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The Effect of Accelerated Storage Temperature Conditions on the Shelf Life of Pasteurized Orange Juice Based on Microbiological, Physicochemical, and Color Attributes

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Abstract: The accelerated life testing (ASLT) method was used to evaluate the effect of increasing the storage temperature from 10 to 40 °C on the aerobic plate count (APC), the pH, and the colorimetric parameters (L^* , a^* , b^*) of pasteurized orange juice during 40 days of storage. For APC growth, a polynomial model was found to fit better, and at the lower temperatures of 10 and 15 °C, the shelf life was longer, as expected. More specifically, 15 and 10 days were needed, respectively, until the rise in the APC population to 1000 cfu/mL. However, for the temperature range of 30–40 °C, only approximately 3 days were needed to reach 1000 cfu/mL APC. Regarding pH, according to an exponential 3P model, a stable trend was apparent at all temperatures until 30 days of storage, followed by a more abrupt decreasing trend at 25 °C. The lightness (L^*), redness (a^*), and yellowness (b^*) of the juice showed a decreasing trend with the temperature increase, and this trend was more profound at higher temperature levels. The multiple regression analysis between the predictors L^* , a^* , b^* , pH, storage temperature, and the APC response showed an increase in APC growth when the colorimetric parameters decreased and the temperature increased.



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Keywords: accelerated life testing (ASLT); orange juice; shelf life; storage temperature; microbiological evaluation; colorimetric parameters

1. Introduction

Orange juice is undoubtedly one of the most commonly consumed products daily worldwide, and thus, it is one of the most commonly exported and imported food products [1]. The pioneer in orange juice production is Brazil, followed by the US, Mexico, and Europe [2]. Moreover, the consumption of orange juice is accompanied by numerous health benefits, including the fact that it is a rich source of vitamin C (ascorbic acid) and a source of many bioactive compounds like carotenoids, flavonoids, folate, and potassium [3]. Despite its many nutritional benefits, orange juice is also a very popular beverage because of its distinguished aroma, flavor, and freshness [4].

However, there is a great necessity to increase the lifetime of the products produced—as they may have to travel a long distance and be stored for a long time to reach their destination—without jeopardizing their safety or their physicochemical and sensory qualities. The most common process through which the safety of the distributed orange juices is guaranteed is thermal pasteurization, which mainly focuses on the inactivation of spoilage and pathogenic microbes and thermally resistant endogenous enzymes, like peroxidase, polyphenol oxidase, and polymethylesterase, which can lead to enzymatic browning [5,6]. However, the thermal processing of orange juice is also correlated with a series of negative sensory attributes, such as color and ascorbic acid retention [6]. Normally, pasteurized orange juice is considered a microbiologically stable product, but several sporofforming bacteria of the genus *Alicyclobacillus* and *Bacillus*, and more specifically *Alicyclobacillus aci-*

doterrestris, *Bacillus coagulans*, and *Bacillus cereus*, can survive pasteurization and germinate in a beneficial environment, thus leading to the deterioration of the product [7].

Nevertheless, apart from the safety point of view, it is also very important to maintain the physicochemical and sensory attributes of the product because they determine consumer acceptability. Among these, the color of orange juice is a significant attribute that is correlated with the freshness and acceptability of the product; so, the handling of the browning reactions that occur during storage before the expiration date is of high importance [8]. The main browning reactions that happen during the storage of pasteurized orange juice are enzymatic and non-enzymatic browning reactions, including the degradation of ascorbic acid, acid-catalyzed degradation of sugars, and Maillard reactions [9]. The kinetics of non-enzymatic browning reactions, which are more difficult to handle, depend on both the physicochemical attributes of products and storage conditions, such as temperature and pH, and more specifically, a higher temperature and higher pH, which intensify these reactions [10].

Under normal conditions, the mean temperature of production and distribution of pasteurized orange juice does not exceed 7 °C, but temperature fluctuations during storage are the main problem that affects the product's acceptability [11]. So, it is very challenging when estimating the shelf life of products to be able to incorporate these unwanted deviations of conditions. Moreover, the shelf life and expiration date estimation are based on microbiological safety and not sensorial and physicochemical characteristics or "sensory shelf life", which poses the risk that the product is considered safe for consumption but its sensory characteristics have been compromised, which has a negative impact on consumer acceptability [12].

A significant innovation in the field of the prediction of food shelf life is accelerated shelf life testing (ASLT), which provides the possibility of predicting the shelf life of products based on both microbial and sensory characteristics during different stressing conditions, like temperature, without extensive amounts of testing and time using different statistical models [13]. In the field of perishable types of food products, like fruit juices, many studies have been conducted using temperature, UV radiation, and others as acceleration factors during different storage periods. These studies mainly focused on the effect of stress conditions on microbial counts, color deterioration, and unwanted oxidation reactions, thus mainly using Arrhenius or Weibull equations [4,5,14–17].

Meanwhile, the present study aims to fill the gap at the research and industrial levels regarding the correlation between the microbial, physicochemical, and color attributes of pasteurized orange juice stored at different temperatures for an extensive amount of time. Moreover, it is the first instance in the literature in which the data used are not from laboratory-produced samples but industrial samples from the actual production line.

2. Materials and Methods

2.1. Materials

Commercial pasteurized orange juice was used in the present study, which was manufactured at a local juice production factory in 500 mL PET bottles. Directly after production, the pasteurized orange juice bottles were stored at different temperatures in the company's industrial refrigerators.

2.2. Methods

2.2.1. Physicochemical Parameters

The pH of the pasteurized orange juice was measured using a bench pH meter (Mettler Toledo FP20, Columbus, OH, USA). The pH of the samples was measured after shaking the flask for 15 s, directly from the flask and in triplicate (identical replicates). For temperature equilibration, before measuring the pH, the flasks were left for 1 h at room temperature. Each day, the calibration of the caliper was carried out with pH 4 and pH 7 buffer.

2.2.2. Color Parameters

The chroma parameters (L^* , a^* , and b^*) were evaluated using the chromameter Lovibond LM200 (Lovibond, Amesbury, UK). The parameters L^* , a^* , and b^* were measured after shaking the bottle for 15 s by taking a 0.5 mL sample directly from the bottle and in triplicate (identical replicates).

