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Late Shelf Life Saturation of Golden Delicious Apple Parameters: TSS, Weight, and Colorimetry

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Abstract: This work aims to estimate the shelf life of Golden Delicious apple fruit stored at room temperature by determining the changing trend in color every week using a non-destructive measurement method. Moreover, the study will measure the changes in weight loss (Δm) and the total soluble solids (TSS) contained in the apple. The research focuses on the last stage of ripening and the effect of shelf life affecting consumer behavior; therefore, the examined fruits were picked at the end of the season and were stored at an ambient temperature and in controlled laboratory conditions for six weeks, at 24 °C under 60% RH relative. Color measurements were performed with a portable color sensor, which provided a simple and effective examination method in the case of an appropriate number of fruit samples. The findings showed a significant increase in TSS and weight loss over time. Color varying (ΔE) and chroma (C*) parameters increased with prolonged storage duration, meaning that the color of the apples became darker and more color-saturated at the end of storage. While weight loss and TSS follow a linear tendency in the given storage period, the color changes in deteriorating fruits were characterized by exponential asymptotic regression. It was found that although the moisture content reaches its limit value during the drying process of apples, the saturation of color coordinates allows for determination of the limit parameters of consumption in the linear stage of weight loss. The saturation limits (70.97; 12.77; 56.34 CIELAB L*; a*; b*), the dominant color part (b*), and the growth rate of the saturation curves allow an accurate characterization of ripening from the visual aspect, thus determining the limit parameters of shelf life and improving the critical analysis factors affecting the life of fruits after harvest. By assessing color characteristics using a non-destructive technology, customers may quickly evaluate the quality of apples and make better decisions during their purchase.

Keywords: Golden Delicious apple; storage; weight loss; color; total soluble solids; shelf life; food engineering

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1. Introduction

Apple (*Malus* × *domestica* Borkh) belongs to the family of Rosaceae and sub-family Pomoideae and is one of the most widely produced and economically significant fruits worldwide. In 2020, the production of apples around the world reached 86,442,716 tons [1], and they are typically most appealing and health-promoting when gathered at their optimum ripeness. The apple is one of those fruits whose quality changes quickly over time while being stored, which causes variations in customer acceptance. First, it is assessed based on its appearance, including color and size, and then its total soluble solids content.

Over the years, research on post-harvest storage of fruits and vegetables has focused on studying fruit's appearance, quality, and mechanical properties under different conditions such as temperature or shelf life to meet consumer expectations [2–4].

Fruits include numerous critical nutrients and phytochemicals that may help prevent and reduce the risk of, for example, chronic illnesses such as heart disease, obesity, diabetes, some forms of cancer, inflammation, stroke, and septic shock [5,6]. It is popular among producers and consumers because of its excellent nutritional content and remarkable ecological resilience [7–9]. Fruits are a good source of water, soluble solids, sugars, organic acids, and dietary fiber [10,11]. For instance, an apple is a "healthy fast food" that replenishes the body's stores of vitamins, minerals, and trace elements. Over 600 essential and intermediate chemicals beneficial to human nutrition and health are found in apple fruits. [12].

Several widespread methods are applied to evaluate fruit quality. Visual examination and destructive procedures are generally used to assess product quality. [13] In recent years, specific spectroscopic and imaging techniques have been effectively used in food quality inspection to deal with destructive methods' challenges [14].

These non-contact imaging techniques are made possible by technological advancements in cameras and robust computer hardware, software, and analysis tools. They are now a crucial instrument in applications for quality evaluation [15,16].

Total soluble solids (TSS) are generally a crucial quality indicator linked to the texture and composition of apples and other fruits [17,18].

Water loss causes the product's weight to drop, causing the quality of the fruit to deteriorate. On the exterior of the apple fruit, there is a natural wax coating that acts like a protective barrier or coating, preserving the fruit as it grows. Fruit weight loss is determined by the skin's structure and the waxes' composition on the fruit's surface [19]. The moisture loss decreases the visual quality and contributes to the loss of turgor pressure and subsequent softening; in industrial terms, moisture loss is also an economic [20,21] Therefore, fruit weight measurement is critical in fruit quality evaluation too.

Although fruit may be kept fresh for a long time in cold storage, fruit storage after harvesting is one of the significant difficulties in the world today. The availability of cold storage facilities is entirely restricted in contrast to fruit production, which raises the price of the produce. Additionally, customers can buy the fruits at their small local market, where they are often kept at room temperature. As a result, it is crucial to evaluate the apple's quality while it is being stored at room temperature. The non-destructive method to measure the color can help consumers to assess the quality of fruit during purchasing [22]. Consumers' first delightful experience with fruits is a healthy, fresh, and colorful appearance, influencing the remainder of the observed sensations. The color is the initial point of contact [23] between the product and the consumer, which is crucial in purchasing [24]. Using a sophisticated picture processing system and RGB and hyperspectral photography, researchers [24] carefully graded and tracked the color progression of the subjects. Compared to RGB imaging, the hyperspectral approach showed more promise for objectively differentiating apple ripeness during shelf life.

The fruit's surface chlorophyll degradation occurs throughout the ripening phase; while-colored pigments, such as carotenoids (yellow) and anthocyanins (red), are created. Two colors may appear: one is the background color, yellow, and the other is the surface color, red. Golden Delicious apples have a faint pinkish tint ranging from green to yellow-green tones [24].

Some cultivars, such as Golden Delicious, have a long shelf life of roughly four weeks at room temperature [25], although the fruit softens and the peel color changes from green to yellow [26]. Analysis of the green-to-yellow skin color shift in Golden Delicious apples revealed that carotenoid production and chlorophyll degradation are responsible for the alterations [27,28]. Rutkowski et al. [29] proposed a non-destructive determination of the Golden Delicious ripening stage. However, they confirmed in the end that their development is still a destructive estimation due to their chlorophyll content assay of the apple peel.

Even though numerous research has been conducted during storage, there is little information about fruit color changes and the classification of ripening stages during shelf life. Cárdenas-Pérez et al. [26] showed that color changes during storage could be used as a classification approach. Apple quality deteriorates significantly during storage, impacting consumer acceptance [30,31]. According to the findings in the literature above, our approach focuses on highlighting the post-harvest late shelf life saturation of Golden Delicious color parameters, based on weight, TSS, and colorimetry data, which is raised as a novel approach in the field.

Due to its resemblance to the human perception of color, CIELAB color space is an appropriate choice to describe the color ingredients of fruits and vegetables [5,32]. The CIELAB color scale comprises L*, a*, and b* coordinates, with L* denoting brightness, a* denoting red or green, and b* denoting yellow or blue color perception.

