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Internal Quality Prediction Method of Damaged Korla Fragrant Pears during Storage

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Abstract: To increase the commercial value of damaged fragrant pears and improve marketing competitiveness, this study explored the degree of damage degree and effects of storage time on the internal quality of fragrant pears during storage and predicted the internal quality of fragrant pears using an adaptive neural fuzzy inference system (ANFIS). The internal quality prediction models of damaged fragrant pears during storage with eight membership functions were constructed, and the optimal model was chosen, allowing for accurate internal quality prediction of damaged fragrant pears. The research results demonstrated that the hardness and soluble solid content (SSC) of fragrant pears decrease as the storage time increases. Given the same storage time, the hardness and SSC of fragrant pears are negatively correlated to the degree of damage. The ANFIS modelling technique is feasible for predicting the internal quality of fragrant pears during storage. The best prediction performances for the hardness and SSC of fragrant pears, respectively, are displayed by the ANFIS using the input membership function of trimf (RMSE = 0.1362, R^2 = 0.9752; RMSE = 0.0315, R^2 = 0.9892). The findings of this study can be used to predict the storage quality of fruits.

Keywords: Korla fragrant pears; internal quality; damages; adaptive neural fuzzy inference system; storage

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1. Introduction

Korla fragrant pears belong to a pear species found in Xinjiang, China [1]. A thin pericarp, fine pulp, rich juice, and sweet and brittle taste make them popular among Chinese and international consumers [2,3]. Due to their thin pericarp and fine pulp, Korla fragrant pears have a high mechanical damage rate (15%) during harvest, transportation, grading, and packaging. Practitioners discard damaged fragrant pears directly before warehousing, resulting in economic losses of 25–45% [4]. The national industrial standard and relevant studies have demonstrated that fragrant pears have pericarp protective effects and some self-healing tissue ability and that fruits with some defects or damage still have economic value [5,6]. Abandoning damaged fragrant pears is an extensive production mode, which significantly decreases marketing competitiveness and severely restricts the expansion of the Korla fragrant pear industry. Practitioners are particularly concerned about the quality of fragrant pears. If damaged fragrant pears are sold before losing the requisite quality regulated by industrial standards, it can effectively improve the imbalance between market supply and demand. Therefore, disclosing the variation laws of the storage quality of fragrant pears, effectively and scientifically anticipating the storage quality of damaged fragrant pears, and putting the pears out to market in a timely mannrt (before losing the requisite quality regulated by industrial standards) can promote the sustainable environmentally friendly development of the Korla fragrant pear industry.

During practical production and processing, fruits are extremely susceptible to mechanical damage, thus influencing storage quality. There is a concern about whether storage quality can meet the industrial standards. Variation laws regarding the quality of damaged fruits during storage are a key concern of scholars. Shao [7] investigated the characteristics of storage quality of Citrus reticulate Blanco after extrusion damage and discovered that hardness, SSC, and titratable acid may show a declining trend if they suffer extrusion larger than 12 mm during storage, although the respiration intensity and ethanol and acetaldehyde contents may continuously increase, resulting in a decrease in quality. Pathare et al. [8] caused different degrees of impact damage to tomato fruits and stored them under 10 °C and 22 °C for 10 days. They found that damage area, weight loss ratio, total colour difference value, colour index, total soluble solids, and pigment content increased significantly with the increase in storage temperature and impact height. Although previous research has shown that damages have some influence on the storage quality of fruits, the effects of mechanical damages on the storage quality of Korla fragrant pears have yet to be explored. Some studies have pointed out that hardness and SSC are the most important internal quality attributes of fruits such as pears and are often used as major indexes to evaluate fruit quality [9,10]. Yu et al. [11] analysed the quality changes in pears during storage and found that hardness and SSC decreased continuously. Yu et al. [12] found that SSC was the key quality parameter of Korla pear. Chen et al. [13] studied the changes in physical and chemical properties of fragrant pear during storage and discovered that, after three months of storage, flesh hardness decreased and SSC increased continuously. Therefore, key attention shall be paid to influencing laws of mechanical damages on hardness and SSC of storage quality of fragrant pears. Furthermore, scientifically proven ways must be used to estimate the internal quality of damaged fragrant pears during storage.

