

Optimization of Postharvest Handling of Eggplant Using the Taguchi Technique

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Abstract
Taguchi technique was used to optimize postharvest handling process to minimize quality loss of fresh eggplant (*Solanum melongena* L.). To date Taguchi approach has been widely used in various subject areas, but no application to postharvest quality has been reported until the present time with the exception of some previous work conducted by the same authors in 2015. Measuring postharvest losses is an essential operational strategy to enhance postharvest management and to curtail quality loss of fresh horticultural commodity. In this study, Taguchi approach was able to quantify the quality for all combinations of environmental factors/levels (T, RH, Light & time) used in this experiment and were expressed in terms of Signal-to-Noise ratios. For each quality attribute, the highest ratio was determined which corresponded to the least variability of the noise factors around the desired target of this attribute. Taguchi method was successfully used to quantify and predict postharvest quality losses in response to different combinations of environmental factors and it identified optimum conditions for handling and storage of eggplant. As a result, this technique can enhance postharvest quality management from field to fork and alleviate quality loss of fresh fruits and vegetables. This technique could, therefore be recommended as a robust design of quality in postharvest technology and could be applied to many other crops exposed to various environmental conditions.
Keywords: Eggplant, postharvest, quality loss, optimization, Taguchi technique, Signal-to-Noise ratio.

1. Introduction

Fresh fruits and vegetables are living systems that continue to be active metabolically after harvest (Gajewski et al. 2009; Kader and Rolle, 2004). They readily lose their quality if not handled properly as they move from farm to fork. Eggplant (*Solanum melongena* L.), commonly known also as aubergine, is best grown in tropical and sub-tropical areas (Concellón et al. 2007; Loose et al. 2014) and is considered among the most important horticultural crops in terms of its economic and nutritional values worldwide (FAO, 2013; Okmen et al. 2009). According to recent statistics from the Food and Agriculture Organization (FAO), the global production of eggplant was 48MT in 2012 occupying an area of 1,853,023 ha. Usually eggplants are egg-shaped or globular and have bright green calyces, firm texture and dark purple skins (Gross et al. 2014). They are highly perishable plant produce and can undergo varying degrees of stress during the postharvest handling process if exposed to undesirable environmental conditions, resulting in major quality and quantity losses (Gajewski et al. 2009; Ghidelli et al. 2014). The major environmental influences that affect the quality of foods include the temperature, the humidity and the direct sunlight (Luning and Marcelis, 2009). In tropical countries, cold storage facilities are limited and below the required capacity. Long-term storage is not practiced for almost all kind of fruits and vegetables (Smith et al. 2000; Van Dijk and Trienekens, 2012). In most of those countries, postharvest infrastructure (cold storage facilities, refrigerated transport, packinghouses, etc.) are either scarce or not functioning properly (Smith et al. 2000; Van Dijk and Trienekens, 2012).

Temperature can be detrimental for quality of fresh produce (Concellón et al. 2007). Kader (2002) stated that temperature is the major environmental factor that affects the deterioration rate of non-chilling sensitive commodities. Exposing harvested commodity to elevated temperature can initiate a favorable environment for pathogens to grow and cause serious safety issues for consumers. Moreover, storing crops at high temperatures was demonstrated to be the driver behind accelerated respiration and transpiration rates, which can further deteriorate the postharvest quality of the produce. Precooling the commodity immediately after harvest can alleviate the effect of high temperature on crop losses and extend their shelf life (Cortbaoui et al. 2005; Vigneault et al. 2007). Relative humidity is another environmental factor that can cause serious quality loss to fresh commodities. The rate of water loss from the fruits and vegetables is greatly dependent on the percent of moisture present in the surrounding air; the lower the relative humidity the higher water loss (Kader, 2002; Watkins, 2003). Undesirable humidity results not only in direct quantitative losses (weight loss) but also in qualitative losses such as wilting, shriveling and softening (FAO, 2007; Hung et al. 2011). The recommended commercial storage for eggplant is set generally for less than 14 days at 10-12^{0}C and 90 to 95%RH (Gross et al. 2014). Light is also one of the most important factors affecting the phytonutrient content in many produces rich in antioxidants (like eggplant) and can cause harmful effects on produce quality (Alcock and Bertling, 2013; Xiao et al. 2014). Sanz et al. (2009) have shown that accelerated degradation in quality and reduced shelf life was observed with stored asparagus under continuous lighting conditions. Further studies carried out by other researchers (Braidot et al. 2014; Martinez-Sanchez et al. 2011) revealed that light could also promote browning of fresh-cut lettuce.