Complex computer vision systems require sensor-based measurements, but flexible and frequent in-situ investigations are a continuous requirement during ambient storage. A calibrated portable device (in a laboratory environment at this research stage) can also be implemented to examine the color changes of different ripening stages, taking multiple, simple, and fast measurements on the surface of given fruits.

Besides examining fresh products, it is also essential to evaluate the results mentioned in the last stage of ripening, where the limiting parameters of shelf life can be observed with the saturation limits of the investigated changes in the crucial color parameters. In the case of room temperature storage, these circumstances can be achieved if the examined fruits are selected from the end of the season.

This study aims to characterize the ripening process with an applied sensor-based colorimetric approach. It aims to identify the changes in the weight, color, and TSS properties of Golden Delicious apple fruit during storage at room temperature, focusing on the changes in TSS and color parameters that objectively indicate the shelf life limitations of the given cultivar based on asymptotic regression. For the description of the observed limits of the parameters, the approach of exponential asymptotic regression was considered instead of power function [25] to characterize the weekly ripening process, and a color sensor-based measurement method was applied to improve the effectivity of such investigations further.

2. Materials and Methods

A fresh "Golden Delicious" variety of apple fruit was collected directly from a farm near Kecskemét, Hungary, in 2021. The fruits were all picked at a maturity stage corresponding to the commercial harvest date.

Golden Delicious apples were placed in six boxes, and each one separately contained 24 apple samples. All apples have an identity code (Example: B1A1, B for box A for apple). The apples were sorted manually for approximately similar sizes and a lack of any external damage. The average weight of the total fruit sample was 150 ± 12 g, and the average diameter size of the apple samples were d = 70 ± 2 mm; three measurements were applied for each sample for geometry and weight measurement. The apples were stored at ambient conditions (24 ± 1 °C) under relative humidity (RH 60%) for six weeks. The samples in the first three groups were examined with non-destructive methods: weight measurement (g) and color parameters (L*, a*, b* in CIELab color space [5,26,32]) acquisition. The fourth, fifth, and sixth batches were prepared to measure the total soluble solids (TSS), which required a destructive approach.

2.1. Measurement of Weight Loss

All of the apples were weighed before, during, and after the storage period, and three measurements were applied for each sample for the weight loss measurement. The same samples were assessed for weight loss at weekly intervals until the end of the experiment.

Weight loss Δm (%) was calculated using the following equation:

$$\Delta \mathrm{m} = \frac{\mathrm{m}_0 - \mathrm{m}}{\mathrm{m}_0} \cdot 100,\ [\%] \tag{1}$$

where m is the mass of apples (g) during storage and m_0 is apples' beginning mass (g). The samples of apple fruits in the first three groups (72 apples) were taken and weighed on a precision scale type KERN (KERN & SHON GmbH, Balingen, Germany, KERN PCB 3500-2, max.: 3500 g ± 0.01 g) to calculate the average fruit weight.

2.2. Measurement of Color

Color parameters were measured using a Nix Pro wireless color sensor (Nix Sensor Ltd., Hamilton, Ont, Canada, NixPro Mini). The device blocks ambient light, provides its own calibrated LED-based light source during measurement, and works with a proprietary sensor module. The Nix Pro Device has a circular shape with a 15 mm diameter and 45/0° measuring geometry. Two high-CRI LEDs designed explicitly for color reproduction provided the light source for the measurements. The instrument has <0.1 DE2000 repeatability.

The color data are used to match physical colors. The results were investigated using the CIELAB color system from the Nix pro color sensor application (App version v1.33, Nix Sensor Ltd., Hamilton, ON, Canada), which displays the RGB, CMYK, HEX, CIELAB, and XYZ values for each color. Three repeated measurement data of 72 apples were obtained for each storage time (from week one to week six) using the HunterLab colorimeter (illuminant D50 and 2° standard observer). The color was recorded using a CIELAB uniform color space (Lab), where L* indicates lightness, a* indicates chromaticity on a green (−) to red (+) axis and b* chromaticity on a blue (−) to yellow (+) axis. We calculated color parameters from the L*, a*, and b* data. ΔE is the difference between two colors represented by two points in the CIELAB color space and chroma (C*), which expresses the degree of color for an area viewed with its brightness.

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2}, \tag{2}$$

$$C^* = \sqrt{a^{*2} + b^{*2}}, \tag{3}$$

where L_0^*, a_0^*, and b_0^* represent the color data based on the samples, and L*, a*, and b* indicate the color of the measured instantaneous data.

At the end of the storage process, the color of the apples will always turn into some shade of brown, which can be considered a final state or limiting color. Since the a* and b* coordinates of green and yellow shades are less than the coordinates of brown shades, the color change process can thus be considered as a saturation or limited growth process, pointing to asymptotic regression analysis.

2.3. Measurement of Total Soluble Solids (TSS)

The apple juice was extracted from the fruit without peeling using a hand mixer (BRAUN, Rubi, Barcelona, Spain, MODEL: MR-5550 BC-HC, 600 W + Turbo, 13,500 RPM) with stainless steel blades to measure the total soluble solids content. The extraction juice takes one minute for all fruit samples. The TSS of juice was measured using a refractometer with automatic temperature compensation. The digital hand refractometer (Ebro Electronic GmbH, Ingolsadt, Germany, Model: DR-10) has a measurement range between 0 and 54 °Brix within the +5 ... +60° sample temperature; the instrument works between the +5 ... +40° temperature range with ±0.2 °Brix/ ±1 °C accuracy and 0.1 °Brix/0.1 °C resolution. The results were expressed in °Brix (±0.2).

2.4. Statistical Analysis

All the quality attributes in each experiment on every apple were measured three times. The results were compared by one-way analysis of variance (ANOVA). Deviations between groups were tested with Levene's test. For post hoc tests, Dunnett's T3 test or Tukey's test was applied, respectively, depending on whether the variances between groups were significant or not. The whole process is presented in detail only in the case of the examination of weight loss, and then the process is consequential for the rest of the cases.

The exponential asymptotic regression can be described with the following differential equation

$$y' = c(a - y), \quad (4)$$

where a is the limit coordinate and c is proportional to the growth rate. The differential equation has the solution:

$$y(w) = a - be^{-cw}, \quad (5)$$

which was fitted for a* and b* (and C*). It is similar to the von Bertalanffy growth function and the differential equation describing the process [33].

Regression analysis was carried out for all investigated variables as a function of time (measured in weeks). The fitted functions were linear (of the form $Y = aw + b$) or based on exponential functions (of the form $Y = a - (a - b)e^{-cw}$ for saturation-like processes or of the form $Y = a + be^{-cw}$ for a process with exponential decay). The method of least squares was used for model fitting. An important parameter of this analysis was the limit where the saturation is nearing the asymptote.