2.2.3. Microbiological Parameters

The automatic analyzer BioMérieux Tempo (bioMérieux, Marcy-l'Étoile, France) was used for the evaluation of the total viable count of the orange juice samples. More specifically, the method is based on ISO 16140:2003 [18] protocol for microbiology of food and animal feeding stuffs. The method manipulates the automated MPN (most probable number). The process of dilutions is performed inside the Tempo card. The Tempo card carries 3 rows of 16 wells each (48 wells in total) corresponding to 3 dilutions with 16 tubes each. The upper MPN threshold of the automatic analyzer at a sample without dilution is 4900. The microbial growth was measured daily from three 500 mL bottles (uniform replicates) until the aerobic plate count (APC) value approached the maximum value of 4900 units, which marked the end of the experimental run.

2.2.4. Statistical Analysis

The temperature was used as an accelerating degradation factor choosing 6 levels (10, 15, 20, 25, 30, and 40 °C) to monitor the APC growth and 4 levels (4, 15, 20, and 25) to plot the three colorimetric parameters and pH with time (days). Several regression equation models were used to find the best fit of the experimental data using AICc and BIC as information criteria and the determinant coefficient R^2 to determine the model reliability. All statistical analyses were performed via JMP 17 (Statistical Discovery LLC, Cary, NC, USA) software.

All models were based on empirical choice since no recent information exists in literature relevant to some fundamental work. To determine microbial growth, five models were used, all of which involved log transformation of the APC response. An exponential equation with 3 parameters was used for pH modeling, a logistic equation with 3 parameters was used for Lightness L^* , and two linear equations were used for Redness a^* and Yellowness b^* .

3. Results and Discussion

3.1. Aerobic Plate Count (APC) of Pasteurized Orange Juice

The parsimonious polynomial model below with only four parameters (4P) best describes the APC growth rate (N) over the storage time (t) at various temperature levels (T) along with the statistical parameters of the model (Table 1):

$$N = N_0 + \exp(b_1 + b_2 * \ln(T)) * t \quad (1)$$

Table 1. Statistical information for APC model.

Parameter	Estimate	Std Error	−95%	95%
b0	−0.238380	0.40665308	−1.035405	0.558645
b1	−3.550622	0.22067326	−3.983134	−3.118111
b2	1.182725	0.06742677	1.050571	1.314880
Sigma	1.130722	0.12053435	0.894479	1.366965

The strong linear shape of standardized and Cox–Snell residuals indicated a very reliable model (AICc = 607.55).

Figure 1 depicts the population of APC (cfu/mL) versus storage time at each storage temperature. As can be seen, at lower temperatures (10 °C and 15 °C), the shelf life is longer than expected, and more specifically, 15 and 10 days are needed, respectively, until the rise of the population to the industrial internal limit of 1000 cfu/mL APC. The APC values

converge at 20–25 °C and at 30–40 °C, indicating that at the temperature range of 20–25 °C, 6.5 days are needed to reach 1000 cfu/mL, whereas, at the same time, for the temperature range of 30–40 °C, only 3.5 days are needed to reach 1000 cfu/mL. The steep increase in the growth rate following the rise in the storage temperature was also observed in work by Caranza et al. (2021) [15], where the Weibull equation was used to model the shelf life of orange juice at different temperature levels. At 5 °C and 22 °C, the inactivation rate, b , of the equation was 0.01 and 3.88, respectively, while in the present study, the same values were 2.18 and 5.67, respectively. Although a direct comparison between the two studies is not feasible due to the different equations (Weibull and polynomial), a rough estimation could be informative. The premature and rapid increase in APC at the higher temperature levels (20–40 °C) is explained by the diminishing of the lag phase at storage temperatures above 15 °C, meaning that this decrease in the lag phase, where the microbial growth rate is zero, consequently leads to a reduction in shelf life due to faster spoilage [17]. More specifically, in the study performed by Raccach and Mellattdoust [17], it was observed that the storage of orange juice at different temperature levels (0, 4, 10, and 15 °C) reduced the APC lag phase period from 9.5 days to 2.8 and 0 days for 10 and 15 °C, respectively. In the present study, this decrease in the APC lag phase, along with the increase in the storage temperature, was also apparent. As a matter of fact, in Figure 1, the lag phase at temperatures of 10, 15, 20, and 25 °C is 8, 4, 2, and 1 day, respectively [19].

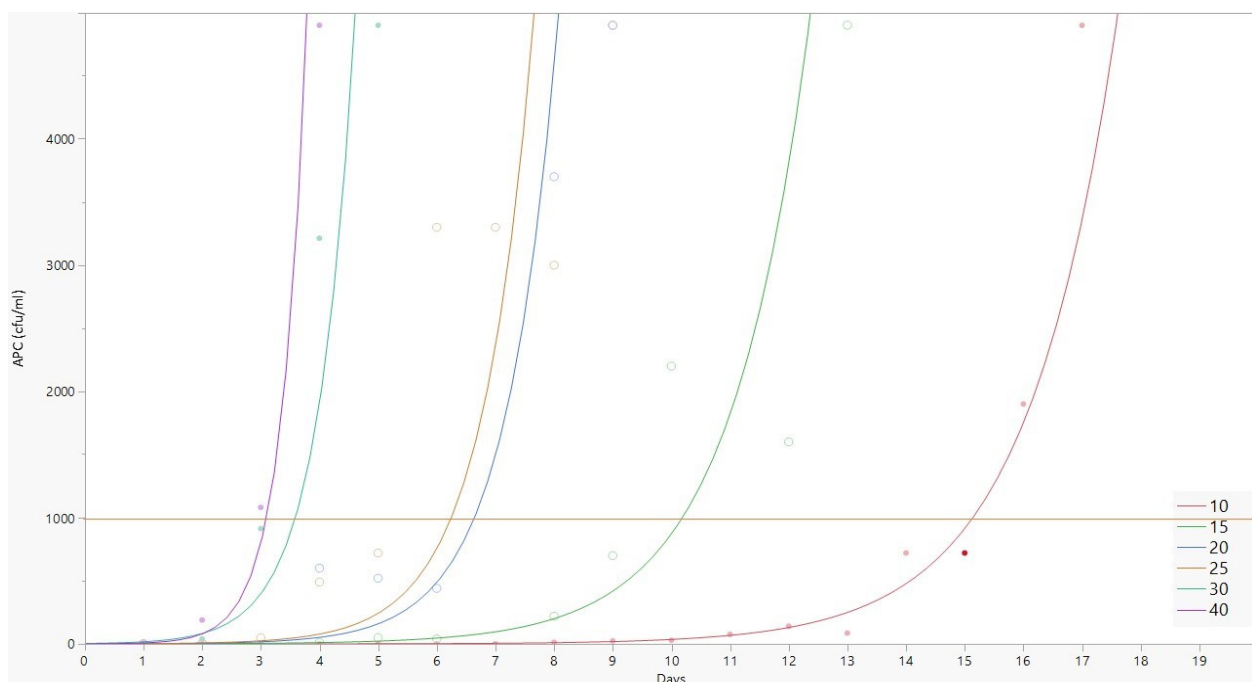


Figure 1. Population changes of APC as a function of storage time in different temperature levels.

