

Article

Shelf-life Assessment on European Cucumber Based on Accelerated Temperature–Humidity Stresses

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Abstract: The supply chain has been significantly impacted recently, and as a result the handling of products at the delivery and supply stage is of great importance. Currently, the agronomic industry is one of the most studied, but the reliability of harvests is not usually evaluated. This study uses a novel reliability analysis with an accelerated life test to expose the European cucumber (*Cucumis sativus* L.) to accelerated temperature and humidity conditions. The objective is to observe the effect of both factors on the deterioration of the product. The analysis includes a degradation analysis to determine the significant factors causing degradation, followed by an accelerated life test (ALT) to determine the product's shelf life. Finally, through the development of a reliability model, storage times for cucumbers under normal storage conditions are predicted.

Keywords: European cucumber (*Cucumis sativus* L.); life assessment analysis; accelerated life testing; lognormal temperature–humidity relationship; supply chain



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1. Introduction

The international trade in fruit and vegetables is a sector that represents one of the main items of exportation and foreign exchange between Mexico and the United States [1]. It is estimated that in Mexico, 20% to 35% of the production of agricultural products to be exported to the United States becomes lost during the postharvest stage (storage and transportation). During these stages, changes are made in quality attributes where the product loses firmness and carries out changes in color and shape [2]. Among other changes that can be presented, is weight loss. It is considered that a horticultural product suffers from wilting when it has a loss of 5% of its weight [3]. Since cucumber is highly perishable, it is prone to physiological damage, moisture loss, shriveling, yellowing, and microbiological deterioration [4]. In trying to minimize the impact of the loss of quality attributes, attention is drawn to highlighting the effects of the usual environmental conditions that the product is exposed to over the storage process to the final consumer [5].

Thus, it is necessary to perform a reliability analysis on European cucumber to analyze the effect of temperature and humidity on the supply chain stage as factors causing the loss of product quality. For reliability tests, a probability model is fitted to determine the product's lifetime by using life–strength relationships. These models allow us to know the process of the degradation of a product considering whether it complies with its quality characteristics [6].

Reliability testing relies on accelerated life testing to obtain lifetime data for a product in less time. For accelerated life tests, the product is induced to lose its quality attributes in

an accelerated way under severe conditions. Such data are useful to infer the reliability of a product under normal conditions of use by mathematical models such as the Arrhenius life–strength relationship, where the response variable is time [7]. In this investigation, the percentage of weight loss is reached over specific humidity and temperature levels.

In works such as Salinas [8], it is explained how the Arrhenius equation can model the dependence of the deterioration reactions of fresh-cut crop products concerning temperature. Similarly, Ocampo [9] used the Arrhenius equation to predict the shelf life of soluble coffee powder at 25, 30, 35, and 40 °C relative to the type of packaging. They evaluated the laminated paper, cardboard, and glass, making physical–chemical, microbiological, sensory, relative humidity, and water activity tests. It was found that the glass packaging had a longer shelf life, maintaining better relative humidity, pH, acidity, and color for 624 days compared with laminated paper and paperboard with 279 and 466 days, respectively.

Xiao [10] investigated accelerated shelf-life testing (ASLT) through sensory evaluation and acceptability of green tea including high temperatures, light, oxygen, and humidity during the test. They showed that it is possible to predict the suitable drinking period of green tea during storage through the Q10 method. Moreover, the shelf life of mayonnaise was estimated through accelerated testing [11]. The specific reaction constants were estimated using the peroxide index as an accelerating deterioration factor, and then the Arrhenius equation was used. They found a relationship to estimate the shelf life of the mayonnaise.

Similarly, estimations of the life of tomato paste were performed through accelerated testing, using color degradation as a stressing deterioration factor. Moreover, with the reaction rates and the Arrhenius equation, a linear relationship was obtained to estimate the shelf life of tomato paste [12].

Temperature has been reported as a factor that influences the decrease in firmness of a fruit; an increase in temperature during storage causes the firmness of the product to decrease. As an example, a study was performed on sagging pepper cultivars. In this study, superficial depression was measured in response to applied finger pressure; a 4.5- to 9-fold increase in flaccidity was observed in peppers stored for 14 days at 14 °C compared with those stored at 8 °C [13]. In [14], Miccolis and Salveit reported a greater decrease in the firmness of melons stored for 3 days at 15 °C and 20 °C compared with those stored at 7 °C.

The most significant chemical reactions involved in the deterioration of food and the reactions between them are related to the situations that are found during the storage and processing of food. Table 1 shows the variables of interest during food storage and processing. Temperature is the most important factor because it influences all kinds of chemical and biological reactions. The effect of temperature on a reaction can be determined from the Arrhenius equation. In food systems, the Arrhenius equation can only be used in a range of experimentally proven temperatures [15].

Table 1. Important factors in the stability of food during processing and storage, adapted from [15].

Food factors	Chemical properties, oxygen content, pH, water activity, glass transition temperature (T_g), and whole grain content (W_g).
Environment factors	Temperature (T), time (t), atmosphere composition, chemical treatments, light exposure, contamination, and physical abuse.

Another important variable in the process of degradation of a food product is time; during storage, it is necessary to know the time in which the product can be maintained at a quality level. Therefore, the lifetime of a product is a function of the structural changes, whether they occur in a physical, chemical, and/or microbiological way during a given storage period. Then, the way in which these changes are combined is discriminant in the specific storage life for each product [15].

Weight loss and lack of firmness are the main types of stress that generate alterations in the characteristics of the cucumber. These alterations are directly related to factors such as the temperature and humidity at which the cucumbers are found during storage in

postharvest refrigeration chambers. In fruits and vegetables, the effect of low temperatures induces structural changes in the water inside the cells, which can lead to the loss of texture. This is because the temperature changes that occur during thawing cause the loss of water retained in the cells, causing the food to lose its rigidity and freshness, transforming to loose and soft tissue [16].

This negatively impacts the economy of the agri-food industry dedicated to the production and export of cucumbers, causing a focus on maintaining the conditions of firmness and weight to the final consumer.

The transpiration or evaporation of water in fruits and vegetables increases with temperature and storage time, causing a weight loss of 1–12% in normal periods and up to 30% in extreme conditions. Weight losses translate into losses of quality characteristics, causing considerable economic losses and even legal problems since the net weight declared for marketing is not met [17].

In practice, accelerated life tests are usually applied. Some of these tests are performed at elevated temperatures and subsequently extrapolated to the storage temperature. Food types of acceleration stress that can be applied to accelerated life tests include temperature, humidity, chemicals, pH, oxygen, and solar radiation [18]. To evaluate the decline in the quality of food items, it is essential to conduct tests to measure their shelf life and assess structural changes that occur due to external factors.

Shelf life refers to the period of time between the product's creation or harvest and when it experiences significant alterations that can lead to it being rejected by the consumer. These modifications depend on the manufacturing method, the product's characteristics, and the storage duration, leading to both microbiological changes and changes in sensory and/or physical–chemical properties of the food [19].