All analyses were performed using Excel and IBM SPSS Statistics v27 software, and differences at the 5% level ($p < 0.05$) were considered statistically significant.

3. Results

3.1. Weight Loss (%)

The percentage cumulative weight loss (Δm) of apple fruit during storage under ambient temperature (24 ± 1 °C, φ = 60RH%) over six weeks is presented in Figure 1.

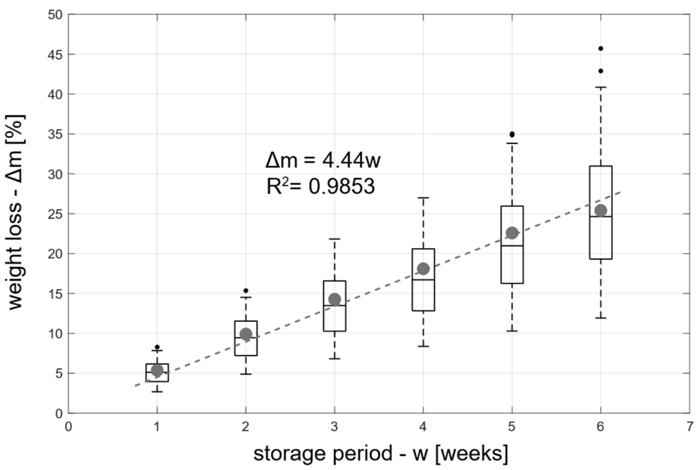

Figure 1. Effect of ambient temperature on the weight loss of Golden Delicious apples during storage.

Apple fruit weight loss increased strongly throughout storage at an ambient temperature. A linear function with a coefficient of determination, $R^2 = 0.9853$, fitted reasonably well to the data regarding the weight loss percentage of the apples during storage under ambient conditions. The moisture and subsequent weight loss in fruits changed linearly with storage duration due to water loss and respiration [34]. The average weight reduction was 5.29% in the first week of measurement, reaching 25.32% at the end of the sixth week (Figure 1). The weight loss percentage grew linearly with each additional week of storage, reaching 22.51 and 25.32 per cent in the fifth and sixth weeks, respectively.

Using ANOVA, this study showed significant ($F = 121.371$, $p < 0.001$) differences in fruit weight loss among the storage durations. Based on Levene's test, there was an important ($F = 8.615$, $p < 0.001$) difference between the variances of groups (that is, the data belonging to each week) for the post-hoc test. Dunnett's T3 test was applied. In Table 1, the p values are presented. Since the table is symmetric and the main diagonal is out of interest, only the values above the main diagonal are included.

Table 1. p values results from one-way analysis of variance ANOVA.

Week	2	3	4	5	6
1	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
2		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
3			$p < 0.001$	$p < 0.001$	$p < 0.001$
4				$p = 0.018$	$p < 0.001$
5					$p = 0.025$

It shows that the weight loss in weeks one, two, and three is statistically different from all other weeks, but it is statistically the same between weeks four and five and five and six. A change describes this phenomenon within the ripening process. The next stage in weight loss tendency is developing to move to an asymptotic model, similar to the moisture content characteristics during the given fruits' drying process [35]. The changes in the fruit during ripening are related to an increase in ethylene production and respiration. Ethylene is considered the primary signal for regulating fruit ripening, which begins just before the onset of this process and determines its correct evolution [36]. Exogenous ethylene speeds up the ripening process in climacteric fruit such as apples, whether it comes from other climacteric fruit or is created artificially by substances such as 2-chloroethyl-phosphonic acid [37].

Interestingly, in line with this, the deterioration of the apples was observed in the samples after the third week and during handling as well. The rapid increase in deviance (from Figure 1) also emphasizes this observation.

In short, the detailed presentation of the post-hoc tests is ignored for the latter examined quantities, and only a summary and discussion of the results are included. In addition, also in short, we state that for all other quantities, Levene's test was significant except in the case of TSS; furthermore, ANOVA showed a significant difference between at least two of the groups (weeks) for all quantities, as noted above.

3.2. Color Analysis

Across the entire storage process, a vast difference in color from week one to week six could be observed, changing from qualitative smooth green to yellow and brown spotted apples (Figure 2).

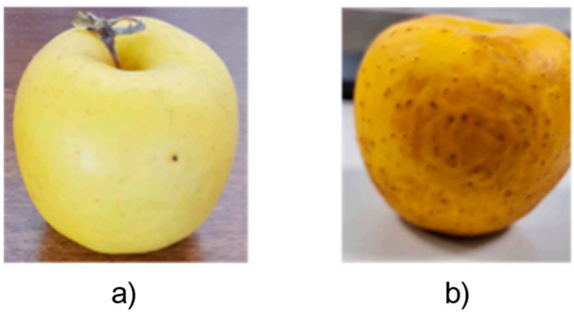

Figure 2. Color of a Golden Delicious apple at week one (**a**) and week six (**b**).

For quantitatively evaluating color changes in apple skin during storage, L*, a*, and b* are plotted in Figures 3–5.

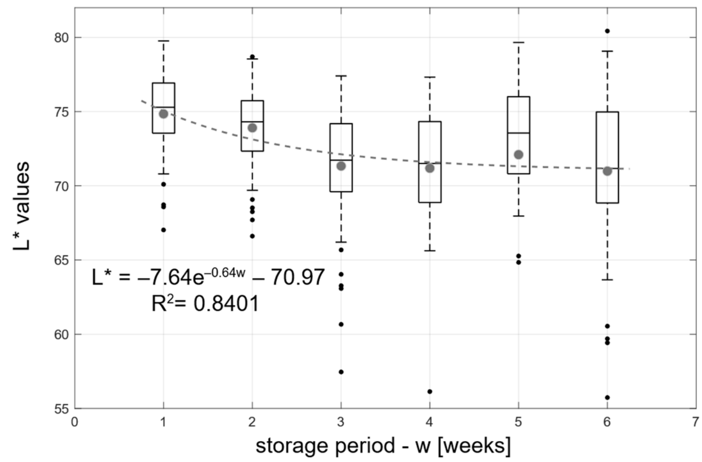

Figure 3. Effect of ambient temperature on L* values of apple during storage: lightness factor decreases to a specific limit.