The advantage of the polynomial model is the perception of shelf life as a continuous and not categorical variable, enabling the prediction of the shelf life at different temperature values than the experimented ones. This is very important when considering that the usual storage temperatures of pasteurized orange juice do not normally exceed 7 °C. Thus, using the degradation profiler (Figure 2), which depicts the APC growth at different time points (days) and temperature levels (°C), the required amount of time for achieving 1000 cfu/mL (internal limit of expiration) at different temperature levels is smoothly obtained. Briefly, if the temperature level of Figure 2 is adjusted at different levels, the predictive table (Table 2) can be created, presenting the shelf life of pasteurized orange juice. In this table, it can be observed that orange juice can be safely consumed for 48, 37, and 30 days if preserved at 4, 5, and 6 °C. However, when the temperature reaches 10 °C, safe consumption is reduced to 16 days, meaning that the 4-degree rise in temperature leads to a 14-day loss of shelf life. In

this context, in the study by Supraditareporn and Pinthong [20] a 6-day loss of shelf life of fresh orange juice was observed when the storage temperature was shifted from 4 to 25 °C. Increasing the storage temperature levels leads to a further reduction in the shelf life, as can also be seen in Figure 1, reaching approximately 3 days at 40 °C. In a similar study, where thermally treated sweet lime juice was subjected to accelerated storage conditions at 4, 15, and 25 °C, the time needed to reach 1000 cfu/mL or 3 logs cfu/mL was ~42, 25, and 12 days, respectively [16]. In the present study, the shelf life under these conditions was 48, 10, and 6 days.

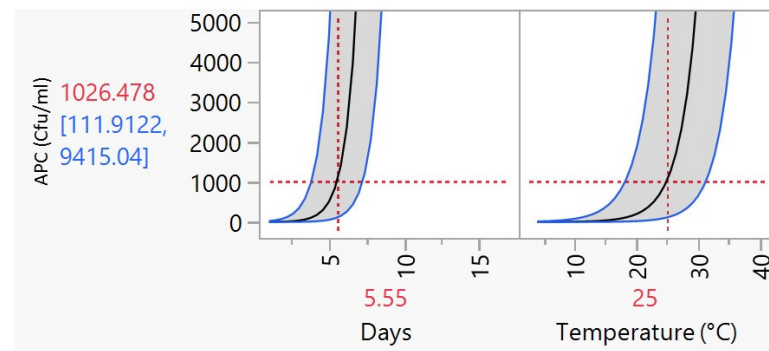


Figure 2. Degradation profiler of APC versus period (days) and temperature level using a polynomial model.

Table 2. Shelf life of pasteurized orange juice at different temperature levels.

Temperature (°C)	Days	APC (Cfu/mL)	−95%	95%
4	48.31	1000.4	109.1	9175.5
5	37.11	1001.5	109.2	9186.3
6	30.03	-	-	-
10	16.35	1002.6	109.3	9195.8
15	10.12	1001.4	109.2	9185.3
20	7.2	1000.1	109	9173.2
25	5.53	1000.3	109.1	9174.8
30	4.46	1001.4	109.2	9184.6
40	3.17	1000.7	109.1	9178.7

3.2. pH of Pasteurized Orange Juice

The following exponential 3P model describes the best-fit change in pH with the storage time via temperature as an accelerating factor (AICc = 418.2, $R^2 = 0.554$):

$$Y = a + b * e^{c*Days} \quad (2)$$

where a is the asymptote, b is the scale, and c is the growth rate.

Table 3 presents comparisons of the inflection points between different aging temperatures of the juice pH. This table highlights the decreasing trend of the pH along with the temperature increase based on the increasing growth rates, although this trend is more evident and statistically significant at higher temperature levels (20–25 °C) based on p -values. Furthermore, the progression of the pH is stable during the storage time at levels ranging between 3.9 and 4 until the 30th day, regardless of the storage temperature (Figure 3). This trend was also observed in the work performed by Wahia et al. [21], where the pH of orange juice remained nearly stable during 24 days of storage at 4 and 25 °C, with values ranging from 4.45 to 4.23 and 4.31 to 4.29, respectively. Also, in the work performed by Cortes et al. (2008) [4], the pH of pasteurized orange juice remained stable for 6 weeks at 2 and 10 °C, with values ranging from 3.32 to 3.49 and 3.32 to 3.48, respectively. In our study, from the 30th to the 40th day of storage, the pH values declined progressively, with greater

intensity for the samples with a higher storage temperature. More specifically, regarding samples preserved at 25 °C, a steep decrease in the pH from 3.8 to 3.4 was observed from the 30th to the 40th day (Figure 3), which is also illustrated by the value of the specific growth rate, i.e., 0.31, compared to the growth rates of 4 °C and 15 °C, which were 0.18 and −0.09, respectively (Table 3). This trend could be attributed to the rapid metabolization of the orange juice simple carbohydrates by the large numbers of aerobic plate counts at prolonged storage periods and higher temperatures, leading to the accumulation of organic acids as by-products of the reaction, subsequently lowering the pH values [21,22]. Under normal conditions, in a pasteurized product, the bacteria that ferment sugars into organic acids are heat-sensitive and are destroyed, but the spore-forming strains of the *Alicyclobacillus* genera and, more specifically, *Alicyclobacillus acidoterrestris*, survive pasteurization and, after germination in ideal conditions, they cause acidification of the juice [23].

Table 3. Statistical information on pH during different aging conditions.