Quality has multidimensional perspectives that underlines the various definitions and concepts of quality based on different views among end users (Luning and Marcelis, 2009). Quality can be seen from a product-based view as a function of a specific measurable variable, from a user-based view as what the consumer wants and from a value-based view as the relationship of usefulness to price (Batt, 2006; Luning and Marcelis, 2009). Defining quality is very difficult and complex and, therefore, there is no one definition that describes quality (Luning and Marcelis, 2009; Roy, 2001). A commonly accepted definition is that "*quality is meeting or exceeding customer and consumer expectations*" (Luning and Marcelis, 2009). In the case of fresh fruits and vegetables, the consumer's quality perception is mainly focused on intrinsic quality attributes such appearance, color, size, shape, firmness and freshness (Florkowski et al. 2014). Food quality management is therefore essential to ensure the performance of a product and production quality. The concept of quality management was initiated by Walter Shewhart and modified by Edward Deming to help companies increase their quality and productivity (Luning and Marcelis, 2009). The Deming's philosophy was to increase product quality by reducing the uncertainty and variation in product development and process design (PMBOK, 2013). In addition to other philosophers such as Juran and Crosby, another guru in quality management, Genichi Taguchi, provided a specific tool to improve the product as well as the process by which it is made (Luning and Marcelis, 2009; PMBOK, 2013).

The Taguchi method is an approach associated with robust quality management that combines engineering and statistical methods in order to reduce commodity loss and improve its quality (Ross, 1996; Taguchi, 1993). Taguchi stated that maintaining the high quality of a commodity would require reducing variations around the "target" by achieving consistency of performance (Roy, 2001). For him, every commodity has a target value. Therefore, minimizing quality loss of a product could be achieved through reducing the variability around a target instead of just meeting customer specifications. For the purpose of this study, this variability is caused by environmental factors (temperature, light and relative humidity) throughout the postharvest handling process of the fresh produce. The Taguchi technique is a form of "design of experiment" or DOE (Roy, 2001). For this, Taguchi has developed several fractional factorial experiments (FFE) matrices that could be used for special applications. This method has generally been adopted to optimize the design parameters of a process and significantly minimize the overall testing time and experimental costs. Taguchi showed that FFE could be used not only to maintain quality, but also to quantify it (Roy, 2001). For this purpose, he created a number of special orthogonal arrays, each of which is used for a number of experimental situations (Maghsoodloo et al. 2004).

To analyze the quality loss of a commodity, Taguchi had developed the signal-to-noise *(S/N)* ratio (Ross, 1996; Roy, 2001; Wang et al. 2012). This ratio helps to assure a design that is robust under the influence of noise or environmental factors (Taguchi, 1993). In other words, the best product will only respond to signals and will be immune to noise factors (Sadeghi et al. 2012). Therefore, the goal of the quality loss reduction effort can be stated as targeting to maximize the signal-to-noise *(S/N)* ratio for the respective product.

To date the Taguchi approach has been widely and successfully used in various subject areas. In general, Taguchi technique can be used for 2 major applications namely (1) determination of optimal parameters of a production process and (2) quantification of quality loss of a product. Sadeghi et al. (2012) had applied the Taguchi approach in environmental sciences where they assessed soil erosion as affected by soil texture, slope, aspect and vegetation cover. Other researchers (Oztop et al. 2007) used the Taguchi technique in food engineering to optimize the microwave frying process of potato slices. The Taguchi method was also recommended in biotechnology field to optimize virus yields for vaccine production (Trabelsi et al. 2006). From literature, the Taguchi approach was found to be successfully applied in construction too to determine the best conditions to obtain the physical properties that will lead to the most durable concretes (Tukmen et al. 2008). This approach was also used in many other research areas including energy (Zeng et al. 2010), aerospace (Singaravelu et al. 2009), sports (Burton et al. 2010) and manufacturing (Dingal et al. 2008; Emadi et al. 2008). Only one application of the Taguchi approach to postharvest quality loss has been reported until the present time. The authors of this study used the Taguchi approach to quantify quality loss in fresh cucumber as affected by different environmental factors (Cortbaoui and Ngadi, 2015). The current research attempted to use the Taguchi technique to reduce the variations of extrinsic factors (temperature, relative humidity, and light) over time on characteristic properties or intrinsic quality attributes of eggplant by optimizing postharvest handling process to maintain the highest quality and minimize losses.

