Journal of Sensory Studies ISSN 0887-8250

METHODOLOGY FOR SENSORY SHELF-LIFE ESTIMATION: A REVIEW

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Accepted for Publication April 5, 2012

doi:10.1111/j.1745-459X.2012.00383.x

ABSTRACT

When talking about shelf life of foods, in the vast majority of cases we are talking about sensory shelf life of foods. The review presents an overview of the published research over the past decades classified according to the following topics: (1) cut-off point methodology (arbitrary and regression-based cut-off points); (2) methods based on product failure or consumers' rejection (failure with no censorship, logistic regression and survival analysis); (3) accelerated studies; and (4) other topics and further research.

PRACTICAL APPLICATIONS

Going through the aisles of the food and beverage sections of a supermarket shows that the number of food products whose shelf life is dependent on their sensory properties is far greater than those products whose shelf life depends on microbiological and/or nutritional properties. The present review allows researchers and practitioners to count on a summary of the salient research articles published on the theme of sensory shelf life. Articles which deal with methodological and design issues are presented, together with a critical review of articles where poor methodology has been applied.

INTRODUCTION

The Institute of Food Science and Technology (IFST) Guidelines (IFST 1993) defined shelf life as the time during which the food product will: (1) remain safe; (2) retain desired sensory, chemical, physical and microbiological characteristics; and (3) comply with any label declaration of nutritional data when stored under the recommended conditions. This definition identifies the key factors that must be considered when assessing shelf life. The ASTM E2454 Standard (2005) defines sensory shelf life (SSL) as: ". . . the time period during which the products' sensory characteristics and performance are as intended by the manufacturer. The product is consumable or usable during this period, providing the end-user with the intended sensory characteristics, performance, and benefits."

The shelf-life limits of some of the factors mentioned in the definitions are defined at a laboratory level without the intervention of sensory analysis. For example, a central issue in declaring a food to be safe is that it must be free of pathogenic bacteria and this can be assessed by standard microbiological analysis. Another example is Vitamin D enriched milk which must comply with a certain concentration measured in an analytical laboratory.

Once the sanitary and nutritional hurdles have been overcome, the remaining barrier depends on the sensory properties of the product (Hough 2010). It could be argued that chemical or physical changes have to be considered, and this is true for a full understanding of the deterioration process, but they directly affect sensory quality. For example, during storage of set-type yogurt there is a physical phenomena which is the contraction of the gel and this liberates a milky looking liquid which is not well seen by the consumer. During the storage of a fruit juice chemical reactions take place which lead to browning. Mechanisms can be sought that delay or suppress these chemical reactions, but what these mechanisms are really after is avoiding a sensory property which has a negative impact on consumer's perception.

Going through the aisles of the food and beverage sections of a local supermarket in Argentina showed that the number of food products whose shelf life is dependent on their sensory properties is far greater than those products whose shelf life depends on microbiological and/or nutritional properties. Even some foods that might be thought of as having their shelf life limited by microbiological deterioration may have their shelf life determined by sensory properties, depending on the manufacturing process and storage condition. This is the case of bologna sausage that takes on a dry appearance if cooked in an autoclave and packaged in a permeable film, before the onset of microbiological failure. Thus, when talking about shelf life of foods, in the vast majority of cases we are talking about SSL of foods.

The present review will cover SSL publications over the last decades, and they have been classified in four topics:

(1) Cut-off point (COP) methodology
- Arbitrary: one of the most frequently used approaches in establishing a COP is for the researcher to decide on an arbitrary value taken from literature or self-defined.
- Regression-based COPs: where the SSL estimation is based on a COP obtained from a regression of the mean consumer panel scores versus mean trained sensory panel scores.

(2) Methods based on product failure or consumers' rejection
- Failure with no censorship: this method uses the exact time for estimating SSL, the censored nature of the data is not considered. A Weibull distribution or a logistic regression can be applied to the data.
- Survival analysis: the fully censored nature of the data is considered.

(3) Accelerated studies: these are used to estimate SSL based on storage under accelerated conditions.

(4) Other topics and further research

COP METHODOLOGY

Arbitrary COPs

One of the first authors to propose the COP methodology was Gacula (1975a) where the SSL estimation was based on regression of the mean panel scores versus storage time, using an arbitrary 2.5 COP on a 1 (none) to 7 (very strong) off-flavor scale. He also proposed staggered and completely staggered designs which increased the experimental units as the shelf-life study progressed.

There are a number of publications reporting SSL values based on poor methodology. For example, Portela and Cantwell (2001) studied the effect of the cutting blade sharpness on SSL of melon. A single assessor, the first author of the paper, measured acceptability on a 1–9 scale and defined 6 as the marketable limit. Ross *et al.* (1987) performed an extensive study on the SSL of military rations at different temperatures and storage times. A small panel of 38 consumers rated the menus on a 1 to 9 hedonic score, and they considered 5 (neither like nor dislike, on their scale) to be the COP for all menus. Considering a universal COP such as this is not reasonable. A highly liked product such as ice cream with initial scores above 8 on the hedonic scale would probably be rejected by consumers if the score were a 6 or a 7 that is long before it reached the low value of 5. Muego-Gnanasekharan and Resurreccion (1992) measured a number of sensory attributes during storage of a peanut paste and decided that oxidized flavor was the critical descriptor as it was the only attribute absent in the fresh sample and appeared only after storage. No other consideration was used for this decision. A multiple regression was calculated considering oxidized flavor as the response variable and storage time and storage temperature (using linear and quadratic terms) as explanatory variables. The percent variance explained was only 69% and yet they proposed the use of this regression equation to estimate SSL with an arbitrary COP of 2 in oxidized flavor. No confidence intervals of predictions were published. Rustom *et al.* (1996) used 7 to 12 panelists who measured acceptability on a 1 (dislike extremely) to 7 (like extremely) hedonic scale to determine SSL of ultra-high temperature-sterilized peanut beverages, defining 4 as the acceptability limit. The use of such a reduced consumer panel and the arbitrary limit of 4 leads to little confidence in the reported SSL values. Martínez *et al.* (2006) researched the combined effects of modified atmosphere packaging and antioxidants on the storage stability of pork sausages. A 6-member trained panel used a 5-point scale to measure off-odor, the scale went from 1 = none to 5 = extreme with 3 = small; this last score being considered as a limit of acceptability in reference to an article by Martínez *et al.* (2005) who in turn traced this limit of acceptability to Djenane *et al.* (2001). In this last paper the 1–5 scale was used by a 6-member trained panel, but there was no mention of 3 = small corresponding to a limit of acceptability. Thus the sequel ends on a lost trail. Martínez *et al.* (2006) stated that their treatment extended the SSL of pork sausages from 8 to 16 days based on this limit of 3 on their 1–5 scale. What a consumer would think when eating these pork sausages was apparently never considered.