Temperature (°C)	Asymptote	Scale	Growth Rate	p-Value
4	3.959574	−0.017114	−0.085518	0.8688
15	3.9830888	−0.000074	0.1864306	0.1460
20	3.9434177	-4.768×10^{-7}	0.322794	0.048
25	3.949530	-2.297×10^{-6}	0.3089789	<0.0001

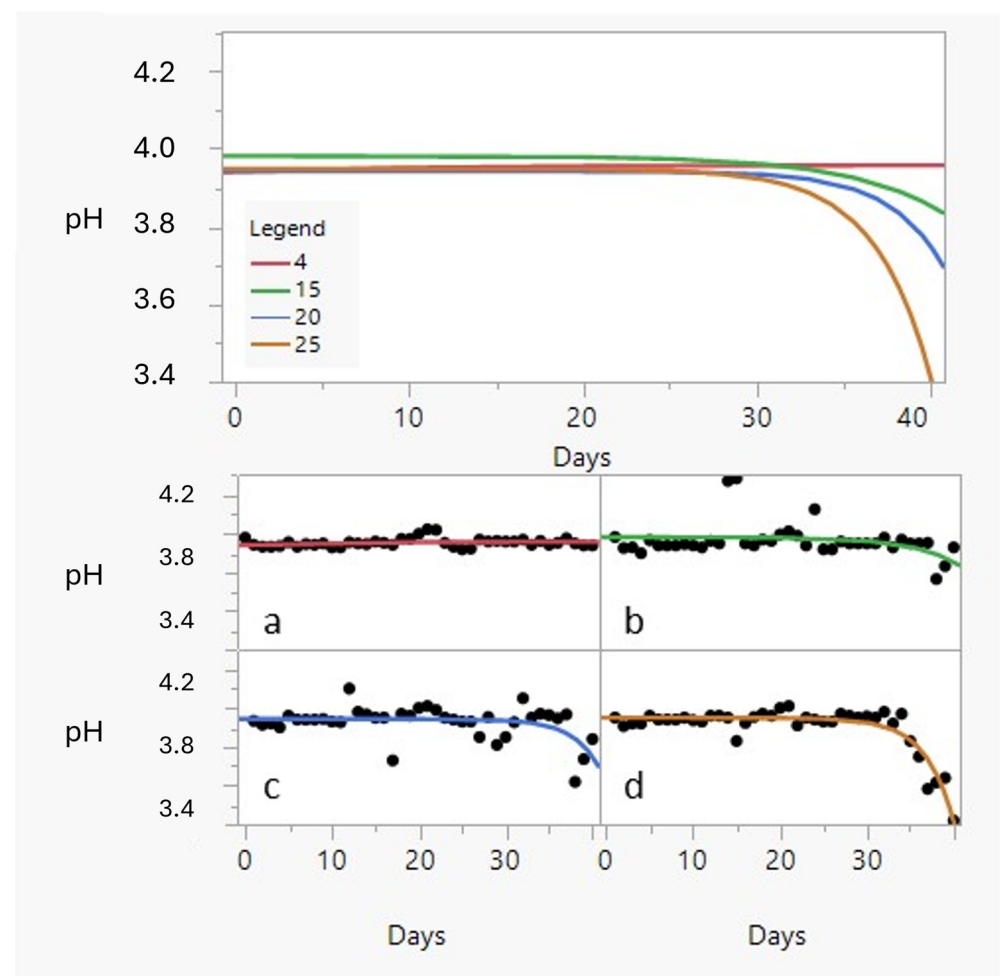


Figure 3. Curve fitting plot of experimental data in the exponential 3P model of pH vs. storage days. (a) 4 °C; (b) 15 °C; (c) 20 °C; (d) 25 °C.

3.3. Color Characteristics of Pasteurized Orange Juice

Regarding the color characteristics of pasteurized orange juice, L^* , a^* , and b^* were regularly monitored during the storage time at increasing temperature levels to model the degradation process.

3.3.1. Lightness (L^*)

The logistic 3P model proved to fit data slightly better than the Gompertz 3P model, as Table 4 indicates (lower AICc and BIC values and higher AICc weight and R^2 values):

$$Y = \frac{c}{1 + e^{-a*(day-b)}} \quad (3)$$

Table 4. Statistical information of the two candidate models used for describing the L^* value.

Model	AICc	AICc Weight		BIC	SSE	MSE	RMSE	R-Square
Logistic 3P	465.22	0.556		502.81	142.06	0.953	0.9764	0.7498
Gompertz 3P	465.67	0.444		503.26	142.46	0.956	0.9773	0.7491

In Table 5, a general decreasing trend of L^* is observed, based on the negative values of the growth rate in all temperature levels, almost all significant, in a decreasing order per level. Although the reduction in the L^* value below 48 initiates at ~30 days of storage at 4 °C, at the higher temperature levels (15, 20, and 25 °C), the reduction initiates at ~25, ~20, and <10 days, respectively (Figure 4). These results follow the trend in the literature, and, more specifically, the study performed by Wahia et al. [21] and Cortes et al. [4], where a decrease in the L^* values of juice during storage is apparent, particularly at higher storage temperatures. Of course, the L^* value indicates the lightness of orange juice, and, expectedly, during the storage duration, oxidative and enzymatic browning reactions lead to a change in the juice color from brighter to darker [24,25]. However, since most of the browning reactions are intensified at higher temperatures, according to the Arrhenius laws, it is reasonable for a premature and more intense reduction in the L^* values to occur as the temperature rises [26]. Another explanation for the browning intensity at higher storage temperatures is the rapid degradation of ascorbic acid at higher temperature conditions. The ascorbic acid acts protectively on the juice color because of its high antioxidant activity; thus, it inhibits the oxidative and non-oxidative reactions that cause browning [27].

Table 5. Statistical information on L^* during different aging conditions.