For this study, the European variety of cucumber (*Cucumis sativus* L.) was used, which is grown under shade mesh and provided by an agricultural packaging company located in Sinaloa, Mexico. According to our industry partner, the ideal temperature range for cucumber harvesting during the day is 20–30 °C. Temperatures above 30 °C can negatively affect the growth of the plants, while temperatures below 17 °C at night can cause malformations in leaves and fruits.

The critical threshold temperature is 14 °C, where growth stops, and temperatures below freezing cause damage to the plants. The cucumber plant requires a high level of humidity, with the optimal relative humidity during the day being 60–70%, and at night being 70–90%. However, excessive humidity during the day can lower production by reducing perspiration and subsequently photosynthesis. When the humidity level exceeds 90% and the atmosphere is saturated with steam, condensations on the crop or dripping from the cover can lead to fungal diseases. Additionally, a wet crop in the morning starts working later as the energy must be directed towards evaporation of water from the surface of the leaves [19,20].

Once collected, the cucumber begins to undergo rapid metabolic changes that lead to tissue aging and death. Postharvest handling contributes to maintaining the product's quality for the final consumer; among the major postharvest problems are physical and chemical changes that detract from the product's appearance and quality; the rate of fruit decomposition varies depending on storage and transport conditions. Ref. [21] presented a study where different degradation tests were made to cucumbers with and without a plastic cover, and a weight loss less than 1% was observed in the cultivars of cucumber with plastic films and about 8% in the cultivars without plastic films. This same procedure was used to execute our degradation test.

Despite the risk of such economic losses, the agricultural industry does not have information on the effects relative humidity conditions and temperature may cause on weight loss and lack of firmness in the European cucumbers during storage in refrigeration chambers. The knowledge of the shelf life of European cucumbers allows us to predict the losses of the quality attributes of the product under normal operating conditions and thus be able to reduce the claims received by the customer.

This research examines how temperature and humidity affect the shelf life of European cucumbers since there is a literature gap on this theme. The study then uses accelerated life testing to model how these factors impact the quality attributes required for exporting these cucumbers. By doing so, the research aims to assist the agricultural industry by providing predictions on the weight and firmness of European cucumbers at various storage temperatures, thus helping to minimize economic losses.

2. Materials and Methods

The objective of this method is to implement an accelerated life test and subsequently conduct a life assessment on European cucumbers in order to identify the most optimal storage and sale conditions. The procedure is the following: First, a design of experiments is carried out to measure percentage of loss of weight, firmness, total soluble solids, and pH of cucumber in environment conditions. This study was complemented by a correlation analysis between weight loss and the rest of quality characteristics. The primary objective was to determine the failure mode at the accelerated life testing. Hence, a temperature humidity is performed to observe the influence of these variables on percentage of weight loss. Once these characteristics have been analyzed, the accelerated life test is designed, including the factors that cause the degradation of the cucumber. Consequently, an accelerated life test is performed by subjecting the cucumbers to temperature and humidity. Finally, life statistics are derived using a reliability model. To determine the optimal conditions for transport and storage of cucumbers that extend their shelf life, percentiles were determined.

2.1. Design of Experiments and Degradation Analysis

In the present study were evaluated postharvest qualities of fresh cucumbers. The degradation test procedure was performed following the method of [21]. Important quality characteristics were measured, such as: percentage of weight, firmness, total soluble solids, and pH. The sampling was taken every three days for a period of 21 days. The cucumber was manually selected during the postharvest selection process following the standards for USDA's premium quality cucumber selection [22] for a premium quality product. This was performed in coordination with our industry partner in Sinaloa, Mexico.

For non-destructive testing, European cucumbers with and without packing were selected in the packing line, then weighed and stored at $96 \pm 2\%$ relative humidity and 9.8 ± 0.2 °C temperature in the refrigeration chamber of the agricultural company where it would remain during the weight loss percentage evaluation time.

For destructive testing, both cucumbers with and without packing were selected in packing line and subsequently the samples were transferred to environmental conditions to the Postharvest Research Laboratory in the Department of Biochemical Engineering of the Technological Institute of Culiacan to perform weight loss, firmness, pH, and total soluble solids analyses. The results of the degradation test under normal conditions were used as a reference for the design of the accelerated life test experiment.

For the statistical analysis of the life test with respect to the percentage of weight loss, firmness, total dissolved solids, and pH, a one-way analysis of variance (ANOVA) was performed. The significance level of the tests was established with a p -value less than alpha level of 0.05 using the statistical package Minitab [23].

2.1.1. Weight Loss Analysis

For the determination of weight loss, 36 European cucumbers were evaluated per treatment. An Ohaus granata scale was used, in which the two treatments of cucumber fruits were weighed individually every third day of storage. The measurements were made in triplicate and the weights were recorded in grams during the time elapsed during storage. The results were expressed in percentage weight loss using Equation (1) as follows:

$$\%WL = \frac{(Iw - Fw)}{Fw} (100) \quad (1)$$

where

- %WL is the weight loss percentage;
- Iw is the starting weight;
- Fw is the final weight.

2.1.2. Firmness Analysis

The determination of firmness was made based on the effort generated to penetrate the pericarp of the fruit (firmness) with a circular punch with a flat tip of 10 mm in diameter using a Chatillon penetrometer model DFGS50. Prior to the analysis, a part of the cuticle of the fruit was removed with a knife to prevent the cuticle from influencing the results, according to the methodology of [24]. The measurements were made in three different areas of the cucumber and the values obtained were expressed in Newton (N). During this experiment, a penetrometer with a 0.5 cm strut was used to determine hardness. This measurement is based on the pressure (N/cm^2) required to pierce the fruit's pericarp. The cucumber pulp and skin were relatively stiff, measuring 3.7 and 20.6 N, respectively [24].

2.1.3. Analysis of Total Soluble Solids ($^{\circ}\text{Brix}$)

For the determination of total soluble solids present in cucumbers, the method recommended by the Association of Official Agricultural Chemists (AOAC) [25] was used. Then, 30 g of the sample was weighed in a digital scale of the brand Milton Roy, and was homogenized using a commercial blender, with 50 mL of distilled water for 30 s. After the sample was filtered with muslin cloth, this volume was graduated to 100 mL. Subsequently, a drop was taken from the sample and placed on a Milton Roy model refractometer, previously calibrated with distilled water to a value of zero. The measurements were carried out in triplicate.

2.1.4. pH Analysis

To determine the pH in the European cucumbers, 30 g of sample were weighed on a digital scale Hach Session 3 model. Then homogenization was performed using a commercial blender, with 50 mL of distilled water for 30 s. After, the sample was filtered with muslin cloth, this volume was forged to 100 mL. Subsequently, a 40 mL aliquot was taken from the sample in a 125 mL Erlenmeyer flask where a reference electrode of the potentiometer, previously calibrated with buffer solutions with pH values of 4.7 and 10, was introduced [25].