2. Objectives

The main objective of this study was to enable the identification of optimum environmental conditions to minimize postharvest loss along the food supply process. This was achieved through (1) finding the highest signal-to-noise ratio for different storage combinations using the Taguchi approach and (2) acquiring the best factor/level combinations for each quality attribute for eggplant.

3. Materials and methods

3.1 Plant material and storage simulation

Samples were obtained from Lufa farms (Montreal, Canada), a local year-round supplier of fruits and vegetables. The samples were labeled and separated into experimental units of similar quantity for further analysis. A storage simulation experiment was carried out afterwards in controlled environment chambers (Conviron Inc., PGR15, Manitoba, Canada) to evaluate postharvest quality loss of fresh produce stored at different conditions of temperature (T), relative humidity (RH) and light according to the Taguchi design. 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 temperature in the range between 10 and 45^{o}C. Airflow inside the unit was distributed uniformly upward using 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 64750 lux using fluorescent and incandescent lamps. This is the typical average of light intensity during a sunny day.

3.2 Experimental design

The Taguchi experimental design was developed and carried out using the JMP v.11 statistical software. The first step in this design of experiment (DOE) was to select the key environmental factors along with their levels. These factors were responsible for causing variability around the quality target of each produce during the handling process. For the purpose of this study, four factors including storage temperature (^{0}C), age of produce corresponding to the time of storage (days), exposure to direct light related to the presence or absence of luminosity during 12 hours/day and relative humidity or RH (%) were selected. As demonstrated in Table 1, three different levels were chosen for each factor as follow: temperature (10, 20 and 30^{o}C), relative humidity (75, 85 and 95%), daily light (0, 12 and 24 hours) and time (1, 5 and 10 days). Based on Taguchi technique, the experiment used 4 three-level factors and an L-9 orthogonal array. A full factorial experimental design gives 3^4 = 81 possible combinations or experimental trials. Using the fractional factorial in Taguchi approach, only 9 experiments with different combinations were needed and conducted as shown in Table 2. To seek out the best design among many combinations, the JMP statistical software was used. The entire experiment was conducted in three replicates.

Table 1. Selected factors and their levels recommended for this study.

Factor	Level		
	1	2	3
A: Temperature (^{0}C)	10	20	30
B: Time (days)	1	5	10
C: Humidity (%)	75	85	95
D: Light	No Light	12hrs. Light / no Light	Light

Table 2. Different combinations according to Taguchi L-9 orthogonal array.

Test	Combination				Factor			
					Temperature	Time	Humidity	Light
Test 1	1	1	1	1	10	1	75	No
Test 2	1	2	2	2	10	5	85	No/Yes
Test 3	1	3	3	3	10	10	95	Yes
Test 4	2	1	2	3	20	1	85	Yes
Test 5	2	2	3	1	20	5	95	No
Test 6	2	3	1	2	20	10	75	No/Yes
Test 7	3	1	3	2	30	1	95	No/Yes
Test 8	3	2	1	3	30	5	75	Yes
Test 9	3	3	2	1	30	10	85	No

An analysis of signal-to-noise ratio was carried out to evaluate the results. For eggplant, quality attributes such as weight loss and total color difference have “smaller the better” quality characteristics since the reduction of postharvest loss is greater when the produce still maintains its fresh color, and looses less moisture during handling. However, quality parameters like firmness and quality index were best desired to have “larger the better” type of measurement because the consumer will always prefer to purchase a firmer and higher quality eggplant. Subsequently, the signal-to-noise ratio was computed based on the following formulas (Ross, 1996; Roy, 2001):

$$\frac{S}{N} = -10Log_{10}\left(\frac{1}{n}\sum\frac{1}{y_i^2}\right) \text{ for larger the better} \quad (1)$$

and

$$\frac{S}{N} = -10Log_{10}\left(\frac{1}{n}\sum y_i^2\right) \text{ for smaller the better} \quad (2)$$

where *"n"* is the number of observations or replicates of the particular commodity under the same experimental conditions, and "*y*" represents the respective values. Here *"y"* is the measured quality attribute for each experimental test. To determine the optimal conditions for minimizing quality loss, the mean S/N ratio of each factor (A, B, C, D) in each level (1, 2, 3) was computed using equation 3 (Sadeghi et al., 2012) and the maximum value of the mean S/N ratio of a certain factor among three levels indicated the optimum conditions.

$$(M)_{Factor=I}^{Level=i} = \frac{1}{n_{Ii}}\sum_{j=1}^{n_{Ii}}\left[\left(\frac{S}{N}\right)_{Factor=I}^{Level=i}\right]_j \quad (3)$$

For each quality attribute, an analysis of variance (ANOVA) followed by a Tukey-Kramer HSD test was conducted to statistically evaluate and compare the effect of different levels of environmental factors on postharvest quality of the produce. Verification and validation experiments were then conducted using optimum conditions.