Temperature (°C)	Growth Rate	Inflection Point	Asymptote	p-Value
4	−0.241786	51.705908	47.720108	0.0569
15	−0.141779	58.235922	47.872129	0.0134
20	−0.135923	55.134761	47.808139	<0.0001
25	−0.068845	63.301295	48.350857	<0.0001

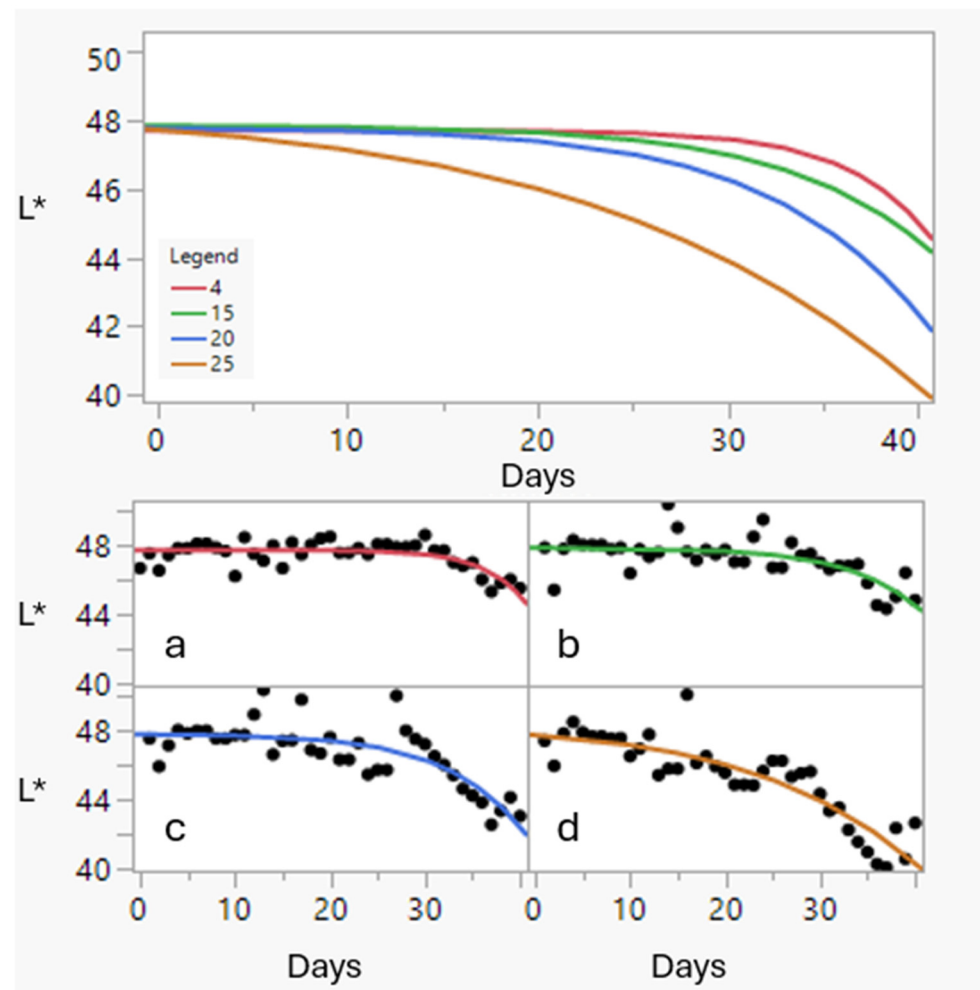


Figure 4. Curve fitting plot of experimental data in the logistic 3P model of L^* value vs. storage days. (a) 4 °C; (b) 15 °C; (c) 20 °C; (d) 25 °C.

3.3.2. Redness (a^*)

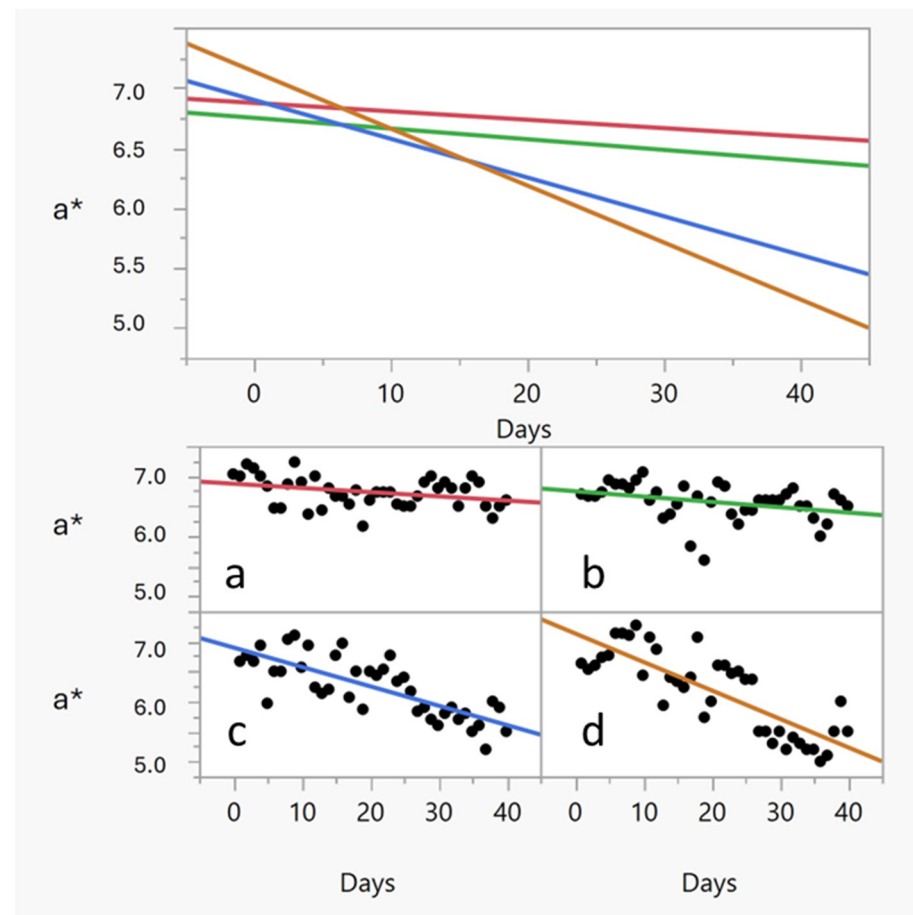
Regarding the redness of the juice, a linear model presented the best fit ($AIC_c = 96.97$, $R^2 = 0.64$):

$$Y = a - b * day \quad (4)$$

The redness of the pasteurized orange juice declines during storage, as manifested in Figure 4 and statistically described in Table 6. In other words, the rate of the decrease is greatly affected by the storage temperature level. Although at 4 and 15 °C, the reduction was relatively mild, with a change from 6.7 to 6.5, at the higher temperature levels of 20 and 25 °C, the reduction was steeper, and dropped from approximately 7 to 5 at the end of the storage time (Figure 5). This observation was also noticed in the study performed by Choi et al. [28], where the a^* parameter of blood orange juice decreased from 17.5 to 15.4 during storage for 7 weeks, and this was associated with both the degradation of anthocyanins, which are the main color agents of orange juice, and ascorbic acid. Anthocyanins, which are polyphenols, present high antioxidant activity and have numerous beneficial effects on human health. Thus, maintaining high levels of anthocyanins after the production of orange juice improves the nutritional value of the product [29]. This fact enhances the relationship between the optical and the nutritional value of orange juice, enabling the establishment of new indirect nutritional indicators.