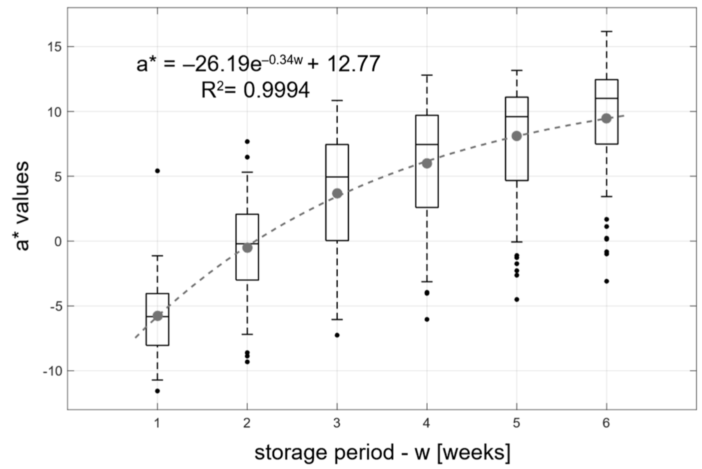

Figure 4. Effect of ambient temperature on a* values of apples during storage: the red color parameter increases to a specific limit.

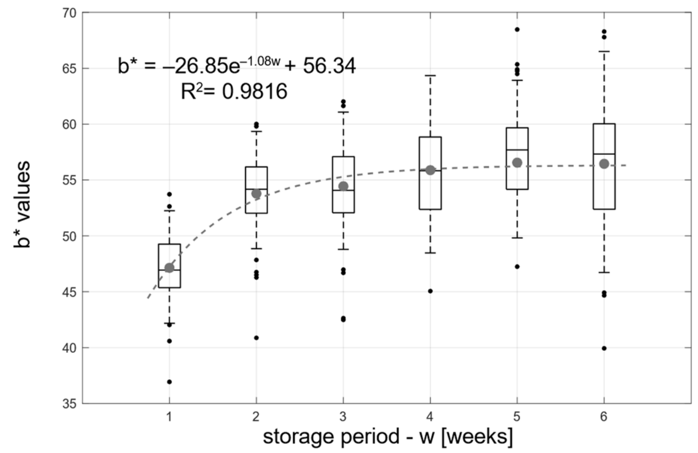

Figure 5. Effect of ambient temperature on b* color values of apple during storage: the yellow color parameter increases to a specific limit.

The L* value decreases from week one to week six. This result could be associated with the change from green to bright green and then yellow with brown spots. L* values change from 74.81 in week one to 71.27 in week six. L* variation is related to PPO (polyphenol oxidase) activity, which alters the tissue surface and reduces apple pigments [38].

This study statistically confirmed a significant difference between this parameter's baseline and end state ($p < 0.05$).

The a* and b* values increase during storage at room temperature. This increase is related to the chlorophyll breakdown processes that lead to its decrease and fruit ripening [38]. The a* values change from −5.77 in week one to 9.47 in week six, and the b* values change from 47.15 in week 1 to a maximum in week 6 of 56.45. For parameters a* and b*, it can also be stated that there is a significant difference between the data measured in the first week and the data measured in the last week ($p < 0.05$).

According to Itle and Kabelka, higher b* values are associated with high carotenoids and xanthophylls and the loss of chlorophylls in the pericarp during climacteric fruit ripening of pumpkins and squash [39]. These changes result from the decrease in the greenness of the apple and an increase in its yellowness. In addition, it must be noted that the yellow (b*) color parameter reaches the limiting asymptote much earlier than the red (a*). This could be because Golden Delicious can develop a red color, even at the storage stage, where both light (blue-violet and UV) and temperature affect this color change [40]. However, we showed that this change is slower than for the other color parameter.

It is also interesting to see how outliers are grouped from Figures 3–5, meaning that these values can be attributed to one outlier sample, apples (giving meaningful outlier results on three different sampling points per apple). It must be noted that the outliers and the deviances generally increase with time, meaning that the investigated parameters vary more with the imminent degradation of the samples, which can also affect consumer preference.one 1 to 25.82 on week six (Figure 6). The higher the Delta E value, the lower the color accuracy. The increment in delta E values confirmed the samples' visual color changes.

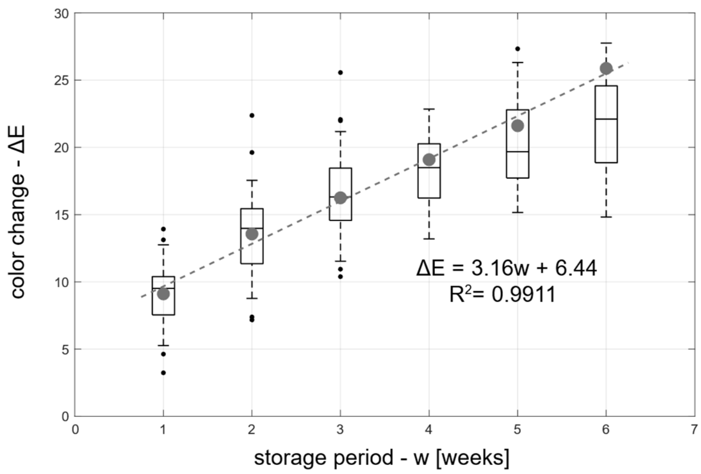

Figure 6. Apple color changes (ΔE) during storage at an ambient temperature: the yellow color parameter increases to a specific limit.

Chroma C* is the distance from the axis of lightness (L) to the origin of color and begins at zero in the center. It describes the degree of color for an area seen with its brightness; it becomes increasingly relevant as color coordinates go away from the origin. Values for C* and are plotted in Figure 7. With regards to the chroma parameter, it is seen to increase from 47.61 to 57.45 across the whole ripening period; during storage, the color of the apple became less bright and more color-saturated than at the time of harvest [26].

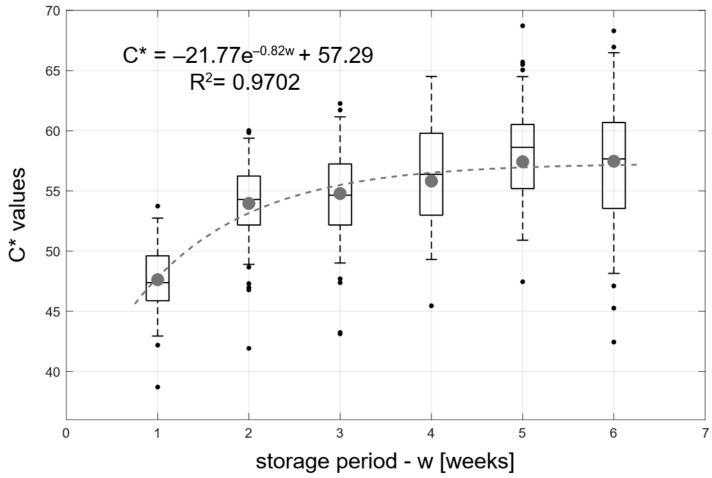

Figure 7. Chroma (C*) values during storage at the ambient temperature of apple.