The COP methodology usually implies a regression of the critical descriptor, e.g., oxidized flavor in vegetable oil, versus storage time (Hough 2010). Some authors have not used a regression; rather they have established SSL when their panel's score complied with a predefined criteria. For example, Vallejo-Córdoba and Nakai (1994) determined SSL of milk by having five trained judges score the milk with the American Dairy Science Association score card. Shelf life was ended whenever a score of 5 or lower was recorded by three of the judges, and the day before was considered the end of the SSL. Duarte *et al.* (2009) studied the changes in blueberries stored in controlled atmosphere with different CO2 levels. Dehydrated, rotten or overripe fruits were weighed, discarded and considered as unmarketable. The percentage of unmarketable fruits was considered as the valid parameter in establishing the effectiveness of the different treatments in extending the product's SSL. However, there was no information as to who performed this evaluation and what criteria were used to establish, e.g., if a fruit was overripe or not.

Some authors have taken arbitrary criteria to the extreme of not even describing the panel that performed the sensory evaluation: no indication of degree of training, no recruitment criteria and no number of panelists (Poubol and Izumi 2005). These authors defined the "limit of marketability" when 20% of the cubes had browning or 60% had water-soaked appearance.

Considering the choice of cut-off values in their research, some authors have adopted unusual expressions. For example, Keogh *et al.* (2001) in a study on microencapsulated fish oil powder, measured fishy, painty and metallic off-flavors with a trained panel during storage. Fishy off-flavor did not change during storage, painty and metallic did. Products with a mean (painty + metallic)/2 < 10 were considered mild, 20 to 30 acceptable and 40 to 50 objectionable. A score of 25 was chosen as the SSL end-point. Most probably consumers would be more sensitive to a painty off-flavor than to a metallic one, thus averaging both these flavors would lead to erroneous SSL estimations. Also no consumer-based data was considered in defining 25 as the end-point. Villanueva and Trindade (2010) used acceptance tests to estimate the SSL of chocolate and carrot cupcakes. The end of shelf life was determined as the storage time at which the quality limit decreased to the preestablished value of 5.0. In one section of their paper they mentioned that this limit was chosen due to the manufacturer's request, and in another they refer to Gacula (1975a). They stated that shelf life determined in this manner is called "practical shelf life," being longer than the one called "high quality life." They then state that "many companies" use the time of a 0.5-point decrease in the hedonic scale as the "high quality life" and the time of a 1.5-point decrease as the "practical shelf life," establishing this as the time of product validity. No references were given to validate these limits. Based on these COPs, the authors conclude that the SSL of the cupcakes can be extended from 120 to 150 days. However, approximately 50% of their consumers would "probably not" or "certainly not" buy the products stored at these times.

Regression-Based COP

Fritsch *et al.* (1997) were the first to introduce a statistically based COP in their research on the SSL of sunflower kernels. A consumer panel measured acceptability of samples with different storage times. The results of the Student–Neuman–Keuls multiple comparison test were used to determine the minimum size of a significant difference in consumer liking score. This value was subtracted from the mean liking score for the fresh sample to provide a minimum acceptable liking score. Next, the consumer liking data were related to the expert panel fresh flavor ratings by regression analysis. Substituting the minimum acceptable liking score in the regression equation allowed estimating the fresh flavor end-point. The only observation to be made to this methodology would be that the Student–Neuman–Keuls multiple comparison test is two-sided. For SSL studies it is assumed that consumers like the fresh flavor, and thus when this flavor decreases their acceptability also decreases. Thus a one-sided test should be considered (Garitta *et al.* 2004b).

Gambaro *et al.* (2006) compared the SSL of baby food using the COP methodology and survival analysis. When estimating the COP based on a significant reduction in consumer acceptability (Hough *et al.* 2002) they estimated a SSL of 8 months. When the COP was based on a minimum average acceptability of 6 on a 1–9 scale, the estimated SSL was 18 months. This value coincided with the SSL estimated by survival analysis corresponding to a 25% rejection probability. Gambaro *et al.*'s (2006) conclusion was that the COP based on a significant reduction in consumer acceptability can lead to overly conservative SSL estimations. It should be noted that considering an arbitrary COP of 6 on a 1–9 scale can also lead to poor SSL estimations as was shown by Giménez *et al.* (2007) when they compared the COP methodology with survival analysis in estimating the SSL of brown pan bread. The survival analysis method provided more realistic estimations.

Makhoul *et al.* (2006) measured acceptability of stored sunflower oil samples with 50 consumers on a 1–9 hedonic scale, and rancid flavor of the same samples with a trained panel. With this data they estimated a COP in a similar way as described by Hough *et al.* (2002) but using the Dunnet test to establish the least significance difference. With this COP they established accept/reject criteria for the trained panel and estimated SSL using a Weibull distribution. Had they asked their consumers if they accepted or rejected each sample, they would have been able to establish SSL directly using survival analysis. The trained panel data would not have been necessary.

METHODS BASED ON PRODUCT FAILURE OR CONSUMERS' REJECTION

Failure Data with No Censoring

Gacula (1975a) was the first to propose the Weibull distribution for estimating SSL based on product failure. A more complete description of these Weibull distribution calculations was given by Gacula (1975b). The information contained in these two articles was also presented by Gacula *et al.* (2009) in a more recently published book.

A similar approach was used by Cardelli and Labuza (2001) in estimating the SSL of coffee stored between 0 and 23.3

weeks. At week 0, three consumers were used. As the storage time increased, the number of consumers used was also increased. Thus, e.g., at 20.1 weeks of storage, 5 new consumers were recruited of which 4 rejected the coffee and 1 accepted it. The rejection storage time for these four consumers was not $t = 20.1$ weeks, rather $t < 20.1$ weeks. That is, all we know is that they rejected the coffee with 20.1 weeks storage, but we do not know if they would have rejected or accepted coffee stored for, say, 15 weeks. This uncertainty in the time of interest is defined as censored data in survival analysis (Meeker and Escobar 1998). Duyvesteyn *et al.* (2001) used a similar procedure with no censoring in determining SSL of milk.

Al-Kadamany *et al.* (2002) had seven semi-trained assessors evaluate "labneh" (a concentrated yogurt) using a 0–6 difference from control test. They arbitrarily considered 2.5 to be the COP and based on this they used the Weibull distribution to model percent rejection versus storage time.