Table 6. Statistical information on a^* during different aging conditions.

Temperature (°C)	Estimate	Std Error	p-Value
4	−0.006992	0.0041714	0.0937
15	−0.008871	0.0043288	0.0404
20	−0.032236	0.0043288	<0.0001
25	−0.047405	0.0043288	<0.0001

**Figure 5.** Curve fitting plot of experimental data in the linear model of a^* value vs. storage days. (a) 4 °C; (b) 15 °C; (c) 20 °C; (d) 25 °C.

3.3.3. Yellowness (b^*)

Regarding the yellowness of the juice, a linear model presented the best fit ($AICc = 450.48$, $R^2 = 0.79$). The linear model is expressed via the following equation:

$$Y = a - b * day \quad (5)$$

Yellowness is a very important color factor of orange juice because it is correlated with the freshness of the product and thus is linked with higher consumer acceptability [30]. During pasteurization, due to the generation of melanoidins at high temperatures, yellowness is prone to decrease, a process that is more intensive as the storage time passes [31]. Thus, it is very important to maintain the yellowness of pasteurized orange juice at relatively high levels. In the present study, the yellowness slowly decreases at lower temperature levels (4, 15, and 20 °C) at values ranging from ~42 to ~40 at the end of the storage time (Figure 6). At 25 °C, a steep decrease in the yellowness is observed during the storage time, with values ranging from ~42 to ~34 at the end of the storage time (Table 7). These results are in an analog accordance with the literature and, more specifically, with the work performed by

Wahia et al. [21], where, during the storage of pasteurized orange juice for 24 days at 4 and 25 °C, the b^* values ranged from 11.02 to 11.15 and 12.91 to 9.34, respectively.

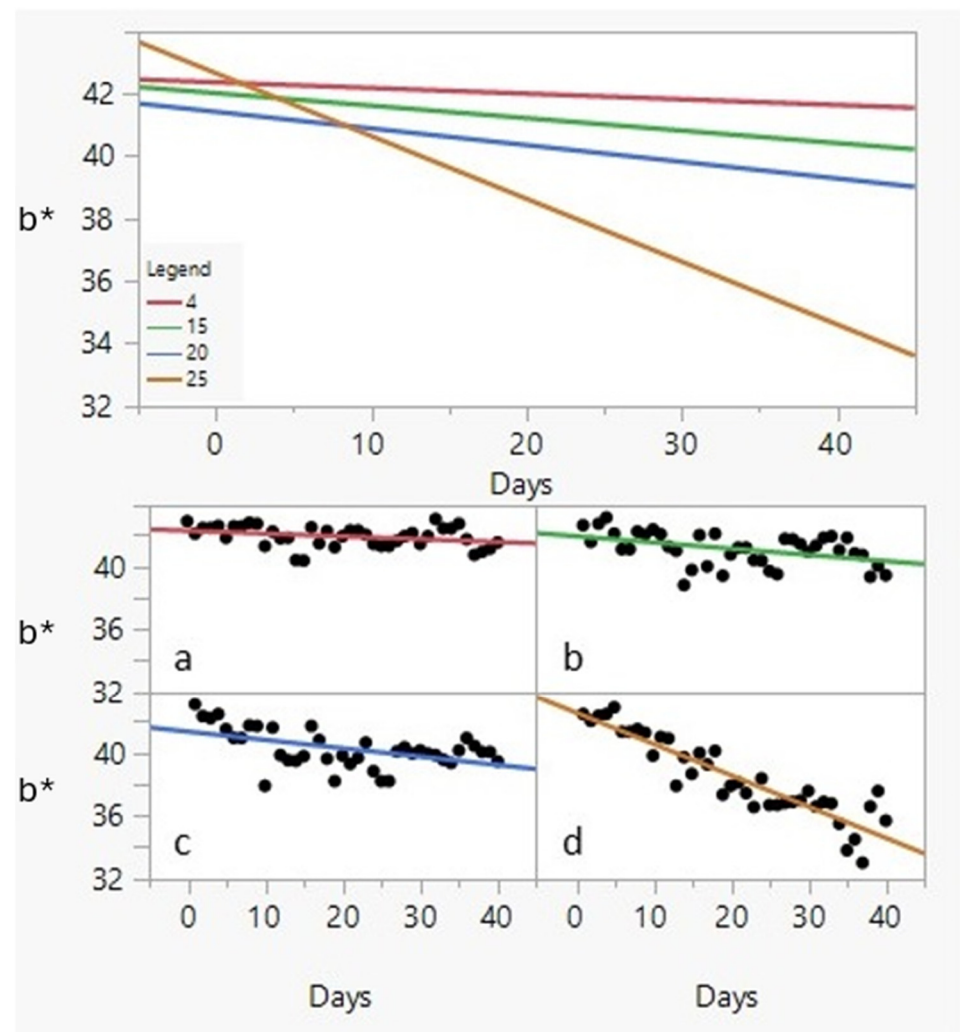


Figure 6. Curve fitting plot of experimental data in the linear model of b^* value vs. storage days. (a) 4 °C; (b) 15 °C; (c) 20 °C; (d) 25 °C.

Table 7. Statistical information on b^* during different aging conditions.

Temperature (°C)	Estimate	Std Error	<i>p</i> -Value
4	−0.018118	0.0125045	0.1473
15	−0.039981	0.0129765	0.0021
20	−0.05344	0.0129765	<0.0001
25	−0.201351	0.0129765	<0.0001

3.4. Relationships Between APC and Predictors

The present study not only tried to evaluate the shelf life of pasteurized orange juice as a function of the aerobic plate count (APC) but also from a physicochemical point of view. Thus, at each time point and storage temperature (stress factor), the color (L^* , a^* , and b^*) and pH were measured. However, the microbiological deterioration of orange juice at each temperature level inevitably affects the physicochemical characteristics [32]. It is thus of great interest to examine the relationship between the APC growth and the physicochemical variables at each storage temperature level. The relationship between the APC and the physicochemical variables was examined by using a reformed spreadsheet

from the present data: four temperature levels (5, 15, 20, 25) at 10 specific storage days and mainly from the last days of storage were selected, and the predicted APC values were extrapolated via the equation models (as previously explained) for a greater number days of storage for reasons of data conformation.