To study variation laws concerning the quality of damaged fruits during storage, it is necessary to obtain fragrant pears with different damage degrees as test samples using devices to measure damage. Some scholars have investigated fruit damage based on the principle of a simple pendulum. AlDairi et al. [14] used a pendulum impactor to obtain damaged bananas. They discovered that, as storage temperature and impact strength increased, banana hardness decreased, weight loss rate increased, and peel brightness decreased significantly. Zhang et al. [15] carried out impact damage tests on yellow peaches, releasing samples from different angles based on the pendulum principle to obtain samples with different damage degrees. Because of the swing angle and traction line shaking, the fruits rotate. As a result, when using the single pendulum principle to gauge damaged fruits, the damaged area cannot be controlled precisely. To effectively solve this problem, damage tests based on fruits' free-fall testbed were widely applied. Cao et al. [16] threw strawberries from three different heights onto a steel plate using a free-drop platform to cause impact damage and detected the volatile organic compounds of strawberries using electronic nose technology to predict the degree of collision damage. Using a free-drop platform, Xu et al. [17] measured ethylene production, respiration rate, hardness, SSC, and electrical conductivity by dropping apples from five different heights onto various contact surfaces. They discovered that, with the exception of a decrease in hardness, all other indicators demonstrated an upward trend. Mencarelli et al. [18] used a free-fall platform to drop kiwifruit from a height of 30 cm onto surfaces that differed in terms of roughness. After storage at different temperatures, the hardness, SSC, ethylene production, and other indicators were measured. During storage, fruit firmness decreased, while SSC and ethylene production increased. Hence, damage tests based on free-fall testbeds can be used as tools to obtain test samples of different damage degrees to fruits.

Although Korla fragrant pears may lead to changes in the warehouse to eliminate the regular corrosion of pears during storage, there are still some problems, such as the inability to determine storage quality. Hence, it is urgent to develop a low-cost and high-efficiency method to predict the storage quality of Korla fragrant pears. Because of its quick convergence, strong self-learning capacity, and great adaption ability, ANFIS is frequently used to forecast the quality of fruits and vegetables [19,20]. It can offer useful methods for predicting the storage quality of Korla fragrant pears. Moreover, some scholars have achieved good prediction effects by using ANFIS. For example, Niu Hao et al. [21] applied the ANFIS model and found that the hardness of Korla fragrant pears is highly correlated with the harvesting maturity period and storage time. It has been verified that the ANFIS model is reliable in predicting variation trends regarding the hardness in Korla fragrant pears. Liu et al. [22] predicted the quality of Korla fragrant pears during storage using ANFIS. They found that the ANFIS with gbellmf as an input membership function had the best prediction effect for SCC, while the ANFIS with trimf had the best prediction effect for VC content. Jiang et al. [23] used ANFIS to estimate the remaining ascorbic acid in fresh-cut pineapples during storage and proved that the ANFIS model with trimf outperforms other ANFIS models in terms of prediction accuracy. Using ANFIS, the above researchers accurately predicted the attributes of undamaged Korla fragrant pears and fresh-cut pineapples. Nevertheless, the application of ANFIS to predict the internal quality of damaged Korla fragrant pears during storage has not yet been reported. Therefore, using ANFIS to predict the internal quality of damaged Korla fragrant pears can accurately control the change law of internal quality during storage, provide a reference for the delivery time, and effectively reduce economic losses in the pear industry.

In this study, hardness and SSC were used as the internal quality evaluation index of fragrant pears during the storage period to study the variation laws of hardness and SSC during the storage of damaged pears. Based on ANFIS, eight fragrant pear quality prediction models with different membership functions were constructed, and the optimal prediction model was screened, aiming to provide theoretical guidance for the prediction of the storage quality of fruits.

2. Materials and Methods

2.1. Sampling of Korla Fragrant Pears

On 15 September 2021, autumn, Korla fragrant pear samples were collected from 14-year-old pear trees in Shiertuan Fragrant Garden (81°12′ E, 40°30′ N, elevation: 1015 m), Alaer City, 1st Division, Xinjiang Production and Construction Corps, China.