Pérez *et al.* (2003) applied what they called the "Weibull method" to estimate the SSL of vacuum-packed sliced cooked chicken breast. A 12-member trained panel measured overall acceptability with a 1–9 hedonic scale and the product was considered rejected if the score was below 5. The authors did not consider this "Weibull method" as adequate for estimating SSL for the following reasons: it is based on another evaluation method like overall acceptability on a hedonic scale; it requires laborious mathematical transformations; and the values obtained were very high. Pérez *et al.* (2003) could have asked their assessors to simply report acceptance or rejection instead of using a hedonic scale; with no censoring mathematics are relatively simple; and the SSL values obtained depended on the % rejection they were willing to accept. In actual fact the methodology applied by these authors was inadequate for reasons other than those mentioned in the article: a small number of trained assessors decided on overall acceptability and they did not consider the censored nature of their data.

Other authors have used percent rejection to define SSL without considering regression analysis, and in some cases having trained assessors measure acceptability. For example, Goncalves *et al.* (2003) studied the quality changes of pink shrimp packed in modified atmosphere. The sensory evaluation was done by a 6–8-member trained panel who measured presence of black spots and overall acceptability (acceptance/rejection). Samples rejected by more than 50% of the assessors were considered unacceptable. No discussion on how representative these trained assessors were of the general consumer was given.

Logistic Regression

Vaisey-Genser *et al.* (1994) used logistic regression analysis to relate the average proportion of acceptance of canola oils to their storage time. An incomplete block design was used whereby not all consumers tasted all storage times. This introduced a certain amount of confounding to the experiment; e.g., the average proportion of acceptance at *D* 10 could be different to that of *D* 12 due to different storage times or due to different consumers. This type of incomplete block designs could have been analyzed more efficiently considering survival analysis concepts.

A similar approach was used by Vankerschaver *et al.* (1996) who predicted SSL of processed endive by a logistic regression of proportion of rejection versus storage time, using 13 to 15 consumers. They considered 30% rejection as the limit to establish SSL. A critique to this methodology of regressing proportion of rejection at different storage times is that the censored nature of the data is not considered. As shown by Hough (2010), when a group of consumers are presented with a set of samples with different storage times, different consumers present different accept/reject patterns in relation to storage time. Using survival analysis statistics takes into account the individual behavior of consumers, while logistic regression does not.

Logistic regression was also applied by Salvador and Fiszman (2004) in a study on prolonged storage of whole and skimmed set-type yogurt; these authors could have used survival analysis methodology to an advantage.

Survival Analysis Methodology

Hough *et al.* (2003) were the first to apply survival analysis statistics to SSL considering the fully censored nature of this type of data. Important features of this methodology are:

(**1**) The hazard is focused on the consumer rejecting the product rather than on the product deteriorating.

(**2**) Experimental sensory work is relatively simple. A group of consumers answer if they accept or reject samples with different storage times.

(**3**) The accept/reject decision is in line with what consumers do regularly when confronted with a food product close to the end of its SSL.

(**4**) Specialized statistical software is necessary to perform the calculations. Garitta *et al.* (2004a) provided instructions using TIBCO Spotfire S+ (TIBCO Inc., Seattle, WA) and Hough (2010) published the functions to be used with the freely available R Statistical Package (http://www.r-project.org/, accessed November 21, 2011).

Cruz *et al.* (2010) applied survival analysis to predict SSL of a probiotic yogurt. Their general conclusion was that from the operational point of view the methodology has the advantage that the work to be carried out is really quite simple. Fifty to a hundred individuals are required to express their acceptance or rejection of samples with different storage times or different formulations, and this is sufficient to estimate the SSL. Another advantage highlighted by Cruz *et al.* (2010) was that these measures are carried out directly on the data obtained in the affective tests, who are the real consumers of these products. Jacobo-Velázquez *et al.* (2010) applied survival analysis methodology to estimate the SSL of high hydrostatic pressure processed avocado and mango pulps; they pointed out that a significant aspect of the survival analysis methodology is the simplicity of the sensory approach used in the study in comparison with other SSL estimation procedures.

Following the initial survival analysis study, further extensions of the methodology have been published. Calle *et al.* (2006) applied Bayesian modeling to SSL estimations as a way of being able to use prior information from previous experience and thus obtain better parameter estimates. Curia *et al.* (2005) presented the necessary equations to study the effect of covariates such as product formulation or consumer demographics on SSL. They applied the model to SSL of yogurts with different flavors and fat content. Hough *et al.* (2006a) developed an accelerated SSL model which allowed estimating an activation energy of how acceptance/rejection behavior of consumers' varied as a function of storage time and temperature. As a case study they applied the model to appearance of minced beef. Araneda *et al.* (2008) presented the case of consumers evaluating a single sample; known as current status data. The recommended number of consumers necessary for survival analysis studies can be found in Hough *et al.* (2007) and Libertino *et al.* (2011).

Larsen *et al.* (2010) compared what they called the ad hoc Weibull modeling (Cardelli and Labuza 2001; Gacula *et al.* 2009) where no censoring was considered, with a maximum likelihood estimation method based on left and right censoring. They focused their estimations on the product failing and not on consumers' rejection. Their conclusion was that the maximum likelihood estimations were more reliable than the ad hoc methods. The survival analysis methodology presented by Hough *et al.* (2003) was based on maximum likelihood estimations.

Gambaro *et al.* (2004) applied survival analysis statistics to estimate the SSL of white pan bread in Uruguay and Spain. For the Spanish bread there were approximately 75% consumers who accepted the bread stored at maximum storage time of 17 days. All that is known about these consumers is that their rejection time is somewhere above the maximum storage time and are thus considered right-censored. This uncertainty in the data is reflected in wide confidence bands for the SSL estimation. In this study, for the Spanish consumers, shelf life for a 50% rejection was 23 days with confidence bands between 17 and 31 days.

Salvador *et al.* (2006) analyzed the suitability of the survival analysis methodology in estimating the SSL of brown pan bread. They concluded that the Weibull, log-normal or log-logistic parametric distributions were equally suitable for estimating the SSL of brown bread. Acceptability scores were correlated versus storage time, then the SSL from survival analysis were introduced in the correlation to thus estimate the corresponding acceptability values. No confidence intervals were reported for these estimations, and by the appearance of the linear regression in relation to the experimental points, the intervals would have been wide.

Varela *et al.* (2005) used survival analysis statistics to determine the SSL of "Fuji" apples based on accept/reject evaluations of only 30 consumers. A more recent paper (Hough *et al.* 2007) recommended 120 consumers for this type of study considering reasonable statistical parameters. Varela *et al.* (2005) complemented the consumer study with trained panel data on the same samples. Although the trained panel did not determine the SSL of the apples, as this was done by the consumers, their data were useful in determining what caused consumer's rejection during prolonged storage.