The results of the multiple regression analysis are shown in the table (Table 8), in which the parameters L^* , a^* , and temperature significantly affect the aerobic plate count. The prediction profiler of the APC versus all the predictors (Figure 7) shows that the increasing APC growth is related to a decrease in lightness (L^*), redness (a^*), and yellowness (b^*) and an increase in the temperature, as expected. As stated by Wahia et al. [21], changes in the colorimetric L^* , a^* , and b^* during the storage of orange juice are interrelated due to both oxidative and non-oxidative darkening reactions. However, it was observed that the color degradation was also directly related to the increase in the APC values. This is mainly attributed to the activity of sporofforming spoilage bacterial strains, which produce hydrolytic enzymes that cause cloudiness, off-odors, and deterioration of the juices [23].

Table 8. Statistical information on APC response using L^* , a^* , b^* , pH, and temperature as predictors.

Term	Estimate	Std Error	t Ratio	p-Value
Intercept	211.08049	35.22313	5.99	<0.0001
L^*	−2.478491	0.888081	−2.79	0.0086
a^*	−8.901556	2.981804	−2.99	0.0052
Temperature (°C)	0.5427967	0.169693	3.20	0.0030
b^*	−0.45272	0.80784	−0.56	0.5789
pH	−3.101464	9.755159	−0.32	0.7525

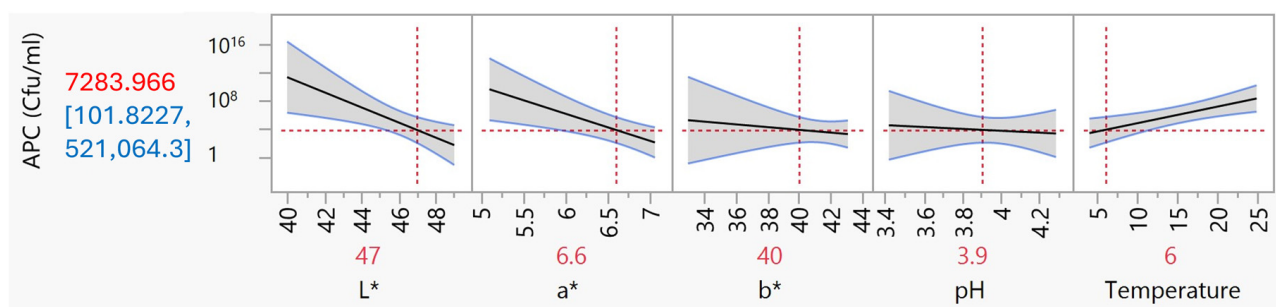


Figure 7. Prediction profiler of APC (cfu/mL) baseline in relation to L^* , a^* , b^* , pH, and temperature level (°C).

The above APC profiler is extremely useful for applications in the industry because, apart from its predictive value, it presents the possibility of using the color characteristics of pasteurized orange juice as indices of the microbiological deterioration at each time point and thus of the shelf life of the products.

4. Conclusions

In this study, pasteurized orange juice was subjected to accelerated storage temperature conditions for 40 days. The tested parameters were the aerobic plate count, the colorimetric parameters (L^* , a^* , and b^*), and pH. The results showed that a polynomial rate model described better the APC growth, which was more intense as the storage temperature level increased. Exponential 3P, logistic 3P, and linear models were found to adequately describe pH, L^* , a^* , and b^* parameters throughout the storage period. A multiple regression analysis using the APC growth as a response against all the aforementioned parameters reveals an APC increase with the downgrading of colorimetric parameters and temperature elevation. Plus, it is very important to highlight the practical aspects of the research and the very important effect of the fluctuations of the preservation temperature in the cold

chain on the shelf life of the juice, which enables the improvement in storage conditions. Secondly, this study creates the basis for the creation of microbiological health indicators of juice that can be measured quickly and directly without the need for microbiological analysis and specialized personnel.