2.2. Experimental Design for Accelerated Life Testing

For this purpose, a completely randomized factorial design of $2 \times 3 \times 3$ [26] was used. The factors and levels are described in Table 2.

Table 2. Complete factorial design of experiments $2 \times 3 \times 3$.

Factor	Level		
Relative Humidity (%)	55	70	85
Temperature ($^{\circ}\text{T}$)	20	30	40
Packaging Cover	With Cover	Without Cover	

Once the point at which it was considered failure was reached, samples were extracted from the incubation chamber for analysis. Subsequently, the results were analyzed using the temperature–humidity relationship.

Table 3 shows the design of experiment used for the accelerated life testing. This design specifies the 18 treatments European cucumbers were subjected to in the incubation chamber during the accelerated life test.

Table 3. Design of experiments for the accelerated life testing.

Treatment	Cover	Relative Humidity (%)	Temperature(°C)
1	without	70	30
2	with	85	20
3	without	55	30
4	with	55	20
5	without	70	40
6	with	70	30
7	without	85	30
8	with	70	20
9	without	55	30
10	with	55	40
11	without	85	40
12	with	85	40
13	without	70	40
14	with	55	20
15	without	55	40
16	with	85	30
17	without	70	20
18	with	85	20

2.3. Accelerated Life Testing Model

The purpose of the accelerated life testing is to establish the life under shipping conditions using a temperature–humidity (T-H) Relationship. The impact of temperature and humidity on life is necessary when employing the T-H ratio. Due to the various stress levels of the temperatures and humidity, the test should be conducted in a variety of ways. In order to allow the effect of temperature to accelerate failure, humidity was chosen to be fixed.

When temperature and humidity are the accelerated stresses in a test, the humidity temperature ratio, a version of the Eyring ratio, is treated to forecast longevity under conditions of usage. Equation (2) combination model [18,27] can be used to estimate life $L(V, U)$:

$$L(V, U) = Ae^{\frac{\phi}{V} + \frac{b}{U}} \quad (2)$$

where

- ϕ is one of the three parameters to be estimated;
- b is the second of three parameters to be estimated (also known as the moisture activation energy);
- A is a constant and the third of the three parameters to be determined;
- U is the relative humidity (decimal or percentage);
- V is the temperature (in absolute units).

Then, life can be achieved by maintaining one of the two stresses while altering the other, as life is now a function of two stresses. If carried out, it results in a straight line where, in addition to the constant $\ln(A)$, the term for stress that stays stable becomes another constant [18,27].

Following [18], the acceleration factor for the T-H ratio is provided by Equation (3) as follows:

$$AF = \frac{L_{Use}}{L_{Accelerated}} = \frac{Ae^{\frac{\phi}{V_U} + \frac{b}{U_U}}}{Ae^{\frac{\phi}{V_A} + \frac{b}{U_A}}} = e^{\phi(\frac{1}{V_U} + \frac{1}{V_A}) + b(\frac{1}{U_U} - \frac{1}{U_A})} \quad (3)$$

where

- L_{Use} is the life at use stress level;
- $L_{Accelerated}$ is the life at accelerated stress level;
- V_u is the use of temperature level;
- V_A is the accelerated temperature level;
- U_A is the accelerated humidity level;
- U_u is the use humidity level.

2.3.1. Temperature Humidity Lognormal Model

At the accelerated life testing (ALT), the Failure Data are demonstrated to be lognormal. Then, using Equation (4), the lognormal pdf is used:

$$f(T) = \frac{1}{T\sigma_{T'}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T' - \bar{T}'}{\sigma_{T'}}\right)^2} \quad (4)$$

where $T' = \ln(T)$ and T = Times to failure. $\bar{T}'$ and $\sigma_{T'}$ are the mean and the standard deviations of the natural logarithms of the times to failure, respectively.

Where the median of the lognormal distribution is provided by (5):

$$\check{T} = e^{\bar{T}'} \quad (5)$$

Once T is set to equal $\check{T} = L(V, U)$, the T-H lognormal model pdf may be produced, leading us to Equation (6):

$$e^{\bar{T}'} = Ae^{(\frac{\phi}{V} + \frac{b}{U})} \quad (6)$$

Taking the logarithm of Equation (5) we obtain now Equation (7):

$$\bar{T}' = \ln(A) + \frac{\phi}{V} + \frac{b}{U} \quad (7)$$

Substituting Equation (7) into (3) the lognormal pdf obtains the T-H lognormal model or pdf (8):

$$f(T, V, U) = \frac{1}{T\sigma_{T'}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T' - \ln(A) - \frac{\phi}{V} - \frac{b}{U}}{\sigma_{T'}}\right)^2} \quad (8)$$

2.3.2. The T-H Lognormal Reliability Function

Reliability estimations are being made, then we use the cumulative distribution function to obtain $R(t)$ (9):

$$R(T, V, U) = 1 - Q(T, V, U) = 1 - \int_0^T F(t) dt \quad (9)$$

Then the reliability function is provided by (10)

$$R(T, V, U) = \int_{T'}^{\infty} \frac{1}{\sigma_{T'}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T' - \ln(A) - \frac{\phi}{V} - \frac{b}{U}}{\sigma_{T'}}\right)^2} dt \quad (10)$$

3. Results

3.1. Degradation and Statistical Analysis

The initial phase of the study, as mentioned in the methodology, included a cucumber degradation analysis. As stated, the main objective was to determine the effects that imply a level of loss of quality of the cucumbers, and then consider it as a failure mode in the accelerated life test. Therefore, every third day for 21 days of sampling, samples of three European cucumbers with plastic covers and three without plastic covers were compared to assess the percentage of weight loss, firmness, °Brix, and pH. The results are shown in Table 4.

Table 4. Mean values of percentage of weight loss, total soluble solids, pH, and firmness in the degradation test.