Korla fragrant pears can readily suffer mechanical injuries during harvest because of their thin pericarp and crispy pulp. Hence, fragrant pear cannot be collected mechanically and manual harvesting is the only option. Workers wore gloves while harvesting fragrant Korla pears to prevent accidental damage. The postharvest pears were wrapped with bubble nets to avoid mechanical damage during transportation. As test samples, fragrant pears that weighed 110 ± 5 g each, had similar shapes, uniform colours, and were free of damage, distortion, and plant or insect diseases were chosen.

2.2. Damage Test of Korla Fragrant Pears

The impact damage test of fragrant pears was carried out using the self-made impact damage testbed for Korla fragrant pears to obtain samples with different damage degrees (Figure 1). The impact damage testbed of fragrant pears was composed of a lifting gear and an absorption device. The latter consists of a vacuum generator, an air compressor and a sucker. The former consists of leading screws, linear guideway, pneumatic motor, and cantilever arms. The operation steps were introduced as follows: The sucker was lifted up to the appointed height through the lifting device. Then, the fragrant pear was adsorbed onto the sucker through the absorption device. Finally, the suction was stopped to allow the fragrant pear to fall freely and cause damage to the fragrant pear on the testbed. After falling, the fragrant pears were quickly collected to avoid secondary damage. This testbed can make impact damage tests at different heights, and the contact materials on the testbed can be changed to explore buffer performances to fragrant pears. It has the advantages of a simple structure, easy operation, and batch sample test. It addresses the issues of poor accuracy in terms of artificial height control and difficult control. In this experiment, the impact contact material used a corrugated board. First, the falling height was adjusted. Fragrant pears began showing visible signs of damage when the falling height was 30 cm. When the impact test was stopped, the pericarp broke and juice spilt over when the falling height was 150 cm. Finally, the falling heights were set at 30 cm, 50 cm, 70 cm, 90 cm, 110 cm, and 130 cm, respectively. Each test group was repeated 20 times. At six different falling heights, 1080 pears with different damage degrees were obtained.

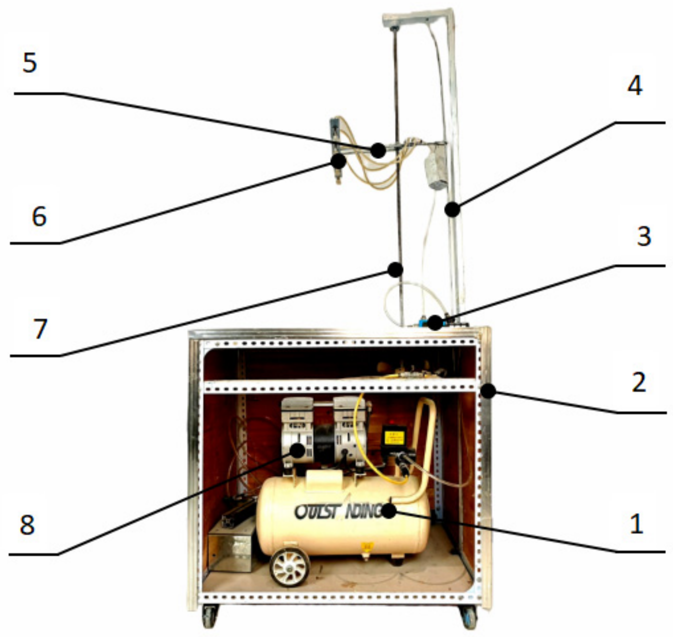


Figure 1. Impact damage testbed of fragrant pears. 1. Air compressor; 2. Engine body; 3. Vacuum generator; 4. Linear guideway; 5. Cantilever arm; 6. Sucker; 7. Leading screw; 8. Pneumatic motor.

The test data were recorded, and the mean results were used. After being damaged, the fragrant pears from Korla were left at room temperature until they turned brown. Using a knife, the pericarp was removed from the damaged areas. According to Wu et al. [24], the damaged shape of fruits is somewhat oval-like. The semi-major axis (a) and the semi-minor axis (b) of the damaged area were measured (Figure 2) in three repetitions, and the mean results were selected. The oval area was considered equal to the damaged area (Equation (1)). According to falling height, the corresponding damage areas were determined at 77.71 mm^2, 296.91 mm^2, 604.05 mm^2, 900.77 mm^2, 952.30 mm^2, and 993.42 mm^2, respectively.

$$S = \pi ab \tag{1}$$

where S is the damaged area (mm^2), a is the semi-major axis of the oval (mm), and b is the semi-minor axis of the oval (mm).

