgreens as impacted by storage temperature, packaging film, and chlorine wash treatment. Lwt-Food Science and Technology, 55(2): 551-558.

Zaro, M. J., Chaves, A. R., Vicente, A. R. and Concellon, A. 2014. Distribution, stability and fate of phenolic compounds in white and purple eggplants (*Solanum melongena* L.). Postharvest Biology and Technology, 92: 70-78.