Day	Cover	Weight Loss (%)		°Brix		pH		Firmness	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	with	1.5788	0.04	3.1333	0.015	6.0	0.006	71.2333	0.55
3	with	3.5386	0.045	3.3667	0.012	6.1433	0.015	70.8555	0.55
5	with	6.1572	0.027	3.6	0.011	6.3566	0.010	70.3555	1.00
7	with	8.3774	0.015	3.3667	0.009	6.7333	0.010	69.9666	1.01
9	with	10.1885	0.31	3.2333	0.012	6.82	0.011	69.6	0.60
11	with	11.7414	0.018	3.2667	0.013	7.12	0.02	69.4444	0.52
13	with	13.8750	0.059	3.6	0.067	7.3033	0.009	69.1888	1.00
15	with	15.9681	0.052	3.8333	0.015	7.75	0.010	68.7555	0.55
17	with	17.6796	0.13	3.9	0.043	7.53333	0.011	67.4888	0.54
1	without	0.1989	0.009	3.0333	0.008	6.06	0.012	69.7111	0.55
3	without	0.2339	0.010	3.4667	0.012	6.0866	0.016	71.1888	0.68
5	without	0.3686	0.016	3.1	0.018	6.22	0.010	71.4888	1.02
7	without	0.4245	0.023	3.1	0.007	6.53	0.012	71.5555	1.00
9	without	0.4799	0.02	3.0333	0.014	6.7233	0.010	71.0555	1.10
11	without	0.5939	0.015	2.9333	0.011	6.7633	0.012	71.0555	1.10
13	without	0.6593	0.012	3	0.012	6.84	0.015	68.8111	0.75
15	without	0.7459	0.016	3.0333	0.012	7.01	0.010	69.9666	0.55
17	without	0.8460	0.009	3.1	0.013	7.0733	0.015	69.8333	0.48

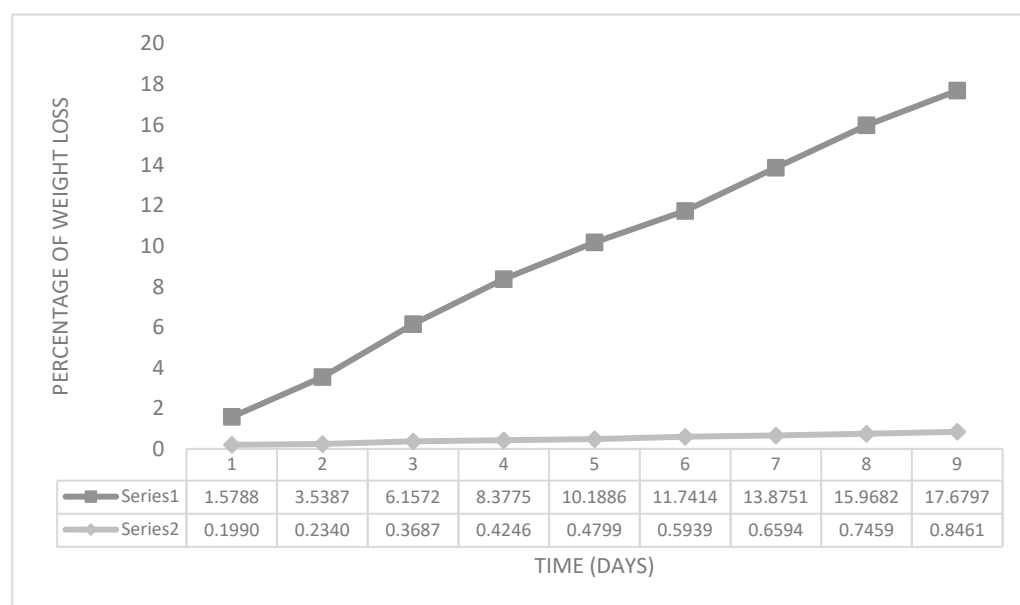
With these values, an ANOVA analysis was performed to obtain the significance of each value over the deterioration of the cucumbers. The outcomes from the evaluated parameters are displayed in Table 5. This table shows the significant factors affecting the degradation of the cucumbers. Regarding the obtained results, it was observed that firmness and pH did not present a significant difference from the statistical analysis. Hence, the decision was made to discard both firmness and pH evaluations during the accelerated life test.

Finding the numbers that the accelerated test would use to be a complete failure was the goal of this investigation. To determine the values at which it is believed that the cucumbers no longer possess the desired quality, the degradation analysis was conducted. The comportment of pH, °Brix, and weight loss over time was then observed.

Clearly, the linearity of weight loss by time is observed. Figure 1 depicts the significant weight loss over time. This measurement is used to identify the point at which the product may fail.

Table 5. Significance obtained from the degradation analysis. Percentage of weight loss, total soluble solids, firmness and pH.

Parameter	Plastic Cover	Mean	<i>p</i> -Values
Weight loss (%)	With cover	8.8689	0.0002
	Without cover	0.3760	
Firmness (N)	With cover	69.3611	0.1
	Without cover	69.7722	
Total soluble solids (°Brix)	With cover	3.5167	0.002
	Without cover	3.0667	
pH	With cover	6.7983	0.277
	Without cover	6.0600	

**Figure 1.** Weight loss with respect to time. Without cover (squares) and with cover (diamonds).

Due to weight loss during the initial days of storage, which causes the cucumber's solids to concentrate, the percentage of °Brix is seen to grow in both treatments. However, as the cucumbers ages, it becomes obvious that the percentage of °Brix drops. At this point, it can be argued that there is a relationship between the increase in pH and the numbers, keeping in mind that when this occurs, organic acids are transformed into sugars throughout the maturation process. However, the values continue to rise. See Figure 2. Moreover, the cover impacts the reduction in moisture loss, so the solids do not have much change. Therefore, small changes in the percentage of weight loss are observed, but impact the °Brix growth at the beginning of the time.

Because organic acids are a source of energy for fruits and vegetables and are used in the breathing process or transformed into sugars during maturation, treatments have a propensity to raise their pH values. This relationship is visualized in Figure 3.

In the firmness analysis shown in Figure 4, a decreasing trend is seen, but an increase in firmness values is also observed. This is caused by the plastic covering. This is another reason of why the firmness analysis on European cucumbers at accelerated life testing were not taken into consideration, since it is observed that this variety develops consistency during storage.

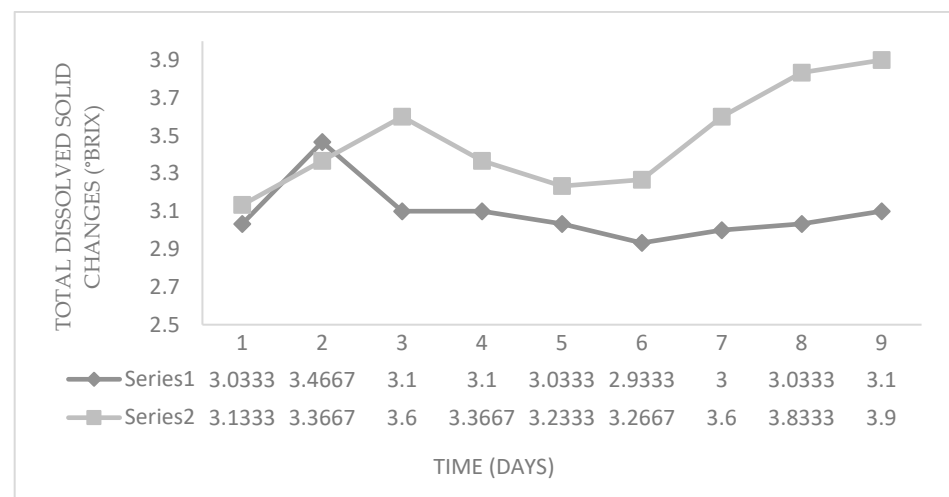


Figure 2. Total dissolved solids changes (°Brix) with respect to time. Without cover (squares) and with cover (diamonds).