Apples lose their green skin and flesh color during maturity as chlorophyll is lost. Before maturation, chlorophyll is continuously regenerated; once growth begins, the rate of chlorophyll production slows, initially causing a loss of green coloration. As the chlorophyll disappears further, other pigmentation, often yellow, dominates [41].

Chlorophyll depletion, the synthesis of new pigments such as carotenoids and anthocyanins and the revealing of other pigments previously created throughout the growth of the fruit are all factors in the color changes that occur in many fruits. Such mechanisms are intimately associated with increased respiration, oxygen generation, and starch degradation in fruits with a climacteric ripening pattern [42].

3.3. Total Soluble Solids

As shown in Figure 8, the TSS of apples increased week by week. At the initial week of storage, the TSS was 13.61 °Brix. The maximum TSS attained during storage was about 14.78 °Brix.

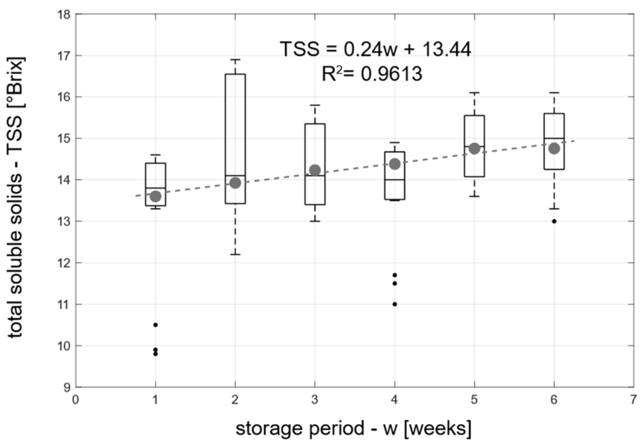

Figure 8. The effect of ambient temperature on the total soluble solids content (TSS) of Golden Delicious apples during storage.

The analysis of the variance homogeneity test showed that the variances for the parameters TSS are the same ($p = 0.053$). Due to the identical standard deviations in the TSS case, Tukey's b-test can be used to distinguish the two groups in terms of means. Tukey's b-test shows that week one is significantly different from weeks five and six ($\alpha = 0.05$).

For TSS, a different (non-linear) trend was reported by Cárdenas-Pérez et al. [26]. They also observed an increase in TSS; our results align with our initial results with weight loss, which is in a linear stage. The rise in TSS could be attributed to moisture loss, leading to the concentration of sugars inside the fruit [43]. The other possible reason for the increased TSS contents is the breakdown of starch into sugars or the hydrolysis of cell wall polysaccharides [44]. The existence of a substrate is recognized to be essential to the respiration process. This substrate serves as a store for carbohydrates such as starch in numerous tissues. These complicated compounds are converted into simple sugars and enter the respiratory route to supply energy for plant vital nutrients. Different quantities of oxygen are used relative to the amount of CO_2 generated when specific substrates are used and fully oxidized. The lower discovered TSS levels of apples in early periods rather than the last weeks may be attributed to the slower respiration process, which reveals the lower total sugar content in apples' tissue. Starch hydrolysis begins during fruit ripening and storage. This pattern may also be explained by considering that the TSS increases with increasing weight loss values. The metabolic processes involved in fruit ripening, including the rapid conversion of starch into sugar and the rise in fruit sweetness during storage, may be the cause of the direct association between TSS and weight loss [38].

In addition, these results back up the studies of Crouch and Ali et al. [45,46]. When several cultivars of apples were maintained at room temperature, they saw an increase in total soluble solids, starch, and sugar content.

According to the current research, total soluble solids in apple fruit increased during storage at an ambient temperature.

4. Discussion

The regression equations and their corresponding coefficients of determination that perfectly represented the weight loss, color values L*, a*, b*, ΔE, C*, and TSS are given in Table 2.

Table 2. Regression equations regarding the storage period with their corresponding coefficient of determination (R^2) for measured quality parameters.

Color Change			
Regression Equations	**Coefficient of Determination (R^2)**	**A-Limit Parameter**	**Consumption Limit (90% Saturation Level)**
$L^* = -7.64\,e^{-0.64w} - 70.97$	0.840	70.97 (decay)	71.35
$a^* = -26.19\,e^{-0.34w} + 12.77$	0.999	12.77 (association)	10.92
$b^* = -26.85\,e^{-1.08w} + 56.34$	0.981	56.34 (association)	55.42
$C^* = -21.77\,e^{-0.82w} + 57.29$	0.970	57.29 (association)	56.32
$\Delta E = 3.16\,w + 6.44$	0.991	-	-
Weight Loss			
Regression Equations	**Coefficient of Determination (R^2)**	**A-Limit Parameter**	**Consumption Limit (90% Saturation Level)**
$\Delta m = 4.44\,w$	0.985	-	-
Total Soluble Solids (TSS)			
Regression Equations	**Coefficient of Determination (R^2)**	**A-Limit Parameter**	**Consumption Limit (90% Saturation Level)**
$TSS = 0.24\,w + 13.44$	0.961	-	-

During the storage period, apples become less acceptable with time from the aspect of consumer evaluation because of color change. The increasing tendency of a* and b* coordinates results in a color shift toward brown and yellow tones on the surface of the examined Golden Delicious specimens. Jha et al., Vieira et al., and Mizrach et al. have also observed similar variations in the values of L*, a*, and b* in the case of Golden Delicious apples and different varieties; however, they used image processing methodologies and other storage conditions [30,47,48]. As a novel and important finding, we can connect the significant changes in TSS in the fifth and sixth weeks, where L* and b* (yellowness) and C* values were nearing saturation.

During the six weeks, the 90% saturation level is defined as the last consumption stage before the total degradation of stored fruits. Table 3 shows the percentage of examined fruits exceeding this quality level each week.

Table 3. The proportion of fruit specimens beyond the consumption limit in the case of color coordinates and TSS.

Storage Time (Weeks)	Parameters beyond Consumption Limit [%]				
	L*	a*	b*	C*	TSS
1	15.3	0.0	0.0	0.0	5.6
2	11.1	0.0	31.9	25.0	16.7
3	44.4	0.0	40.3	36.1	30.6
4	50.0	11.1	55.6	51.4	25.0
5	36.1	34.7	66.7	67.1	27.8
6	58.3	55.6	63.9	60.0	63.9

By investigating the time constant (τ) of the a* and b* values (4.216 and 2.012 weeks, respectively), it must be noted that the b* constant reaches this value significantly earlier, rendering it the dominant part of the visual degradation based on CIELAB color space. It must be pointed out that all asymptotic curves present their τ in the investigated time region (Figure 9).