Guerra *et al.* (2008) presented a simulation study to test different methodologies used to estimate SSL. They argued that the "consumer approach" (which includes the COP and survival analysis methodologies) presents several problems, of which they mentioned three:

(1) Inconsistency of consumers' judgments: this is true, consumers are inconsistent. However, this inconsistency is not ignored in survival analysis, on the contrary, it is incorporated into estimations (Hough 2010),

(2) The variability of the result when different consumer panels are used. To sustain this argument they cite Giménez *et al.* (2007) who prepared breads in Spain and Uruguay, using different recipes and these breads were evaluated by Spanish and Uruaguayan consumers. SSL estimations in both countries varied; this could have been due to the different recipes and/or to different consumer demographics. This in no way undermines the "consumer approach."

(3) Organizational problems for a company, since a consumer cannot evaluate more than three or four samples in one session. Consumers can generally evaluate more than 3–4 samples in one session, especially if the only task they have is to express their acceptance or rejection of each sample. And if for some reason consumers cannot evaluate more than a single sample, the current-status approach can be used applying survival analysis (Araneda *et al.* 2008).

Guerra *et al.* (2008) concluded that given the number of arbitrary choices, the shelf life concept for microbiologically stable food products is more company or researcher driven than product or consumer dependent. What the authors mean by "company or researcher driven" is not clear. What is clear is that SSL is finally established by the consumer, who is the one who will decide if the company or researcher were right or wrong in deciding what the consumer would tolerate. The "arbitrary" choices the authors refer to are generally statistical choices. Just as arbitrary, e.g., as choosing α, β and p_d values in designing a triangle test.

ACCELERATED STUDIES

Palazon *et al*. (2009) conducted a SSL study on a fruit-based baby food. A 25-member trained panel measured acceptability using a 1–9 hedonic scale; they considered a score of 4 as the arbitrary limit for rejection. A trained panel is not recommended for acceptability measurements, and 25 is too small a number of assessors (Hough *et al*. 2006b) for acceptability measurements. Samples were stored at 23, 30 and 37C. They estimated SSL for each of these temperatures and used log (shelf-life) versus temperature (in C) (Labuza 1982) to estimate SSL at 20C to be 1,641 days. To highlight the goodness of fit of this relationship they reported an R^2 value of 0.9996. However, with only 3 experimental points for the regression, the 95% confidence interval of their prediction was between 1,140 days and 2,300 days; the interval is magnified due to the logarithmic scale of the *y*-axis and because the prediction was extrapolated outside the range of the experimental temperature range. This data highlights the risk of using the log (shelf-life) versus temperature regression with only 3 experimental points: confidence bands for the predictions are most likely to be very wide.

Another statistical issue in accelerated studies is when activation energy is estimated based on a linear regression of the Arrhenius equation with only 3 temperatures. Kong and Chang (2009) presented data on soymilk and tofu stored at three temperatures. For example, for the Hunter L luminosity value, they reported values of reaction rate constants of 0.083, 0.196 and 0.835 1/mol for 22, 30 and 40C, respectively. Based on this data and performing a linear regression of log (rate constant) versus 1/T°K the authors reported an activation energy of 98.95 kJ/mole with an R^2 value of 0.99. However, the 95% confidence interval (not reported by the authors) for this activation energy is −26.3 to 224 kJ/mole; totally unsatisfactory. Based on the same data the nonlinear approach (Hough 2010) provides much sounder activation energy calculations. Activation energy estimations based on only 3 points have been reported in numerous studies, e.g., Rustom *et al*. (1996) and Al-Kadamany *et al*. (2002).

Ross *et al*. (1987) used the nonlinear approach to activation energy calculations at a time where the rule was the use of the simple linear regression Arrhenius plot (Hough 2010). The nonlinear approach has also been used by Garitta *et al*. (2004b) and by Curia and Hough (2009) in their studies on the SSLs of dulce de leche and a human-milk replacement formula, respectively.

Siegmund *et al*. (2001) in an accelerated storage study on a strawberry drink assumed that 1 week storage at 37C was equivalent to 2 months storage at room temperature (20C ± 2C). They based this assumption on their own experience with other fruit juices, nectars and drinks; and on data on a reduced number of compounds which showed similar concentrations under these conditions. Whether this reduced number of compounds was related to consumer perception of the product was not discussed. There was no indication of the confidence interval this assumption had and thus the SSL values they publish are of doubtful validity. Another flaw in their research was defining SSL by a duo-trio test performed by 13–17 assessors; this number of assessors implies a test with very low statistical power (ISO 2004).

Lee and Resurreccion (2006) presented one of the few studies where both temperature and humidity were analyzed as accelerating factors in SSL estimations, in their case for roasted peanuts. The experimental design consisted of four storage temperatures of 23, 30, 35 and 40C and five storage water activities of 0.33, 0.44, 0.54, 0.67 and 0.75 evaluated over storage time. Consumer acceptance and intensity attributes of roasted peanuts were predicted by storage time and water activity. Based on an arbitrary COP of 5 on a 1–9 hedonic scale they estimated SSLs for the different water activities and also estimated how SSL was affected by a change in 0.1 in water activity.

Lareo *et al*. (2009) used the accelerated survival model published by Hough *et al*. (2006a) to estimate SSLs of lettuce stored at different temperatures. They determined that shelf life of lettuce in passive modified atmosphere packages was limited by sensory properties and not by microbial growth, thus showing the importance of SSL for fresh vegetable products such as lettuce.

OTHER TOPICS AND FURTHER RESEARCH

A number of authors have applied sensory profiling by trained panels to describe changes over storage time, without necessarily estimating an SSL value. Jensen *et al*. (2010) followed the sensory profile of wheat and whole wheat bread during prolonged storage focusing on aroma and flavor attributes rather than the classical texture changes that occur during bread storage. Samples stored for 3 weeks were rated to have a high intensity of aroma and flavor attributes such as "Dust," "Aged" and "Rancid" whereas samples stored for 0 week mainly were described as having a high degree of the aroma attribute "Burned crust." Lee and Chambers (2010) analyzed green tea over a 2-year storage period using descriptive analysis with a trained panel. They chose this period because green tea is usually given a SSL of 2 years. Only a few descriptors showed significant differences over storage time, and these differences were less than 1 point on the 1–15 scale they used. Talavera-Bianchi *et al*. (2011) analyzed pac choi (*Brassica rapa* var. Mei Qing Choi) over 18 days storage using descriptive analysis. They concluded that changes were minimal. Some chemical changes were registered that did not translate to sensory changes. Results obtained from descriptive analysis are of value in understanding changes during storage, however, as Lee and Chambers (2010) concluded: further investigation is needed to determine if these changes are perceived by consumers.