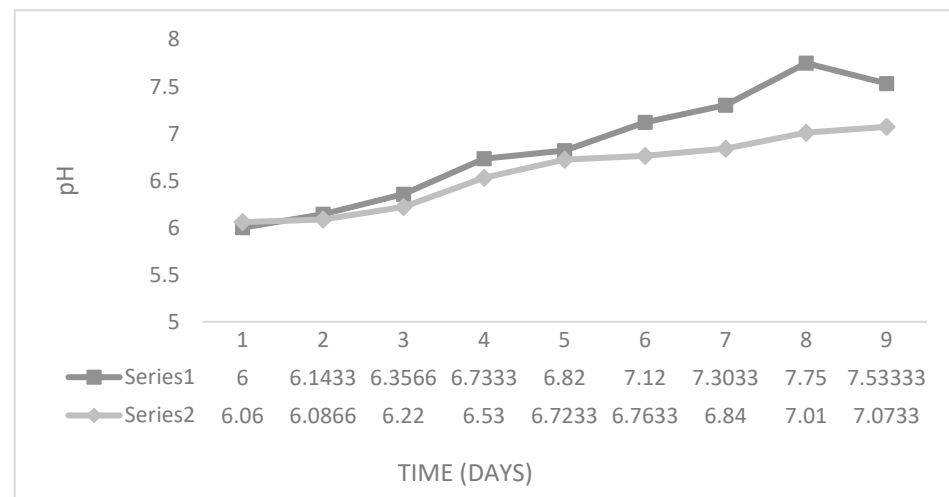


Figure 3. pH changes with respect to time. Without cover (squares) and with cover (diamonds).

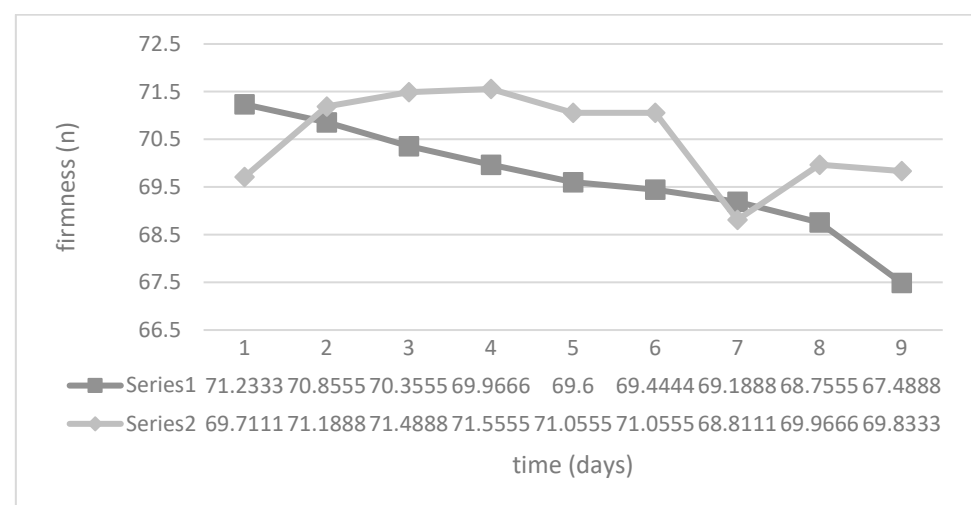


Figure 4. Changes in firmness relating to time. Without cover (squares) and with cover (diamonds).

The percentage of weight loss of the European cucumbers revealed a statistically significant variation regarding temperature and relative humidity ($p = 0.000$). Table 6 presents a statistical examination of the influence of temperature, and relative humidity on the percentage of weight loss.

Table 6. Regression ANOVA table with significance of factors of weight loss. * is indicating the interaction between the factors.

Source	Degrees of Freedom	Sum Squares	Mean Squares	F-Value	p-Value
Model	13	601,594,098	46,276,469	116.28	0.000
Linear	5	458,050,430	91,610,086	230.19	0.000
Temperature	2	173,051,457	86,525,729	217.41	0.000
Humidity	2	157,847,555	78,923,778	198.31	0.000
Cover	1	12,204,962	12,204,962	30.67	0.000
2-Way Interactions	8	134,191,318	16,773,915	42.15	0.000
Temperature*Humidity	4	93,275,372	23,318,843	58.59	0.000
Temperature*cover	2	44,029,652	22,014,826	55.32	0.000
Humidity*cover	2	1,145,869	572,935	1.44	0.243
Error	88	35,022,097	397,978		
Lack-of-Fit	3	19,282,700	6,427,567	34.71	0.000
Pure Error	85	15,739,397	185,169		
Total	101	636,616,195			

As mentioned before, Wills [3] stated that although wilting is well-known, the commercial quality of cucumber is impacted with a weight loss of more than 5%, in addition to other physicochemical parameters changing. According to Muy [28], fruits and vegetables begin to show signs of water loss when they lose between 5 and 10% of their weight, primarily as a result of perspiration and the structural makeup of the tissues. Moreover, the methodology we followed for degradation analysis included a previous study showing that weight loss is presented in less than 1% in cucumbers with plastic films and about 8% in the cultivars without plastic films [21].

Based on our experimentation the weight loss percentage of European cucumbers, began at 5% for cucumbers without plastic covers and 0.5% for cucumbers with plastic covers; therefore, these values serve as reference limits for the incubation and testing phase. With the intention of determining and confirming the levels at failure due to quality loss, a correlation analysis was performed.

Figure 5 shows the correlation analysis between the percentage of weight loss versus firmness, °Brix, and pH. A high correlation is observed as weight loss increases, firmness, °Brix, and pH, are considerably changed. Moreover, it can be observed that the scale is showing values between 0.1 and 0.9% of weight loss. Therefore, based on the correlation plot and the impact on changes on quality characteristics, 0.7 was determined as a point of failure in the case of cucumbers with covers.

Figure 6 depicts the analysis of the correlation between the percentage of weight loss and firmness, °Brix, and pH in the absence of a cover. It was observed that as weight loss increases, firmness, °Brix, and pH are significantly altered. Moreover, the scale indicates weight loss values between 1 and 19%. On the basis of the correlation plot and the effect of changes on quality characteristics, the point of failure for cucumbers without a cover was determined to be 5%.