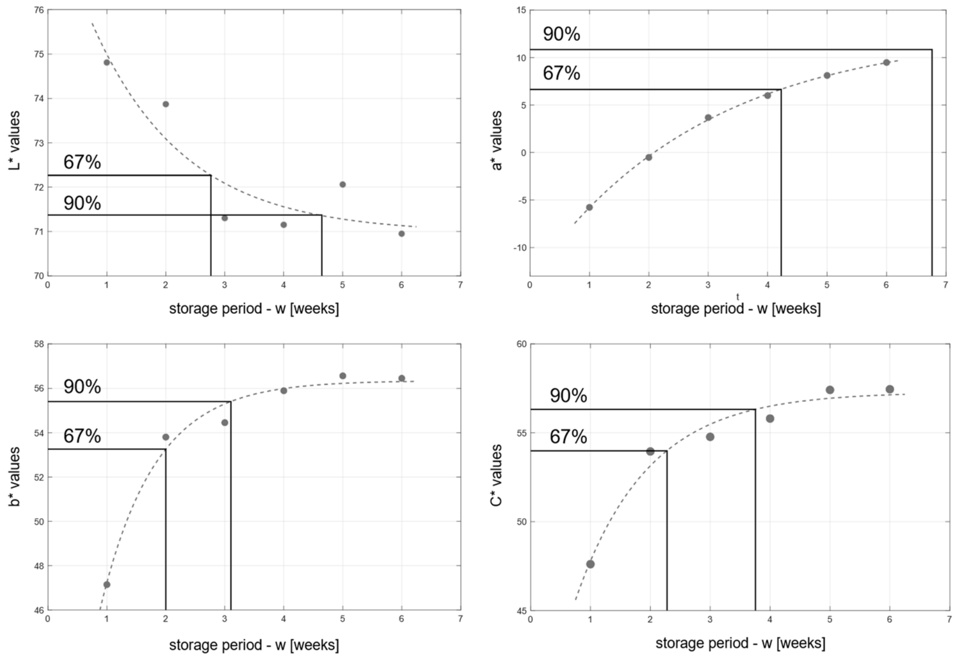

Figure 9. Time constants of color coordinates at 67% and 90% saturation levels during ripening (top left: L*, top right: a*, bottom left: b*, bottom right: C*).

Apples have a short shelf life because they are perishable foods with a rapid metabolism and respiration rate. Because losses during post-harvest handling might reach 25–28% [49], improvements in the post-harvest handling of fresh fruit are crucial for boosting food supply [50].

Apples contain a variety of nutritional benefits; however, they are destroyed during processing after harvest. Both internal and external circumstances influence losses that happen during storage. The most significant effects on apple storage effectiveness, fruit quality traits, and shelf life are caused by temperature and relative humidity during post-harvest handling activities [51]. For instance, they impact the fruit's firmness, weight loss, color, and total soluble solids. Fruit's shelf life is affected by the pectin degradation process that occurs during ripening and plays a significant part in breaking the fruit's cell walls [52].

Proper post-harvest treatment requires changing the product's natural environment to extend the product's post-harvest life. A new approach must be developed to increase the shelf life of fruit stored at room temperature and to prevent softening and senescence [53].

Physical means can satisfy this demand (high-voltage electric field, UV–C light, IR radiation, and microwave radiation).

5. Conclusions

Apple fruit undergoes a post-harvest ripening process that leads to generalized softening and a decline in quality, noticeable in physical and biochemical parameters such as a decrease in weight, color change, and increased sugar content in the juice. All these changes primarily affect the shelf life. The changes in the fruit during ripening are related to an increase in ethylene synthesis; the respiration process and the process of pectin degradation play an essential role in cell wall degradation, affecting the shelf life.

In this study, we combined the changes in weight loss, TSS, and color properties (L*, a*, b*, ΔE and C*) of Golden Delicious apple fruit during storage under room temperature in a novel way to improve their assessment during ambient shelf life with a novel multidisciplinary approach. Analysis using IBM SPSS Statistics v27 software showed a significant difference between the values measured at the beginning and the end state for all parameters during the six weeks of the apple storage experiment. We found all measured apple quality parameters to vary during storage at 24 °C during the study.

The weight loss of samples was increased, indicating that the internal transpiration of the fruit mainly influenced the weight loss. Although the moisture content reaches its limit value during the drying process of apples, the saturation of color coordinates allows for determination of the limit parameters of consumption in the linear weight loss stage. In the laboratory, we applied a flexible and effective measurement method, which can easily be used in a commercial environment. These results improve the provision of helpful information regarding apples' quality changes during storage, which influences customer behavior.

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References

1. FAOSTAT. Available online: https://www.fao.org/faostat/en/#home (accessed on 28 February 2022).
2. Ziv, C.; Fallik, E. Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables for Reducing Food Loss. *Agronomy* **2021**, *11*, 1133. [CrossRef]
3. Kassebi, S.; Korzenszky, P. The Effect of Post-Harvest Storage on the Weight of Golden Delicious Apples. *Sci. Technol. Innov.* **2021**, *13*, 7–11. [CrossRef]
4. Farkas, C.; Fenyvesi, L.; Petróczki, K. Multiple Linear Regression Model of Golden Apple's Failure Characteristics under Repeated Compressive Load. *Potravin. Slovak J. Food Sci.* **2019**, *13*, 793–799. [CrossRef] [PubMed]