3.3 Quality evaluation

Both initial (used as control) and final qualities after each storage combination were evaluated. The 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 (Table 3) for eggplant summarizing all these parameters was determined and the total score for each parameter was calculated.

Table 3. 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.

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:

$$\Delta E = \sqrt{\left(\Delta L^2\right)+\left(\Delta a^2\right)+\left(\Delta b^2\right)} \quad (4)$$

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

Another important quality attribute such as weight loss *(WL)* was quantified using the formula:

$$WL = 100 * \left(W_i - W_f\right) / W_i \qquad (5)$$

where W_i and W_f were the initial and the final weight of the produce calculated before and after treatment.

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 50 N. 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). For each replicate of the experiment, a total of three readings were acquired for every sample and an average firmness was registered.

4. Results and discussion

4.1 Signal-to-Noise ratios

Table 4 showed the highest and lowest S/N ratios (boldfaced) for each quality attribute among all different combinations used in the Taguchi design. For eggplant, test 1 resulted in higher S/N ratio for all quality parameters. Similarly, storing the eggplant for one day at elevated daytime temperatures and full light was also shown to maintain its color, weight, firmness and overall quality index. The results also revealed that the produce continued to maintain its fresh color (S/N = 2.95) after 5 days of storage at 10°C and 85% RH under 12 hours of daily light. However, storage for longer period (10 days) at 20°C caused a significant ($P < 0.05$) color loss (S/N = -15.61) when the eggplant was exposed to the same amount of light daily. From Table 4, a longer and continuous exposure to light dramatically reduced the S/N ratio as shown at 10°C and 30°C (tests 3 and 8). In terms of weight reduction during handling, factors such as high temperature, longer storage duration, low relative humidity in the surrounding environment and permanent light exposure were responsible for increased weight loss of eggplant (S/N = -27.15). Firmness response was decreased under 30°C after 10 days (S/N = 2.59) and was not affected by the light factor. Similar to weight loss, the general quality index of the eggplant was affected by all noise factors as demonstrated in test 8 (S/N = 2.01).

Table 4. Results of signal-to-noise ratios for all test combinations.

Test	Factors				S/N *for*			
	Temperature (°C)	Time (days)	Relative Humidity (%)	Light	Total Color Difference	Weight Loss	Firmness	Quality Index
Test 1	10	1	75	No	**4.49***	**25.31***	**16.05***	**19.08***
Test 2	10	5	85	No/Yes	2.95	-16.90	8.64	13.86
Test 3	10	10	95	Yes	-14.09	-14.54	4.42	13.98
Test 4	20	1	85	Yes	1.35	3.90	15.07	16.84
Test 5	20	5	95	No	-10.73	-12.87	6.75	14.31
Test 6	20	10	75	No/Yes	**-15.62****	-13.58	3.11	11.21
Test 7	30	1	95	No/Yes	3.76	11.50	14.45	16.31
Test 8	30	5	75	Yes	-14.99	**-27.16****	2.68	**2.01****
Test 9	30	10	85	No	-3.90	-20.03	**2.60****	9.20

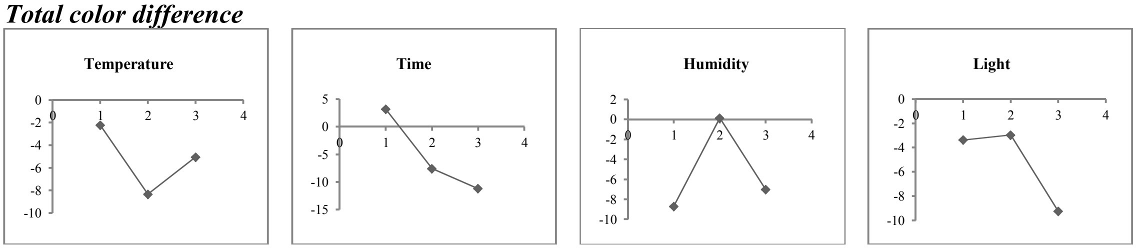
* The highest S/N ratio
** The lowest S/N ratio