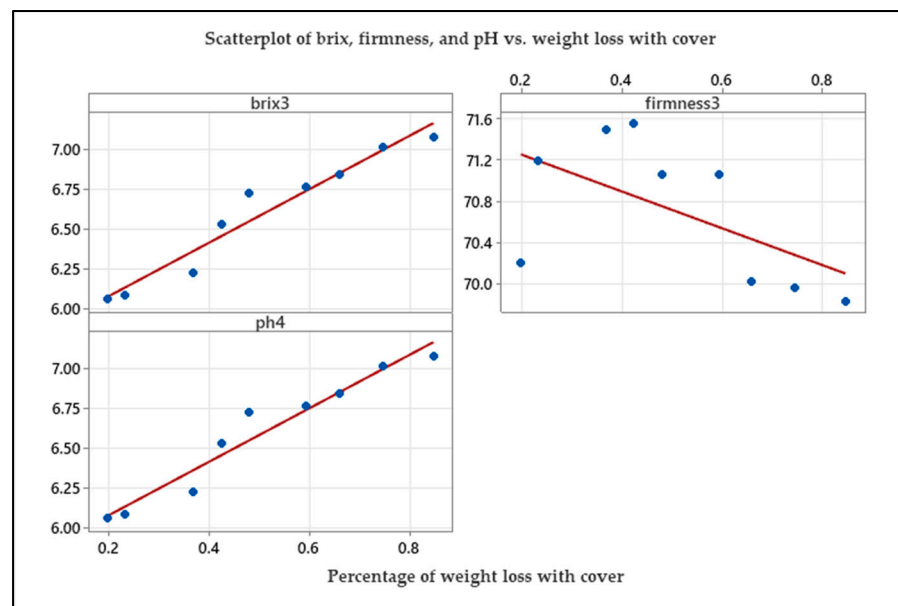


Figure 5. Correlation analysis of percentage of weight loss vs. firmness, °Brix, and pH with cover.

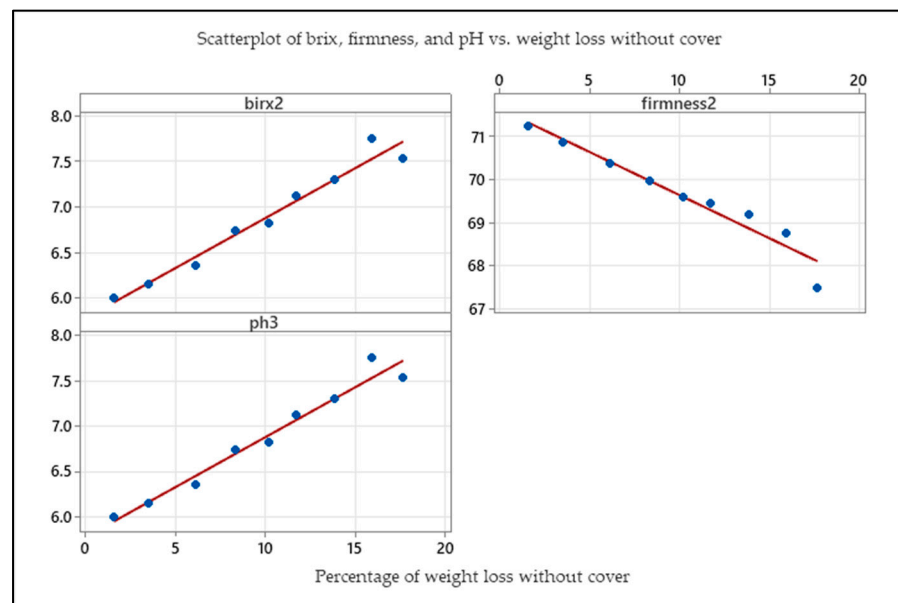


Figure 6. Correlation analysis of percentage of weight loss vs. firmness, °Brix, and pH without cover.

3.2. Accelerated Life Testing and Reliability Estimations

After the degradation analyses were complete, the accelerated life test was performed to acquire the failure times for the Temperature–Humidity model. To determine the postharvest parameters, six samples of European cucumbers with plastic covers and six samples without plastic covers were compared. The product was put under accelerated stress conditions to perform the accelerated life test, and weight loss was used to determine when it had failed. Failure times were determined, and life–stress relationships were then applied. Table 7 shows the stress levels and failure times under accelerated stresses (relative humidity and temperature) showing time to reach 5% weight loss for cucumbers with packaging covers and 0.7% for cucumbers without packaging covers (Failure Data).

Table 7. Accelerated failure times to reach the percentage of weight loss.

COVER	RH (%)	T (°C)	TIME (Min)					
			Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
With cover	55	20	3195	3195	3360	4240	3720	3300
		30	2462	2295	2672	1666	2218	1573
		40	967	1216	747	968	1185	1099
	70	20	2604	2817	2648	2240	2830	2550
		30	3178	3161	3039	2779	3036	3170
		40	2267	2133	1999	1985	2310	2159
	85	20	8426	6603	6932	8634	7682	7149
		30	3085	4098	4396	5043	5326	3722
		40	1638	1609	1525	1522	1550	1530
Without cover	55	20	2520	3150	2898	3150	2520	2898
		30	1120	1244	1291	1031	1171	1031
		40	920	620	1101	930	956	920
	70	20	6743	7554	7070	8326	6630	6743
		30	2675	2675	2525	2675	2525	2525
		40	1300	1095	1095	1240	1300	1300
	85	20	9153	9261	10,539	8667	8883	8235
		30	5290	4600	5580	5290	5824	4600
		40	981	1275	880	1230	1110	880

Using the accelerated life testing results, the impact of the influence of temperature, humidity, and plastic covers on the life of the cucumber was determined. Figure 7 illustrates how the various factors affect the life of the cucumber. This graph shows how life decreases as temperature increases. Furthermore, it is irrefutable that a cucumber's lifespan increases as the relative humidity rises.

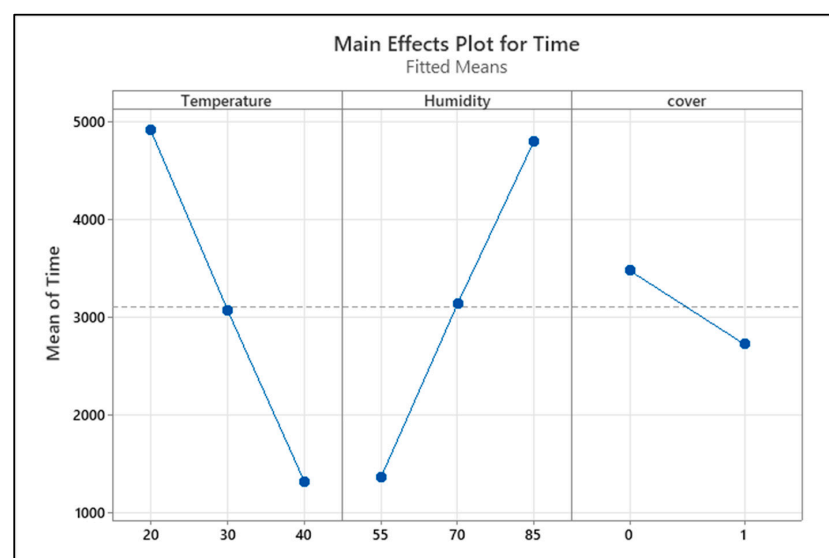


Figure 7. Significance on factors over mean life degradation. Blue lines indicate the mean life at different levels of temperature, humidity and packaging cover.