There has been limited research on the effect of storage at ambient temperatures prior to refrigeration, mainly due to poor transport or handling. Surti *et al.* (2001) studied this effect for grouper, a species of tropical fish. They stored fish between 0 and 12 h at an ambient temperature between 29 and 32C, prior to storing the fish in ice. If the fish was placed on ice immediately it maintained their standard of quality (arbitrarily chosen as 6 on a 0–10 freshness scale) for as long as 18 days. If 6 h elapsed at ambient temperature before placing the fish on ice, it reached a score of 6 after 4 days on ice. For a number of products such as fresh meat, fruits and vegetables these studies should be pursued to encourage good handling practices.

A conceptually similar study was performed by Salvador *et al.* (2007) on two groups of "Flor de Invierno" pears (*Pyrus communis L.*) stored at 20C in a normal atmosphere, one recently harvested and another stored in a refrigerated controlled atmosphere for 7 months. Survival analysis was used to estimate SSL, which was 29 and 15 days for a 50% rejection probability for recently harvested and stored pears, respectively. This was an interesting application of survival analysis to show up the differences in previous storage conditions on the final SSL of fruits.

Anese *et al.* (2006) estimated what they called the "secondary shelf life" of ground coffee, referring to the product's SSL once the package had been opened and exposed to air at different humidities. Few studies have focused on this important issue of SSL during home storage. They applied survival analysis methodology with each consumer evaluating a single sample; this type of design is referred to as "current status data" (Hough 2010).

Manzocco and Lagazio (2009) applied survival analysis methodology to estimate the SSL of brewed coffee with each consumer evaluating a single sample. They also measured pH and acidity changes during storage and they combined these changes with the % rejection logistic distribution obtained from survival analysis. They thus proposed a final equation which allowed SSL evaluation based on pH changes and consumer rejection probability. The approach is interesting; however, to be fully applicable, confidence interval calculations have to be incorporated to the final estimations. Ares *et al.* (2009) presented a similar approach to define the SSL of strawberries based on a quality index related to consumer rejection, but confidence interval calculations were not included in this work either.

Some food products' shelf life is highly dependent on their appearance, e.g., vegetables such as broccoli or ground beef. A challenge in the sensory evaluation of these products is their heterogeneous appearance which complicates the evaluation of attributes such as color. As broccoli ages yellow and brown spots start appearing, while the rest of the sample maintains its original green. Assessors get confused as to what color they should be evaluating. Jimenez-Villarreal *et al.* (2003), in evaluating the sensory effects of antimicrobial agents on the storage stability of ground beef, asked assessors to evaluate overall color and worst-point color. This last descriptor is an interesting innovation which has not been pursued by other researchers.

Computer vision systems show promise in classifying certain food samples whose critical storage attribute is appearance. Mendoza and Aguilera (2004) implemented a computer vision system to identify the ripening stages of bananas based on color, development of brown spots, and image texture information. Results showed that in spite of variations in data for color and appearance, a simple classification technique is as good to identify the ripening stages of bananas as professional visual perception. Computer vision showed promise for online prediction of ripening stages of bananas.

Ares *et al.* (2008a) presented lettuce with different storage times to consumers and asked them if they would buy the lettuce and if they would consume the lettuce. They showed that the SSL when buying the lettuce was shorter than when consuming it at home. Analogously, Ares *et al.* (2009) showed this same effect for consumers buying or consuming strawberries with different ripening stages. This showed that a product's SSL can depend on the context of the consumer's interaction with the product. Ares *et al.* (2008b) in another lettuce study showed that from a consumer's perspective cut lettuce had a shorter SSL than the whole leaf lettuce.

Wansink and Wright (2006) conducted an interesting experiment to analyze the influence of freshness dating on acceptability of yogurt samples. The same yogurt 30 days prior to its "best if used by . . ." date, was labeled as 30 days before (+30), 1 day before (+1), 1 day after (−1) and 30 days after (−30) its "best if used by . . ." date. A non-labeled sample was also evaluated. There was a significant decrease in acceptability between +30 days and +1 day; and then decreased to a lesser degree for −1 and −30 days. Perceived freshness also decreased similarly. With no labeling acceptability and freshness was intermediate between +30 and +1 labeled samples. This experiment raises the question of whether consumers should be told that the samples they are presented with in an SSL study have different storage times. For what category of consumers do we conduct SSL tests? For those conscientious consumers who read food labels and are aware of the "best if used by . . ." date of their products. In this case, as Wansink and Wright (2006) showed, the knowledge of the date can influence their acceptability. Considering these issues Hough (2010) recommended informing consumers they were being presented with samples that had different storage times.

Giménez *et al*. (2008) estimated percent rejection of dulce de leche samples with different degrees of plastic flavor (Garitta *et al*. 2004b) among 50 consumers. Consumers evaluated the samples blind and with a label indicating that the samples were close to the end of their SSL. The difference between both evaluations was not significant, showing that for this product and this reduced number of consumers, knowing that the samples were close to the end of their SSL did not influence rejection. This result is different to the one described above for yogurt (Wansink and Wright 2006). In Giménez *et al*.'s (2008) study all samples had the same date information and both tests, blind and labeled, were performed in the same session. Thus consumers could have been biased by this single date and by having received the same set of samples blind a few minutes before.

Through an experimental auction procedure Lund *et al*. (2006) studied the effect of different storage times on willingness to pay for apples. Overall, their study demonstrated that both sensory and emotional aspects to consumer assessments of freshness influenced consumer perceptions of monetary value of apples. As discussed in survival analysis methodology, SSL is a function of how consumers interact with a food product, and not a property of the food on its own. Lund *et al*.'s (2006) research is an additional confirmation of this concept.

When SSL measurements are performed it is particularly difficult to compare sensory quality at times separated by several weeks or more, when standardized references are not available, as is the case, e.g., of fruits and vegetable. Thybo *et al*. (2005) presented a procedure to correct for possible drifts in sensory measurements based on instrumental measurements taken on the same samples.

Ledauphin *et al*. (2006, 2008) used a Markovian chain approach to SSL estimation. A panel of experienced assessors classified salmon with different storage times in one of three categories: fresh, decayed and very decayed. It is not clear why they used these three categories when consumers use only two: fresh or decayed. In their first paper (Ledauphin *et al*. 2006) they had to make adjustments to account for inconsistencies in the assessors' evaluations; however, they corrected for this in their second paper (Ledauphin *et al*. 2008) where the model took account of these inconsistencies. The final result of their calculations was a correspondence analysis biplot where they could observe the transitions of different salmon varieties from fresh to decayed and to very decayed. The Markovian approach presented by these authors does not present any distinctive advantage over the survival analysis methodology (Hough 2010).

Pedro and Ferreira (2006) proposed a novel approach to shelf life estimation via principal component analysis (PCA). The method consists of measuring a number of K variables (instrumental and/or sensory) over several N storage times and for C accelerating factors (e.g., three temperatures). A PCA analysis is conducted on the NxC rows and K columns matrix. COPs are chosen for each one of the K variables, and using matrix algebra on the PCA linear transformation, an overall COP is determined for the principal component mainly related to storage time. This method would have the advantage of considering an overall COP in estimating the shelf life of the product instead of relying on a single critical descriptor. The drawbacks of the method are that COPs have to be established for all K variables; this can imply considerable experimental work.