4.2 Optimum conditions

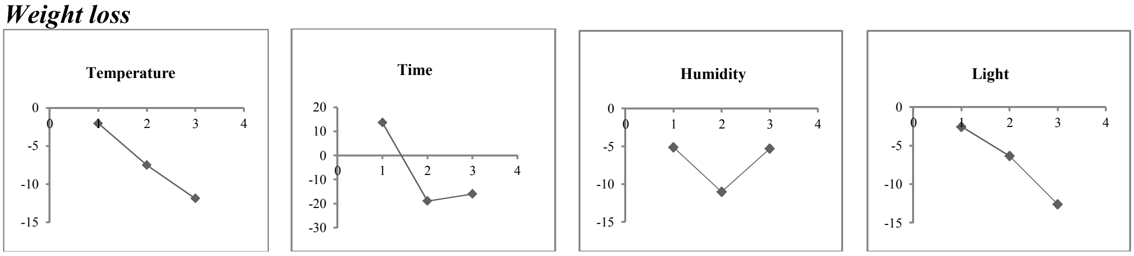
In this study, the optimization of the postharvest handling process seeks to reduce variability caused by environmental or noise factors in order to reduce quality loss of fresh commodity. By substituting S/N ratios from equations 1 and 2 into equation 3, the mean ratios for each factor in their different levels was obtained as illustrated in Figure 1. The results revealed that continuous exposure of direct light has significantly ($P < 0.05$) decreased the quality of the produce during storage. Similar effect to light, storing the eggplant at 75% RH showed a significant ($P < 0.05$) quality loss in terms of color change, firmness and general quality index. Therefore, low environmental humidity during postharvest handling is not suitable to maintain fresh quality of eggplant. Similar results were stated by Zaro et al. (2014). Significant ($P < 0.05$) difference was also noticed between the three temperatures; storing the eggplant at elevated temperature (30°C) caused major weight loss as well as losses in firmness and quality index compare to lower temperature (10°C) with the exception of color where major loss happened at 20°C. In addition to all the above, the factor time has demonstrated to be a major driver for quality degradation during postharvest process. Significant ($P < 0.05$) increase in loss occurred after 5 days of harvesting and continued to increase for longer storage period. However, a different scenario was observed in the case of weight loss, where, the eggplant has shown a higher reduction in its weight after only 5 days of storage.

Figure 1. Graphical representation of means S/N ratios for all factors at different levels.