Moreover, through the accelerated life testing, the significance of the regression parameters was determined. The values in Table 8 demonstrate how temperature and humidity have an impact on the cucumber's lifetime since the p -value is below any alpha level. These factors contribute to the failure mode in some way.

Table 8. Regression coefficients from accelerated life testing.

Predictor	Coefficient	Standard Error	Z Value	p -Value
Intercept	−13.3911	0.975692	−13.72	0.000
Temperature	0.506857	0.0259818	19.51	0.000
Humidity	0.0281539	0.0023371	12.05	0.000
Shape	3.77249	0.286562		

The accelerated life relationship was obtained following the discovery of the significant factors. Estimates of the parameters were obtained after analyzing a lognormal temperature–humidity graph. The connections for each stress level are shown in Figure 8. This connection demonstrates the rate of product failure over time. Moreover, the linear correlations between the accelerated temperatures and humidity are shown in Figure 8. This graph shows that life spans decrease with increasing temperature.

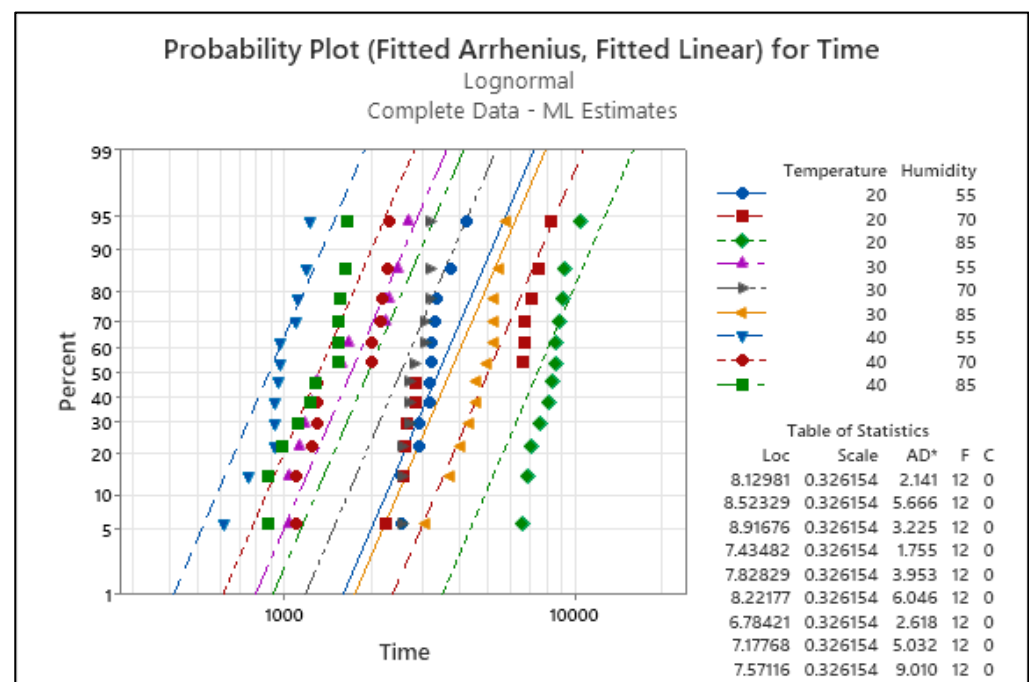


Figure 8. Linear relationships based on log-normal temperature–humidity model. AD* is the Anderson-Darling value for each relationship.

The obtained accelerated life relationship enables one to observe the behavior of life and the effect of stresses on life. As shown in Figure 9, life expectancy decreases as temperatures increase.

Also, the effect of relative humidity on the durability of cucumbers is significant. Figure 10 shows that lifetime decreases as relative humidity decreases.

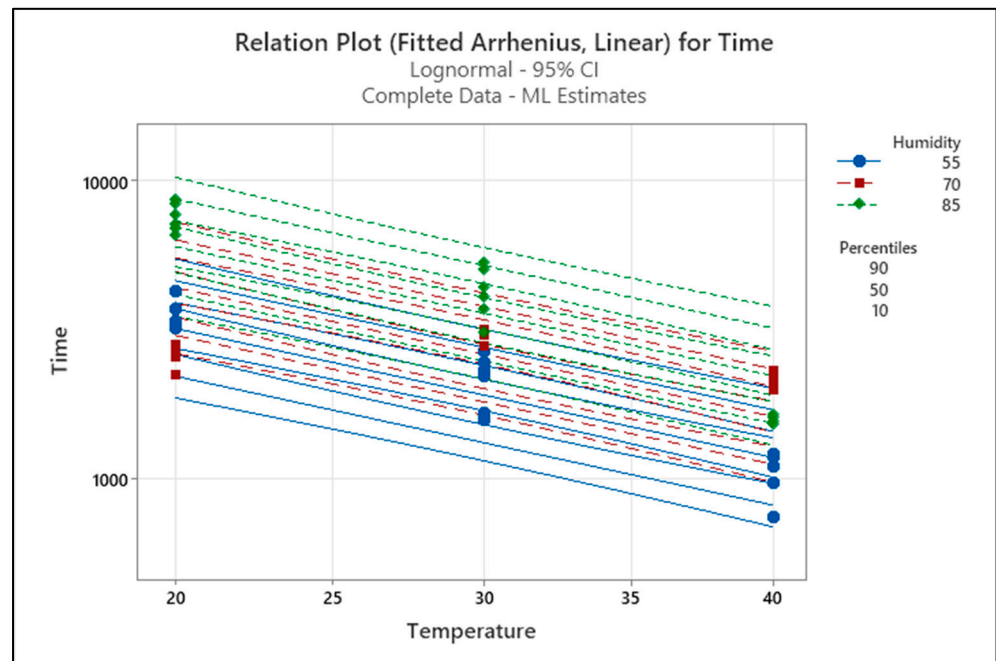


Figure 9. Linear effect of temperature over lifetime.