Principal component regression was used by Peneau *et al*. (2007) to analyze the attributes that contributed to consumers' perception of apple freshness. Although apple SSL was not estimated, all regressions showed a clear importance of the texture attributes of apples for freshness but a rather low importance of flavor attributes.

TABLE 1. SUMMARY OF SENSORY SHELF LIFE (SSL) METHODOLOGIES

Method	Features	Advantages	Disadvantages
Arbitrary cut-off points	SSL estimations usually based on trained sensory panels Cut-off points taken from literature or decided by researchers	Easy and inexpensive	Arbitrary criteria lead to doubtful estimations.
Regression-based cut-off point	SSL estimations based on cut-off points obtained from consumer panel vs. trained panel regressions	Useful in studies where there are several variations factors SSL estimations based on consumer input	Based on a hedonic scale that does not necessarily represent rejection SSL estimations based on this method tend to be conservative.
Failure data with no censoring	SSL estimations based on exact failure times	Relatively simple calculations SSL estimations based on consumer input	The censored nature of data is not considered.
Failure data with survival analysis	SSL estimations based on censored data	SSL estimations based on consumer input Experimental sensory work is relatively simple. Trained panel is not necessary.	Specialized statistical software is necessary High number of consumers when there are many variation factors in the experiment

CONCLUSIONS AND RECOMMENDATIONS

Table 1 provides a summary of the methods reviewed in the present article.

Over the last decades researchers have often applied poor methodology in SSL estimations, and they should be more careful in the method they choose and how it is applied. General recommendations are to use:

- Representative consumer panels
- Nonarbitrary COPs
- Include confidence intervals in SSL estimations
- Trained panels for descriptive analysis, i.e., not ask the panel for acceptability evaluations.
- Clear definition of the critical descriptor

Survival analysis is the most sound methodology, both from experimental and statistical viewpoints; its advantages are the following:

- It is focused on the consumer rejecting the product rather than on the product deteriorating.
- The accept/reject decision is in line with what consumers do regularly when confronted with a food product close to the end of its SSL.
- Takes into account the individual behavior of consumers
- Experimental sensory work is relatively simple.
- Considers the fully censored nature of the data
- Provides more realistic SSL estimations

REFERENCES

AL-KADAMANY, E., TOUFEILI, I., KHATTAR, M., ABOU-JAWDEH, Y., HARAKEH, S. and HADDAD, T. 2002. Determination of shelf life of concentrated yogurt (Labneh) produced by in-bag straining of set yogurt using hazard analysis. J. Dairy Sci. *85*, 1023–1030.

ANESE, M., MANZOCCO, L. and NICOLI, M.C. 2006. Modeling the secondary shelf life of ground roasted coffee. J. Agric. Food Chem. *54*, 5571–5576.

ARANEDA, M., HOUGH, G., WITTIG DE PENNA, E. 2008. Current-status survival analysis methodology applied to estimating sensory shelf life of ready-to-eat lettuce (*Lactuta sativa*). J. Sensory Studies *23*, 162–170.

ARES, G., MARTINEZ, I., LAREO, C. and LEMA, P. 2008a. Failure criteria based on consumers' rejection to determine the sensory shelf life of minimally processed lettuce. Postharvest Biol. Technol. *49*, 255–259.

ARES, G., GIMENEZ, A. and GAMBARO, A. 2008b. Sensory shelf life estimation of minimally processed lettuce considering two stages of consumers' decision-making process. Appetite *50*, 529–535.

ARES, G., BARRIOS, S., LAREO, C. and LEMA, P. 2009. Development of a sensory quality index for strawberries based on correlation between sensory data and consumer perception. Postharvest Biol. Technol. *52*, 97–102.

ASTM E2454 Standard. 2005. *Standard Guide for Sensory Evaluation Methods to Determine the Sensory Shelf Life of Consumer Products*. American Society for Testing of Materials, West Conshohocken, PA.

CALLE, M., HOUGH, G., CURIA, A. and GÓMEZ, G. 2006. Bayesian survival analysis modelling applied to sensory shelf life of foods. Food Qual. Prefer. *17*, 307–312.

CARDELLI, C. and LABUZA, T.P. 2001. Application of Weibull hazard analysis to the determination of the shelf life of roasted and ground coffee. LWT – Food Sci. Technol. *34*, 273–278.

CRUZ, A.G., WALTER, E.H.M., SILVA CADENA, R., FARIA, J.A.F., BOLINI, H.M.A., PINHEIRO, H.P. and SANTANA, A.S. 2010. Survival analysis methodology to predict the shelf-life of probiotic flavored yogurt. Food Res. Int.*43*, 1444–1448.

CURIA, A. and HOUGH, G. 2009. Selection of a sensory marker to predict the sensory shelf life of a fluid human milk replacement formula. J. Food Qual.*32*, 793–809.

CURIA, A., AGUERRIDO, M., LANGOHR, K. and HOUGH, G. 2005. Survival analysis applied to sensory shelf life of yogurts. I: Argentine formulations. J. Food Sci. *70*, S442–S445.

DJENANE, D., SÁNCHEZ-ESCALANTE, A., BELTRÁN, J.A. and RONCALÉS, P. 2001. Extension of the retail display life of fresh beef packaged in modified atmosphere by varying lighting conditions. J. Food Sci. *66*, 181–186.

DUARTE, D., GUERRA, M., DANIEL, P., LOPEZ CAMELO, A. and YOMMI, A. 2009. Quality changes of highbush blueberries fruit stored in CA with different CO_2 levels. J. Food Sci. *74*, S154–S159.

DUYVESTEYN, W.S., SHIMONI, E. and LABUZA, T.P. 2001. Determination of the end of shelf-life for milk using Weibull hazard method. LWT – Food Sci. Technol. *34*, 143–148.

FRITSCH, C.W., HOFLAND, C.N. and VICKERS, Z.M.J. 1997. Shelf life of sunflower kernels. J. Food Sci.*62*, 425–428.

GACULA, M.C. 1975a. The design of experiments for shelf life study. J. Food Sci.*40*, 399–403.

GACULA, M.C. 1975b. Statistical models for shelf life failures. J. Food Sci. *40*, 404–409.

GACULA, M.C., SINGH, J., BI, J. and ALTAN, S. 2009. *Statistical Methods in Food and Consumer Research*, Chapter 8, Academic Press, London, U.K.