5. Cömert, E.D.; Mogol, B.A.; Gökmen, V. Relationship between Color and Antioxidant Capacity of Fruits and Vegetables. *Curr. Res. Food Sci.* **2020**, *2*, 1–10. [CrossRef] [PubMed]
6. Majdan, M.; Bobrowska-Korczak, B. Active Compounds in Fruits and Inflammation in the Body. *Nutrients* **2022**, *14*, 2496. [CrossRef]
7. Butkeviciute, A.; Abukauskas, V.; Janulis, V.; Kviklys, D. Phenolic Content and Antioxidant Activity in Apples of the 'Galaval' Cultivar Grown on 17 Different Rootstocks. *Antioxidants* **2022**, *11*, 266. [CrossRef]
8. Peace, C.P.; Bianco, L.; Troggio, M.; van de Weg, E.; Howard, N.P.; Cornille, A.; Durel, C.-E.; Myles, S.; Migicovsky, Z.; Schaffer, R.J.; et al. Apple Whole Genome Sequences: Recent Advances and New Prospects. *Hortic. Res.* **2019**, *6*, 59. [CrossRef]
9. Chen, Z.; Yu, L.; Liu, W.; Zhang, J.; Wang, N.; Chen, X. Research Progress of Fruit Color Development in Apple (Malus Domestica Borkh.). *Plant Physiol. Biochem.* **2021**, *162*, 267–279. [CrossRef]
10. Musacchi, S.; Serra, S. Apple Fruit Quality: Overview on Pre-Harvest Factors. *Sci. Hortic.* **2018**, *234*, 409–430. [CrossRef]
11. Milošević, T.; Milošević, N.; Mladenović, J. Role of Apple Clonal Rootstocks on Yield, Fruit Size, Nutritional Value and Antioxidant Activity of 'Red Chief® Camspur' Cultivar. *Sci. Hortic.* **2018**, *236*, 214–221. [CrossRef]
12. Milošević, T.; Milošević, N.; Mladenović, J. The Influence of Organic, Organo-Mineral and Mineral Fertilizers on Tree Growth, Yielding, Fruit Quality and Leaf Nutrient Composition of Apple Cv. *'Golden Delicious Reinders.' Sci. Hortic.* **2022**, *297*, 110978. [CrossRef]
13. Caballero, D.; Antequera, T.; Caro, A.; del Mar Ávila, M.; G Rodríguez, P.; Perez-Palacios, T. Non-Destructive Analysis of Sensory Traits of Dry-Cured Loins by MRI–Computer Vision Techniques and Data Mining. *J. Sci. Food Agric.* **2017**, *97*, 2942–2952. [CrossRef] [PubMed]
14. Caballero, D.; Pérez-Palacios, T.; Caro, A.; Amigo, J.M.; Dahl, A.B.; ErsbØll, B.K.; Antequera, T. Prediction of Pork Quality Parameters by Applying Fractals and Data Mining on MRI. *Food Res. Int.* **2017**, *99*, 739–747. [CrossRef] [PubMed]
15. Ma, J.; Sun, D.-W.; Qu, J.-H.; Liu, D.; Pu, H.; Gao, W.-H.; Zeng, X.-A. Applications of Computer Vision for Assessing Quality of Agri-Food Products: A Review of Recent Research Advances. *Crit. Rev. Food Sci. Nutr.* **2015**, *56*, 113–127. [CrossRef]
16. Ekramirad, N.; Adedeji, A.; Alimardani, R. A Review of Non-Destructive Methods for Detection of Insect Infestation in Fruits and Vegetables. *Innov. Food Res.* **2016**, *2*, 6–12.
17. Yang, S.; Meng, Z.; Li, Y.; Chen, R.; Yang, Y.; Zhao, Z. Evaluation of Physiological Characteristics, Soluble Sugars, Organic Acids and Volatile Compounds in 'Orin' Apples (Malus Domestica) at Different Ripening Stages. *Molecules* **2021**, *26*, 807. [CrossRef]
18. Kamiloğlu, Ö. Influence of Some Cultural Practices on Yield, Fruit Quality and Individual Anthocyanins of Table Grape CV. *"Horoz Karasi." J. Anim. Plant Sci.* **2011**, *21*, 240–245.
19. Yang, Y.; Zhou, B.; Zhang, J.; Wang, C.; Liu, C.; Liu, Y.; Zhu, X.; Ren, X. Relationships between Cuticular Waxes and Skin Greasiness of Apples during Storage. *Postharvest Biol. Technol.* **2017**, *131*, 55–67. [CrossRef]
20. Khodaei, D.; Hamidi-Esfahani, Z.; Rahmati, E. Effect of Edible Coatings on the Shelf-Life of Fresh Strawberries: A Comparative Study Using TOPSIS-Shannon Entropy Method. *NFS J.* **2021**, *23*, 17–23. [CrossRef]
21. Sinha, S.R.; Singha, A.; Faruquee, M.; Jiku, A.S.; Rahaman, A.; Alam, A.; Kader, M.A. Post-Harvest Assessment of Fruit Quality and Shelf Life of Two Elite Tomato Varieties Cultivated in Bangladesh. *Bull. Natl. Res. Cent.* **2019**, *43*, 185. [CrossRef]
22. Mardziah, O.; Mat Jafri, M.Z.; Abdul Aziz, A.; Omar, A. Non-Destructive Quality Evaluation of Fruit by Color Based on RGB LEDs System. In Proceedings of the 2014 2nd International Conference on Electronic Design, ICED 2014, Penang, Malaysia, 19–21 August 2015; pp. 230–233.
23. Mesa, A.R.; Chiang, J.Y. Multi-Input Deep Learning Model with RGB and Hyperspectral Imaging for Banana Grading. *Agriculture* **2021**, *11*, 687. [CrossRef]
24. Garrido-Novell, C.; Pérez-Marin, D.; Amigo, J.M.; Fernández-Novales, J.; Guerrero, J.E.; Garrido-Varo, A. Grading and Color Evolution of Apples Using RGB and Hyperspectral Imaging Vision Cameras. *J. Food Eng.* **2012**, *113*, 281–288. [CrossRef]
25. Cen, H.; Lu, R.; Mendoza, F.; Beaudry, R.M. Relationship of the Optical Absorption and Scattering Properties with Mechanical and Structural Properties of Apple Tissue. *Postharvest Biol. Technol.* **2013**, *85*, 30–38. [CrossRef]
26. Cárdenas-Pérez, S.; Chanona-Pérez, J.; Méndez-Méndez, J.V.; Calderón-Domínguez, G.; López-Santiago, R.; Perea-Flores, M.J.; Arzate-Vázquez, I. Evaluation of the Ripening Stages of Apple (Golden Delicious) by Means of Computer Vision System. *Biosyst. Eng.* **2017**, *159*, 46–58. [CrossRef]
27. Khorshidi, J. Storage Temperature Effects on the Postharvest Quality of Apple (Malus Domestica Borkh. Cv. Red Delicious). *N. Y. Sci. J.* **2019**, *3*, 67–70.
28. de AlmeidaTeixeira, G.H.; Meakem, V.; Morais, C. de L.M. de; Lima, K.M.G. de; Whitehead, S.R. Conventional and Alternative Pre-Harvest Treatments Affect the Quality of 'Golden Delicious' and 'York' Apple Fruit. *Environ. Exp. Bot.* **2020**, *173*, 104005. [CrossRef]
29. Rutkowski, K.; Michalczuk, B.; Konopacki, P. Nondestructive Determination of "Golden Delicious" Apple Quality and Harvest Maturity. *J. Fruit Ornam. Plant Res.* **2008**, *16*, 39–52.
30. Jha, S.N.; Rai, D.R.; Shrama, R. Physico-Chemical Quality Parameters and Overall Quality Index of Apple during Storage. *J. Food Sci. Technol.* **2012**, *49*, 594–600. [CrossRef]
31. Bavisetty, S.C.B.; Venkatachalam, K. Physicochemical Qualities and Antioxidant Properties of Juice Extracted from Ripe and Overripe Wax Apple as Affected by Pasteurization and Sonication. *J. Food Process. Preserv.* **2021**, *45*, e15524. [CrossRef]