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References

- Charfi, S.; Boujida, N.; Abrini, J.; Senhaji, N. Study of chemical composition and antibacterial activity of Moroccan Thymbra capitata essential oil and its possible use in orange juice conservation. *Mater. Today Proc.* **2019**, *13*, 706–712. [CrossRef]
- Citrus: World Markets and Trade. 2023. Available online: <https://downloads.usda.library.cornell.edu/usda-esmis/files/w66343603/cz30rd902/vh53zg80g/citrus.pdf> (accessed on 24 July 2024).
- Ivanova, N.N.; Khomich, L.M.; Perova, I.B. Orange juice nutritional profile. *Vopr Pitan* **2017**, *86*, 103–113. (In Russian) [PubMed]
- Cortés, C.; Esteve, M.J.; Frigola, A. Color of orange juice treated by High Intensity Pulsed Electric Fields during refrigerated storage and comparison with pasteurized juice. *Food Control* **2008**, *19*, 151–158. [CrossRef]
- Wibowo, S.; Grauwet, T.; Kebede, B.T.; Hendrickx, M.; Van Loey, A. Study of chemical changes in pasteurised orange juice during shelf-life: A fingerprinting-kinetics evaluation of the volatile fraction. *Food Res. Int.* **2015**, *75*, 295–304. [CrossRef] [PubMed]
- Mandha, J.; Shumoy, H.; Matem, A.O.; Raes, K. Characterization of fruit juices and effect of pasteurization and storage conditions on their microbial, physicochemical, and nutritional quality. *Food Biosci.* **2023**, *51*, 102335. [CrossRef]
- Colás-Medà, P.; Nicolau-Lapeña, I.; Viñas, I.; Neggazi, I.; Alegre, I. Bacterial Spore Inactivation in Orange Juice and Orange Peel by Ultraviolet-C Light. *Foods* **2021**, *10*, 855. [CrossRef]
- Fernández-Vázquez, R.; Hewson, L.; Fisk, I.; Vila, D.H.; Mira, F.J.H.; Vicario, I.M.; Hort, J. Colour influences sensory perception and liking of orange juice. *Flavour* **2014**, *3*, 1. [CrossRef]
- Buvé, C.; Pham, H.T.T.; Hendrickx, M.; Grauwet, T.; Van Loey, A. Reaction pathways and factors influencing nonenzymatic browning in shelf-stable fruit juices during storage. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 5698–5721. [CrossRef]
- Karseno, E.; Yanto, T.; Setyawati, R.; Haryanti, P. Effect of pH and temperature on browning intensity of coconut sugar and its antioxidant activity. *Food Res.* **2017**, *2*, 32–38. [CrossRef]
- Khasanov, A.; Matveeva, N. Determination of the shelf life of a functional beverage by accelerated testing. *E3S Web Conf.* **2020**, *164*, 01003. [CrossRef]
- EFSA; Guidance on date marking and related food information: Part 1 (date marking). *EFSA J.* **2020**, *18*, e06306.
- Haouet, M.N.; Tommasino, M.; Mercuri, M.L.; Benedetti, F.; Di Bella, S.; Framboas, M.; Pelli, S.; Altissimi, M.S. Experimental accelerated shelf life determination of a ready-to-eat processed food. *Ital. J. Food Saf.* **2018**, *7*, 189–192. [CrossRef] [PubMed]
- Buvé, C.; Van Bedts, T.; Haenen, A.; Kebede, B.; Braekers, R.; Hendrickx, M.; Van Loey, A.; Grauwet, T. Shelf-life dating of shelf-stable strawberry juice based on survival analysis of consumer acceptance information. *J. Sci. Food Agric.* **2018**, *98*, 3437–3445. [CrossRef] [PubMed]
- Hernández-Carranza, P.; Peralta-Pérez, A.; Avila-Sosa, R.; Ruiz-López, I.I.; Benitez-Rojas, A.C.; Ochoa-Velasco, C.E. Effect of ultraviolet-C light and mild thermal treatment on the storage life of orange juice. *Czech J. Food Sci.* **2021**, *39*, 106–112. [CrossRef]
- Shaik, L.; Chakraborty, S. Effect of different storage conditions on the quality attributes of sweet lime juice subjected to pulsed light and thermal pasteurization. *Sustain. Food Technol.* **2023**, *1*, 722–737. [CrossRef]
- Raccach, M.; Mellatdoust, M. The effect of temperature on microbial growth in orange juice. *J. Food Process. Preserv.* **2007**, *31*, 129–142. [CrossRef]
- ISO 16140:2003; Microbiology of Food and Animal Feeding Stuffs—Protocol for the Validation of Alternative Methods. ISO: Geneva, Switzerland, 2003.
- Buchanan, R.; Whiting, R.C.; Damert, W.C. When is simple good enough: A comparison of the Gompertz, Baranyi, and three-phase linear models for fitting bacterial growth curves* 1,* 2. *Food Microbiol.* **1997**, *14*, 313–326. [CrossRef]

20. Supraditareporn, W.; Pinthong, R. Physical, Chemical and Microbiological Changes during Storage of Orange Juices cv. Sai Nam Pung and cv. Khieo Waan in Northern Thailand. *Int. J. Agric. Biol.* **2007**, *9*, 726–730.
21. Wahia, H.; Zhou, C.; Mustapha, A.T.; Amanor-Atiemoh, R.; Mo, L.; Fakayode, O.A.; Ma, H. Storage effects on the quality quartet of orange juice submitted to moderate thermosonication: Predictive modeling and odor fingerprinting approach. *Ultrason. Sonochem.* **2020**, *64*, 104982. [\[CrossRef\]](#)
22. Zhu, W.; Ai, Y.; Fang, F.; Liao, H. Application of Thermosonication in Red Pitaya Juice Processing: Impacts on Native Microbiota and Quality Properties during Storage. *Foods* **2021**, *10*, 1041. [\[CrossRef\]](#)
23. Sourri, P.; Tassou, C.C.; Nychas, G.-J.E.; Panagou, E.Z. Fruit Juice Spoilage by *Alicyclobacillus*: Detection and Control Methods—A Comprehensive Review. *Foods* **2022**, *11*, 747. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Polydera, A.; Stoforos, N.; Taoukis, P. Quality degradation kinetics of pasteurised and high pressure processed fresh Navel orange juice: Nutritional parameters and shelf life. *Innov. Food Sci. Emerg. Technol.* **2005**, *6*, 1–9. [\[CrossRef\]](#)
25. Pham, H.T.T.; Kityo, P.; Buvé, C.; Hendrickx, M.E.; Van Loey, A.M. Influence of pH and Composition on Nonenzymatic Browning of Shelf-Stable Orange Juice during Storage. *J. Agric. Food Chem.* **2020**, *68*, 5402–5411. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Fustier, P.; St-Germain, F.; Lamarche, F.; Mondor, M. Non-enzymatic browning and ascorbic acid degradation of orange juice subjected to electroreduction and electro-oxidation treatments. *Innov. Food Sci. Emerg. Technol.* **2011**, *12*, 491–498. [\[CrossRef\]](#)
27. Yin, X.; Chen, K.; Cheng, H.; Chen, X.; Feng, S.; Song, Y.; Liang, L. Chemical Stability of Ascorbic Acid Integrated into Commercial Products: A Review on Bioactivity and Delivery Technology. *Antioxidants* **2022**, *11*, 153. [\[CrossRef\]](#)
28. Choi, M.; Kim, G.; Lee, H. Effects of ascorbic acid retention on juice color and pigment stability in blood orange (*Citrus sinensis*) juice during refrigerated storage. *Food Res. Int.* **2002**, *35*, 753–759. [\[CrossRef\]](#)
29. Marszałek, K.; Woźniak, L.; Kruszewski, B.; Skapska, S. The Effect of High Pressure Techniques on the Stability of Anthocyanins in Fruit and Vegetables. *Int. J. Mol. Sci.* **2017**, *18*, 277. [\[CrossRef\]](#)
30. Tepper, B.J. Effects of slight color variation on consumer acceptance of orange juice. *J. Sens. Stud.* **1993**, *8*, 145–154. [\[CrossRef\]](#)
31. Aghajanzadeh, S.; Ziaifar, A.M.; Verkerk, R. Effect of thermal and non-thermal treatments on the color of citrus juice: A review. *Food Rev. Int.* **2021**, *39*, 3555–3577. [\[CrossRef\]](#)
32. Kaddumukasa, P.P.; Imathiu, S.M.; Mathara, J.M.; Nakavuma, J.L. Influence of physicochemical parameters on storage stability: Microbiological quality of fresh unpasteurized fruit juices. *Food Sci. Nutr.* **2017**, *5*, 1098–1105. [\[CrossRef\]](#)

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