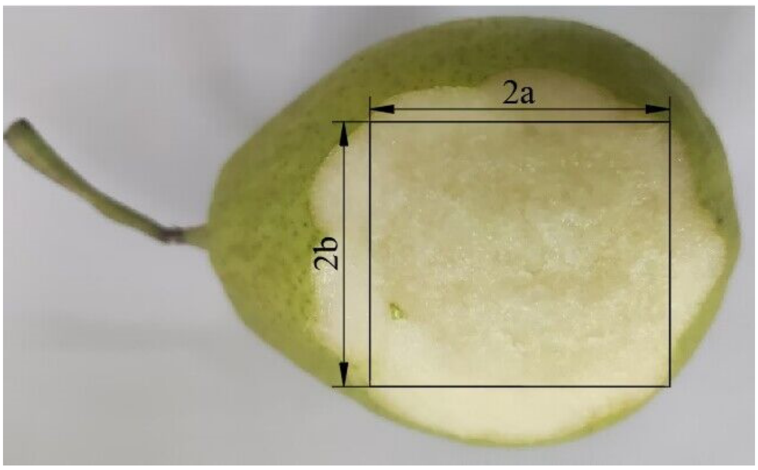


Figure 2. Measurement diagram of the damaged area.

2.3. Storage Tests of Korla Fragrant Pears

Based on the natural environments in Xinjiang, the storage test of fragrant pears was carried out at room temperature in a key laboratory of modern agricultural engineering at Xinjiang Tarim University. The mean temperature and average relative humidity were set at 15 °C and 56%, respectively. According to the industrial standards of Korla fragrant pears [5], the commercial value of fragrant pears decreases when SSC < 11% and hardness <3.9 kg/cm^2. When these values were reached, the storage test was stopped. Therefore, fragrant pears were stored for 0, 5, 10, 15, 20, 25, 30, 35, and 40 days, and their hardness and SSC were measured every five days. A total of 1260 fragrant pears were needed for the storage test.

2.4. Measurement of Peeling Hardness

Ten fragrant pears were chosen randomly for hardness testing. At random, four symmetric points were selected at the equator of fragrant pears. The pericarp was removed with a scalpel. The measuring positions at the equator of the fragrant pears are shown in Figure 3. The hardness was measured using a fruit hardness tester (GY-1, Tuopu Instrument Co., Ltd., Hangzhou, Zhejiang, China). Before using the hardness tester, it was zeroed by rotating the dial indicator until the driving pointer was in line with the first scale line. The rob indenter was used to puncture the flesh uniformly and slowly while the hardness tester was held in the hand and positioned perpendicular to the surface of the measurement point. According to the industry standard, a diameter of 8 mm indenter was selected when determining the hardness of pears [25]. The measurement was complete when the indenter reached and was expressed in kg·cm^{-2}. After zeroing, the next measurement was performed, and the average of the four measurements was calculated. A total of 630 fragrant pears were needed to measure peeling hardness.

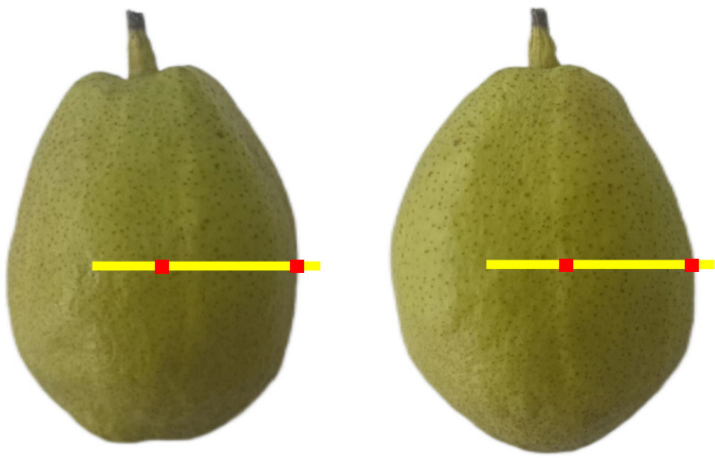


Figure 3. Measuring points of the quality index of Korla fragrant pears (■).