GAMBARO, A., FISZMAN, S., GIMÉNEZ, A., VARELA, P. and SALVADOR, A. 2004. Consumer acceptability compared with sensory instrumental measures of white pan bread: Sensory shelf-life estimation by survival analysis. J. Food Sci. *69*, S401–S405.

GAMBARO, A., ARES, G. and GIMÉNEZ, A. 2006. Shelf-life estimation of apple-baby food. J. Sensory Studies *21*, 101–111.

GARITTA, L., GÓMEZ, G., HOUGH, G., LANGOHR, K. and SERRAT, C. 2004a. *Estadística de supervivencia aplicada a la vida útil sensorial de alimentos. Tutorial introductorio y cálculos a realizar utilizando S-Plus*. Madrid: Programa CYTED.

GARITTA, L., HOUGH, G. and SÁNCHEZ, R. 2004b. Sensory shelf life of dulce de leche. J. Dairy Sci. *87*, 1601–1607.

GIMÉNEZ, A., VARELA, P., SALVADOR, A., ARES, G., FISZMAN, S. and GARITTA, L. 2007. Shelf life estimation of brown pan bread: A consumer approach. Food Qual. Prefer. *18*, 196–204.

GIMÉNEZ, A., ARES, G. and GAMBARO, A. 2008. Consumer attitude toward shelf-life labeling: Does it influence acceptance? J. Sensory Studies *23*, 871–883.

GONCALVES, A., LOPEZ-CABALLERO, M. and NUNES, M. 2003. Quality changes of deepwater pink shrimp (*Parapenaeus longirostris*) packed in modified atmosphere. J. Food Sci. *68*, 2586–2590.

GUERRA, S., LAGAZIO, C., MANZOCCO, L., BARNABA, M. and CAPPUCCIO, R. 2008. Risks and pitfalls of sensory data analysis for shelf life prediction: Data simulation applied to the case of coffee. LWT – Food Sci. Technol. *41*, 2070–2078.

HOUGH, G. 2010. *Sensory Shelf Life Estimation of Food Products*, Taylor & Francis Group, Boca Raton, FL.

HOUGH, G., SÁNCHEZ, R.H., GARBARINI DE PABLO, G., SÁNCHEZ, R.G., CALDERÓN VILLAPLANA, S., GIMÉNEZ, A.M. and GÁMBARO, A. 2002. Consumer acceptability versus trained sensory panel scores of powdered milk shelf-life defects. J. Dairy Sci. *85*, 1–6.

HOUGH, G., LANGOHR, K., GÓMEZ, G. and CURIA, A. 2003. Survival analysis applied to sensory shelf-life of foods. J. Food Sci. *68*, 359–362.

HOUGH, G., GARITTA, L. and GÓMEZ, G. 2006a. Sensory shelf-life predictions by survival analysis using accelerated storage models. Food Qual. Prefer. *17*, 468–473.

HOUGH, G., WAKELING, I., MUCCI, A., CHAMBERS IV, E., MÉNDEZ GALLARDO, I. and RANGEL ALVES, L. 2006b. Number of consumers necessary for sensory acceptability tests. Food Qual. Prefer. *17*, 522–526.

HOUGH, G., CALLE, M.L., SERRAT, C. and CURIA, A. 2007. Number of consumers necessary for shelf-life estimations based on survival analysis statistics. Food Qual. Prefer. *18*, 771–775.

IFST. 1993. *Shelf Life of Foods- Guidelines for Its Determination and Prediction*, Institute of Food Science & Technology, London, U.K.

ISO. 2004. ISO Standard 10399: Sensory analysis- Methodology- Duo-trio test. Geneva: International Organization for Standardization.

JACOBO-VELÁZQUEZ, D.A., RAMOS-PARRA, P.A. and HERNANDEZ-BRENES, C. 2010. Survival analysis applied to the sensory shelf-life dating of high hydrostatic pressure processed avocado and mango pulps. J. Food Sci. *75*, S286–S291.

JENSEN, S., OESTDAL, H. and THYBO, A.K. 2010. Sensory profiling of changes in wheat and whole wheat bread during a prolonged period of storage. J. Sensory Studies *25*, 231–235.

JIMENEZ-VILLARREAL, J., POHLMAN, F., JOHNSON, Z. and BROWN, A. 2003. Lipid, instrumental color and sensory characteristics of ground beef produced using trisodium phosphate, cetylpyridinium chloride, chlorine dioxide or lactic acid as multiple antimicrobial interventions. Meat Sci. *65*, 885–891.

KEOGH, M.K., O'KENNEDY, B.T., KELLY, J., AUTY, M.A., KELLY, P.M., FUREBY, A. and HAAHR, A.M. 2001. Stability to oxidation of spray-dried fish oil powder microencapsulated using milk ingredients. J. Food Sci. *66*, 217–224.

KONG, F. and CHANG, S.K.C. 2009. Statistical and kinetic studies of the changes in soybean quality during storage as related to soymilk and tofu making. J. Food Sci. *74*, S81–S89.

LABUZA, T.P. 1982. *Shelf-Life Dating of Foods*, Food & Nutrition Press, Inc, Westport, CT.

LAREO, C., ARES, G., FERRANDO, L., LEMA, P., GAMBARO, A. and SOUBES, M. 2009. Influence of temperature on shelf life of butterhead lettuce leaves under passive modified atmosphere packaging. J. Food Qual. *32*, 240–261.

LARSEN, R.A., SCHAALJE, G.B. and LAWSON, J.S. 2010. Food shelf life: Estimation and optimal design. J. Stat. Comput. Simul. *80*, 143–157.

LEDAUPHIN, S., POMMERET, D. and QANNARI, M. 2006. A Markovian model to study products shelf-lives. Food Qual. Prefer. *17*, 598–603.

LEDAUPHIN, S., POMMERET, D. and QANNARI, M. 2008. Application of hidden Markov model to products shelf lives. Food Qual. Prefer. *19*, 156–161.

LEE, C.M. and RESURRECCION, A.V.A. 2006. Consumer acceptance of roasted peanuts affected by storage temperature and humidity conditions. LWT – Food Sci. Technol. *39*, 872–882.

LEE, J. and CHAMBERS, D.H. 2010. Flavors of green tea change little during storage. J. Sensory Studies *25*, 512–520.

LIBERTINO, L., LÓPEZ-OSORNIO, M.M. and HOUGH, G. 2011. Number of consumers necessary for survival analysis estimations based on each consumer evaluating a single sample. Food Qual. Prefer. *22*, 24–30.

LUND, C.M., JAEGER, S.R., AMOS, R.L., BROOKFIELD, P. and HARKER, F.R. 2006. Tradeoffs between emotional and sensory perceptions of freshness influence the price consumers will pay for apples: Results from an experimental market. Postharvest Biol. Technol. *41*, 172–180.