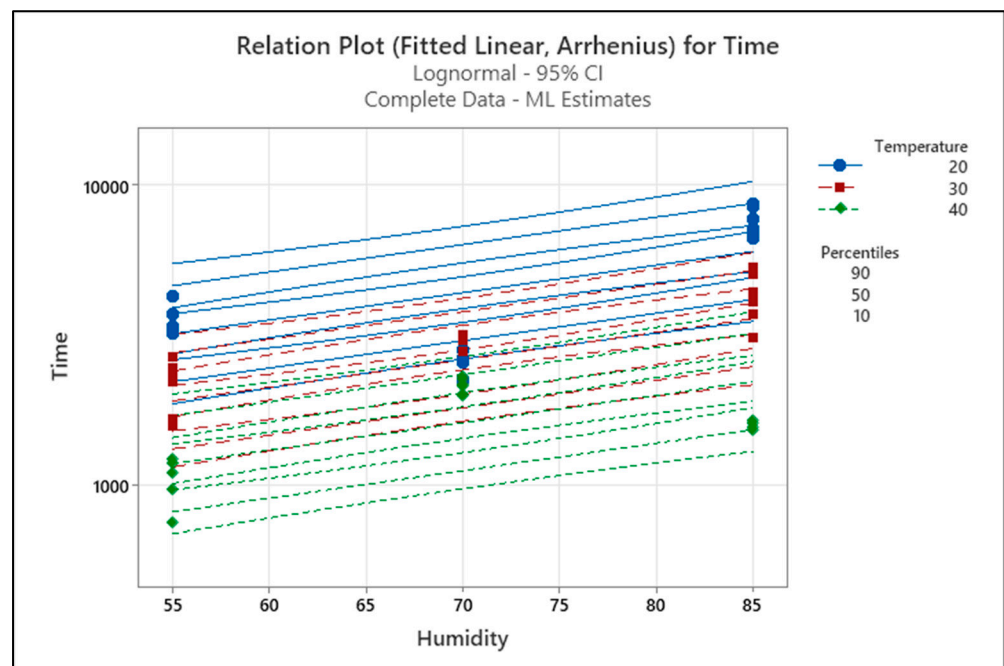


Figure 10. Linear effect of relative humidity over lifetime.

3.2.1. Accelerated Life Testing of Cucumber without Packaging

As was already said, three typical transport and storage handling scenarios were identified. The temperatures are 11, 9, and 7 °C here, while the relative humidity is 96%. The percentiles of interest for the life study are shown in Table 9. A temperature of 11 °C and a RH of 96% were used to calculate percentiles 1, 5, 10, 50, 95, and 99. This serves as a guide for how long a product remains usable given the conditions of storage, transit, and sale. Table 9 demonstrates that just 5% of the product survives storage for more than 13.5 days, while 90% survives storage for 5.9 days at 11° and 96% relative humidity. Moreover, Table 7 shows that 90% of the product survives storage for 6.7 days at 9° and

96% relative humidity, whereas just 5% survives for 15.45 days. Finally, Table 7 shows that, under the storage conditions of 7° and 96% relative humidity, 90% of the product survives 7.5 days and just 5% does so for more than 17.35 days.

Table 9. Percentiles in minutes without packaging.

Percent	Temperature	Humidity	Percentile
1	11	96	6217.74
5	11	96	7561.35
10	11	96	8392.57
50	11	96	12,124.8
90	11	96	17,516.8
95	11	96	19,442.4
99	11	96	23,643.8
1	9	96	7117.11
5	9	96	8655.06
10	9	96	9606.51
50	9	96	13,878.6
90	9	96	20,050.5
95	9	96	22,254.7
99	9	96	27,063.7
1	7	96	7990.12
5	7	96	9716.73
10	7	96	10,784.9
50	7	96	15,581.0
90	7	96	22,510.0
95	7	96	24,984.5
99	7	96	30,383.5

3.2.2. Accelerated Life Testing of Cucumber with Packaging

Three typical transport and storage handling scenarios were found, as was previously stated. Here, the temperature ranges between 11, 9, and 7, and the relative humidity is 96% including packaging cover. The pertinent percentiles for the life study are displayed in Table 10, utilizing a packing cover, an RH of 96%, and a temperature of 11 °C. The 1, 10, 50, 95, and 99th percentiles were calculated. Taking into account the circumstances of storage, transit, and sale, this provides a basic notion of how long a product continues to be valuable. Table 10 shows that just 5% of the product is stable for more than 32 days in storage, while 90% of the product is stable for 14.2 days at 11° and 96% relative humidity. Additionally, it is clear that just 5% of the product is stable for more than 40 days in storage, while 90% of it does so for 17 days at 9° and 96% relative humidity.

Table 10. Percentiles in minutes from ALT with packaging cover.

Percent	Temperature	Humidity	Percentile
1	11	96	15,318.1
5	11	96	18,547.4
10	11	96	20,538.6
50	11	96	29,430.6
95	11	96	46,699.8
99	11	96	56,544.8
1	9	96	19,193.1
5	9	96	23,239.3
10	9	96	25,734.3
50	9	96	36,875.6
95	9	96	58,513.5
99	9	96	70,849.0
1	7	96	23,368.6
5	7	96	28,295.1
10	7	96	31,332.8
50	7	96	44,898.1
95	7	96	71,243.3
99	7	96	86,262.4

4. Discussion

This research extended existing reliability analyses to food, and specifically to cucumber handling and processing after harvest. The principal objective was to determine the exact time of logistics of the product under different conditions. It was demonstrated that engineering models, specifically reliability analysis, can be used in perishable products. Moreover, supply chain management can benefit from the application of the Survival Analysis to perishable food.

Although accelerated life test (ALT) models are widely used in the manufacturing industry, it is not very common to use them in the perishable food industry. This paper presents a new way to predict the lifetime of perishable food products using a reliability theory, especially ALT. The data in this study were obtained using design of experiments (DOEs) and the results were verified through chemical analysis of the subject such as its pH value, °Brix, firmness, and the loss of weight. We used the European cucumber as the subject for our case study and implemented ALT to predict the suitable eating period for the cucumber under different storage conditions and provide instructions to preserve freshness. The suitable eating period for the cucumber is relatively short, so it is important to identify the possible lifetimes of the cucumber stored at certain temperatures and humidity levels. Therefore, the ALT of the cucumber was evaluated using the temperature–humidity model.

The obtained results are quite clear: there is a correlation between the temperature and humidity levels over the course of the lifetime of the cucumber. Through the adjusted life–strength relationship, it is observed that lifetime decreases as temperatures become higher and humidity becomes lower. Using the life prediction model, we were able to estimate a desired storage condition for the cucumber at 7 °C which allows the cucumber to keep its freshness for up to 31 days. Additionally, the study reveals the impact of packaging. It is observed that packaging has a significant impact on the longevity of cucumbers.

Results from this investigation show how the methodology implemented is a powerful tool for reliability and life prediction for perishable food, which can easily be expanded to assess the lifetimes of other perishable foods and provide insight into more potential solutions for extending said lifetimes.

Extensive literature review was performed to determine significant factors for consideration of failure in European cucumbers. However, further research may be necessary to determine the exact point of what can be considered complete failure.

Consequently, the design of the accelerated life test can change. This is why new experiments can be performed to determine an optimal accelerated life test design.

Although the design used for collecting data seems reliable when the development of ALT is being performed, multivariate accelerated life testing is highly recommended in future studies for more accurate results.

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