32. Dobrzański, B.; Rybczyński, R. Colour Change of Apple as a Result of Storage, Shelf-Life, and Bruising. *Int. Agrophysics* **2002**, *16*, 261–268.
33. Calrson, J.K.; Goldman, K.J. (Eds.) *Special Issue: Age and Growth of Chondrichthyan Fishes: New Methods, Techniques and Analysis*, 1st ed.; Springer: Dordrecht, The Nederlands, 2006.
34. Li, M.; Feng, F.; Cheng, L. Expression Patterns of Genes Involved in Sugar Metabolism and Accumulation during Apple Fruit Development. *PLoS ONE* **2012**, *7*, e33055. [CrossRef] [PubMed]
35. Alibas, I.; Zia, M.P.; Yilmaz, A.; Asik, B.B. Drying Kinetics and Quality Characteristics of Green Apple Peel (Mallus Communis L. Var. "Granny Smith") Used in Herbal Tea Production. *J. Food Process. Preserv.* **2020**, *44*, e14332. [CrossRef]
36. Verde, A.; Míguez, J.M.; Gallardo, M. Melatonin Stimulates Postharvest Ripening of Apples by Up-Regulating Gene Expression of Ethylene Synthesis Enzymes. *Postharvest Biol. Technol.* **2023**, *195*, 112133. [CrossRef]
37. Chen, Y.; Wang, T.; Zhou, M.; Hou, H.; Xue, Y.; Wang, H. Rice Husk and Sewage Sludge Co-Combustion Ash: Leaching Behavior Analysis and Cementitious Property. *Constr. Build. Mater.* **2018**, *163*, 63–72. [CrossRef]
38. Sadat Razavi, M.; Golmohammadi, A.; Nematollahzadeh, A.; Ghanbari, A.; Davari, M.; Rovera, C.; Carullo, D.; Farris, S. Impact of Bacterial Cellulose Nanocrystals-Gelatin/Cinnamon Essential Oil Emulsion Coatings on the Quality Attributes of 'Red Delicious' Apples. *Coatings* **2022**, *12*, 741. [CrossRef]
39. Itle, R.A.; Kabelka, E.A. Correlation Between L*a*b* Color Space Values and Carotenoid Content in Pumpkins and Squash (Cucurbita Spp.). *HortScience* **2009**, *44*, 633–637. [CrossRef]
40. Fruit Color—Promoting Red Color Development in Apple. Available online: https://extension.psu.edu/fruit-color-promoting-red-color-development-in-apple (accessed on 13 December 2022).
41. Kingston, C.M. Maturity Indices for Apple and Pear. In *Hortical Reviews*; Janick, J., Ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2010; Volume 13, pp. 407–432.
42. Łysiak, G.; Kurlus, R.; Zydlik, Z.; Walkowiak-Tomczak, D. Apple Skin Colour Changes during Harvest as an Indicator of Maturity. *Acta Sci. Pol. Hortorum Cultus* **2014**, *13*, 71–83.
43. Arendse, E.; Fawole, O.A.; Opara, U.L. Influence of Storage Temperature and Duration on Postharvest Physico-Chemical and Mechanical Properties of Pomegranate Fruit and Arils. *CyTA J. Food* **2014**, *12*, 389–398. [CrossRef]
44. Ahmad, F.; Zaidi, S.; Arshad, M. Postharvest Quality Assessment of Apple during Storage at Ambient Temperature. *Heliyon* **2021**, *7*, e07714. [CrossRef]
45. Ali, M.A.; Raza, H.; Khan, M.A.; Hussain, M. Effect of Different Periods of Ambient Storage on Chemical Composition of Apple Fruit. *Int. J. Agric. Biol.* **2004**, *6*, 568–571.
46. Crouch, I. 1-Methylcyclopropene (Smartfresh Tm) as an Alternative to Modified Atmosphere and Controlled Atmosphere Storage of Apples and Pears. In Proceedings of the 8th International Controlled Atmosphere Research Conference, Rotterdam, The Netherlands, 8–13 July 2001; pp. 433–436.
47. Vieira, F.G.K.; Borges, G.D.S.C.; Copetti, C.; Amboni, R.D.D.M.C.; Denardi, F.; Fett, R. Physico-Chemical and Antioxidant Properties of Six Apple Cultivars (Malus Domestica Borkh) Grown in Southern Brazil. *Sci. Hortic.* **2009**, *122*, 421–425. [CrossRef]
48. Mizrach, A.; Lu, R.; Rubino, M. Gloss Evaluation of Curved-Surface Fruits and Vegetables. *Food Bioprocess. Technol.* **2009**, *2*, 300–307. [CrossRef]
49. Saletnik, B.; Zaguła, G.; Saletnik, A.; Bajcar, M.; Słysz, E.; Puchalski, C. Method for Prolonging the Shelf Life of Apples after Storage. *Appl. Sci.* **2022**, *12*, 3975. [CrossRef]
50. Ghazanfar, M.; Khan, M.; Khan, C.; Bhatti, R. Post Harvest Losses in Apple and Banana During Transport and Storage. *Pak. J. Agric. Sci.* **2007**, *44*, 534–539.
51. Tano, K.; Oulé, M.K.; Doyon, G.; Lencki, R.W.; Arul, J. Comparative Evaluation of the Effect of Storage Temperature Fluctuation on Modified Atmosphere Packages of Selected Fruit and Vegetables. *Postharvest Biol. Technol.* **2007**, *46*, 212–221. [CrossRef]
52. Gwanpua, S.G.; Mellidou, I.; Boeckx, J.; Kyomugasho, C.; Bessemans, N.; Verlinden, B.E.; Hertog, M.L.A.T.M.; Hendrickx, M.; Nicolai, B.M.; Geeraerd, A.H. Expression Analysis of Candidate Cell Wall-Related Genes Associated with Changes in Pectin Biochemistry during Postharvest Apple Softening. *Postharvest Biol. Technol.* **2016**, *112*, 176–185. [CrossRef]
53. González-Aguilar, G.A.; Ayala-Zavala, J.F.; Olivas, G.I.; de la Rosa, L.A.; Álvarez-Parrilla, E. Preserving quality of fresh-cut products using safe technologies. *J. Verbr. Lebensm.* **2010**, *5*, 65–72. [CrossRef]