MAKHOUL, H., GHADDAR, T. and TOUFEILI, I. 2006. Identification of some rancidity measures at the end of the shelf life of sunflower oil. Eur. J. Lipid Sci. Technol. *108*, 143–148.

MANZOCCO, L. and LAGAZIO, C. 2009. Coffee brew shelf life modelling by integration of acceptability and quality data. Food Qual. Prefer. *20*, 24–29.

MARTÍNEZ, L., CILLA, I., BELTRÁN, J.A. and RONCALÉS, P. 2005. Effect of different concentrations of carbon dioxide and low concentration of carbon monoxide on the shelf-life of fresh pork sausages packaged in modified atmosphere. Meat Sci. *71*, 563–570.

MARTÍNEZ, L., CILLA, I., BELTRÁN, J.A. and RONCALÉS, P. 2006. Combined effect of modified atmosphere packaging and addition of rosemary (*Rosmarinus Officinalis*), ascorbic acid, red beet root (*Beta Vulgaris*), and sodium lactate and their mixtures on the stability of fresh pork sausages. J. Agric. Food Chem. *54*, 4674–4680.

MEEKER, W.Q. and ESCOBAR, L.A. 1998. *Statistical Methods for Reliability Data*, John Wiley & Sons, New York, NY.
MENDOZA, E. and AGUILERA, J.M. 2004. Application of image analysis for classification of ripening bananas. J. Food Sci. *69*, E471–E477.
MUEGO-GNANASEKHARAN, K.F. and RESURRECCION, A.V.A. 1992. Physicochemical and sensory characteristics of peanut paste stored at different temperatures. J. Food Sci. *57*, 1385–1389.
PALAZON, M.A., PEREZ-CONESA, D., ABELLAN, P., ROS, G., ROMERO, F. and VIDAL, M.L. 2009. Determination of shelf-life of homogenized apple-based beikost storage at different temperatures using Weibull hazard model. LWT – Food Sci. Technol. *42*, 319–326.
PEDRO, A.M.K. and FERREIRA, M.M.C. 2006. Multivariate accelerated shelf-life testing: A novel approach for determining the shelf-life of foods. J. Chemometr. *20*, 76–83.
PENEAU, S., BROCKHOFF, P., HOEHN, E., ESCHER, F. and NUESSLI, J. 2007. Relating consumer evaluation of apple freshness to sensory and physico-chemical measurements. J. Sensory Studies *22*, 313–335.
PÉREZ, M., COSANO, G., GIMENO, R., ALCALÁ, E. and RODRIGUEZ, A. 2003. Evaluation of vacuum-packed sliced cooked chicken breast, shelf-life estimation. J. Food Qual. *26*, 105–122.
PORTELA, S.I. and CANTWELL, M.I. 2001. Cutting blade sharpness affects appearance and other quality attributes of fresh-cut cantaloupe melon. J. Food Sci. *66*, 1265–1270.
POUBOL, J. and IZUMI, H. 2005. Shelf life and microbial quality of fresh-cut mango cubes stored in high CO2 atmospheres. J. Food Sci. *70*, M69–M74.
ROSS, E.W., KLICKA, M.V., KALICK, J. and BRANAGAN, M.T. 1987. A time-temperature model for sensory acceptance of a military ration. J. Food Sci. *52*, 1712–1717.
RUSTOM, I.Y.S., LOPEZ-LEIVA, M.M. and NAIR, B.M.J. 1996. UHT-sterilized peanut beverages: Kinetics of physicochemical changes during storage and shelf-life prediction modeling. J. Food Sci. *61*, 198–203.
SALVADOR, A. and FISZMAN, S. 2004. Textural and sensory characteristics of whole and skimmed flavored set-type yogurt during long storage. J. Dairy Sci. *87*, 4033–4041.
SALVADOR, A., VARELA, P., FISZMAN, S. and GOMEZ, G. 2006. Estimating the shelf life of brown pan bread, suitability of survival analysis methodology. J. Food Sci. *71*, S32–325.
SALVADOR, A., VARELA, P. and FISZMAN, S. 2007. Consumer acceptability and shelf life of "flor de invierno" pears (*Pyrus communis L*) under different storage conditions. J. Sensory Studies *22*, 243–255.
SIEGMUND, B., DERLER, K. and PFANNHAUSER, W. 2001. Changes in the aroma of a strawberry drink during storage. J. Agric. Food Chem. *49*, 3244–3252.
SURTI, T., ANTHONY TAYLOR, K.D. and MARUF FARID, W. 2001. The effect of storage at tropical ambient temperature on the quality and shelf life of grouper (*Plectropomus maculatus*). Int. J. Food Sci. Technol. *36*, 517–522.
TALAVERA-BIANCHI, M., CHAMBERS, D.H., CHAMBERS IV, E., ADHIKARI, K. and CAREY, E.E. 2011. Sensory and chemical properties of organically and conventionally grown pac choi (*Brassica rapa* var. Mei Qing Choi) change little during 18 days of refrigerated storage. LWT – Food Sci. Technol. *44*, 1538–1545.
THYBO, A.K., BECHMANN, I.E. and BRANDT, K. 2005. Integration of sensory and objective measurements of tomato quality: Quantitative assessment of the effect of harvest date as compared with growth medium, variety and maturity. J. Sci. Food Agric. *85*, 2289–2296.
VAISEY-GENSER, M., MALCOLMSON, L.J., RYLAND, D., PRZYBYLSKI, R., ESKIN, A.M. and ARMSTRONG, L. 1994. Consumer acceptance of canola oils during temperature-accelerated storage. Food Qual. Prefer. *5*(4), 237–243.
VALLEJO-CÓRDOBA, B. and NAKAI, S. 1994. Keeping quality assessment of pasteurized milk by multivariate analysis of dynamic headspace gas chromatographic data 1. Shelf-life prediction by principal component regression. J. Agric. Food Chem. *42*, 989–993.
VANKERSCHAVER, K., WILLCOX, F., SMOUT, C., HENDRICKX, M. and TOBBACK, P.J. 1996. Mathematical modeling of temperature and gas 3composition effects on visual quality changes of cut endive. J. Food Sci. *61*, 1094–1098.
VARELA, P., SALVADOR, A. and FISZMAN, S. 2005. Shelf-life estimation of "Fuji" apples: Sensory characteristics and consumer acceptability. Postharvest Biol. Technol. *38*, 18–24.
VILLANUEVA, N.D.M. and TRINDADE, M.A. 2010. Estimating sensory shelf life of chocolate and carrot cupcakes using acceptance tests. J. Sensory Studies *25*, 260–279.
WANSINK, B. and WRIGHT, A. 2006. "Best if used by . . ." How freshness dating influences food acceptance. J. Food Sci. *71*, S354–S357.