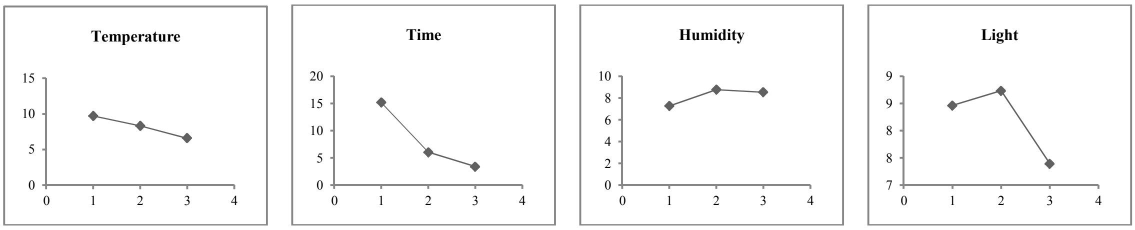
Total color difference



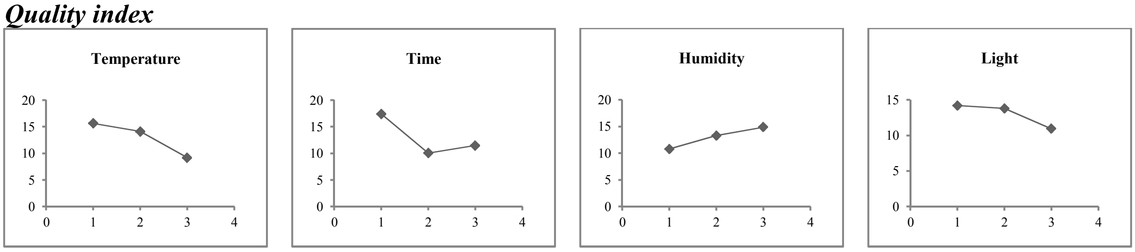
Weight loss



Firmness



Quality index



By selecting the highest mean ratios (peak values) for the same factor among its 3 levels (Figure 1), this allowed for the determination of the optimum conditions for handling of eggplant that best retain their quality. Therefore, the optimal environmental settings to minimize color loss for the study crop were at 10^{o}C and 85% RH for 1 day under an interval of 12 hours of lightness/darkness daily. In terms of weight loss, higher S/N ratios for eggplant resulted from combining A/1-B/1-C/3-D/1 together. From the results obtained, the optimum conditions to provide firmer produce during postharvest handling process were achieved through storing the produce for 1 day at 10^{o}C and 85% RH with 12 hours daily light. Similar to optimal conditions of commercial storage for fresh eggplant (Gross et al., 2014), the Taguchi design recommended storing the produce for 1 day at 10^{o}C and 95% RH with no light exposure in order to obtain the best quality index of this crop during handling. It was also important to mention that the second best storage conditions to curtail postharvest quality loss and to maintain high quality index were found under storage for 10 days at 20^{o}C and 85% RH with a rotation of 12 hours daily light (A/2-B/3-C/2-D/2).

4.3 Verification experiment

A verification or validation experiment is usually the final step in any DOE. Therefore, in this study, a test including all combinations at optimum conditions of noise factors and their levels in response to different signals of quality loss was conducted in order to validate the Taguchi approach during the postharvest handling process. Confirmation experiments were carried out in triplicates for each quality attribute. As shown in Table 5, all S/N ratios obtained when storing the eggplant under optimum conditions not used previously in this Taguchi design were higher compared to the best test combinations used in L-9 orthogonal arrays. Storing the eggplant for 1 day after harvesting at a combination of 10^{0}C, 85% RH and 12 hours of light interval was shown to be a better strategy (S/N = 4.90) compared to 75% RH and absence of light (S/N = 4.48) for retaining less color difference and higher firmness of the produce. Likewise, maintaining the highest quality index and lowest weight loss for eggplant was found at A1/B/1/C2/D1 rather than A1/B/1/C1/D1 combinations.

Table 5. Response of S/N ratios of best combination used in Taguchi experiments and optimum condition recommended by Taguchi design.

	Factor				*S/N*
	Temperature (^{o}C)	**Time (days)**	**Relative Humidity (%)**	**Light**	
Total Color Difference					
Test 1	10	1	75	No	4.48
Optimum Conditions	10	1	85	No/Yes	4.90
Weight Loss					
Test 1	10	1	75	No	25.30
Optimum Conditions	10	1	95	No	26.13
Firmness					
Test 1	10	1	75	No	16.04
Optimum Conditions	10	1	85	No/Yes	16.60
Quality Index					
Test 1	10	1	75	No	19.08
Optimum Conditions	10	1	95	No	19.08

Those results confirmed that the Taguchi technique was valid and excellent tool that allowed the researchers to gain more knowledge on better or alternative environmental handling conditions for fresh eggplant aiming to reduce its quality loss after harvest.

5. Conclusions

Taguchi approach was used as a new technique to optimize the postharvest handling process and to minimize quality loss of fresh eggplant. This approach enabled the researchers to express the quality of eggplant for all combinations used in this experiment in terms of S/N ratios. The eggplant continued to maintain its fresh color (S/N = 2.95) after 5 days of storage at 10^{o}C and 85% RH under 12 hours of daily light. However, storage for longer period (10 days) at 20^{o}C caused a significant color loss (S/N = -15.61). Factors such as high temperature, longer storage duration, low relative humidity and permanent light exposure were responsible for increased weight loss of eggplant (S/N = -27.15). Firmness response was decreased under 30^{o}C after 10 days (S/N = 2.59) and was not affected by the light factor. Similar to weight loss, the quality index of the eggplant was affected by all noise factors (S/N = 2.01). The Taguchi method was proved to be able to identify optimum conditions of environmental or uncontrollable factors throughout the handling process of eggplant. Postharvest quality management is very complex, however, the Taguchi approach was an excellent statistical tool to manage the supply chain settings in a holistic manner rather than segregating it into independent segments. Consequently, this technique can enhance postharvest quality management from field to fork and alleviate quality loss of fresh fruits and vegetables. Finally, the Taguchi method could be recommended as a robust design of quality in postharvest technology and could be applied to many other crops exposed to various environmental conditions not studied in this work.

Recommendations for future studies include applying Taguchi's approach to measure postharvest losses of other fresh horticultural crops, as well as applying it to optimize postharvest handling practices as affected by other factors and levels such as: farm and farmer related factors, level of mechanization, distance to storage, quality of storage, processing plant related factors, quality of supply chain, use of standards and grading, firm and operator related factors, quality of packaging, transportation, retail outlet and manager related factors, quality of logistics and inventory control, and biological factors (respiration, transpiration, ethylene).

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