2.5. Measurement of SSC

The SSC was measured using a portable sugar content measuring refractometer (B32T, Mingrui Electronic Technology Co., LTD., Guangzhou, Guangdong, China). The portable refractometer for sugar measurement must be calibrated before SSC measurement. Following this, 10 fragrant pears were chosen randomly for the test. During the test, four symmetric uniform points were chosen at the equator of the fragrant pears, and the measuring points are depicted in Figure 3. A scalpel was used to remove the pericarp, which was then manually squeezed. The squeezed juice was dropped at the deviation prism before being covered with the cover plate. SSC of fragrant pears was observed through an ocular lens. After each measurement, the deviation prism and cover plate were cleaned with clean water. The mean of the test results was used (unit: %). A total of 630 fragrant pears were needed to measure SSC.

2.6. ANFIS Model

ANFIS combines the self-study ability and fuzzy system. The fuzzy processing, fuzzy reasoning, and accurate calculation of the fuzzy system are expressed by the fuzzy structure of ANFIS, thus realizing the hybrid neural network of self-organisation and self-study of the fuzzy system [26,27].

In this study, 70% of the test data was randomly selected as the training set, while the remaining 30% was selected as the test set. The Matlab tool cabinet was used for ANFIS modelling. The Matlab software version was R2017a (MathWorks, Natick, MA, USA). The system input considered damage area, and storage time and the system output considered quality indicators. Grid Partition was selected to create the basic fuzzy reasoning system once the training set was input. Eight types of input membership functions were used, including trimf, trapmf, gbellmf, gaussmf, gasuss2mf, pimf, psigmf, and dsigmf. The type of membership function has a direct impact on the output results of the prediction model and is crucial for predicting the quality of damaged fragrant pears. In the modelling training stage, the initial ANFIS models were produced by the meshing technique, and the models with different membership functions were used for the fuzzification of input data. The error tolerance and the times of iterations were set as 0 and 100, respectively. The test dataset was input into trained models with different membership functions to obtain the prediction value. In this study, the system structure of the quality prediction model of damaged fragrant pears is shown in Figure 4.

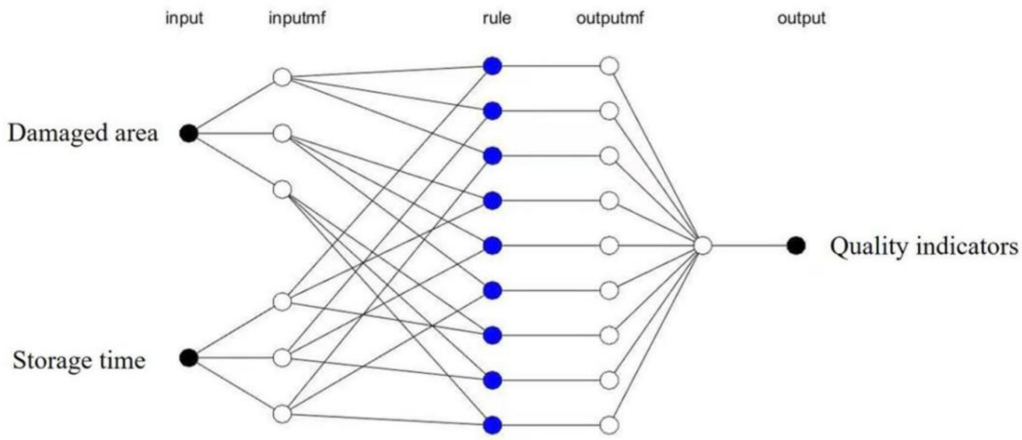


Figure 4. ANFIS structure model. Note: **O** and — represent nodes and connecting lines of neural network, respectively.

2.7. Factors and Variables

Hardness and SSC were used as the internal quality evaluation index, and the effect of storage time and damage degree on the hardness and SSC of damaged fragrant pear during storage was studied. Therefore, damage degree and storage time were independent variables that served as input to the ANFIS prediction model. Two indices, hardness and SSC, were dependent variables and were the output part of the ANFIS prediction model. This study explored the effects of damage degree and storage time on the hardness and SSC of fragrant pears during storage and predicted the internal quality of fragrant pears using an adaptive neural fuzzy inference system.

2.8. Criteria for Evaluating the Optimal Detection Model

To screen the optimal quality prediction model of damaged fragrant pears, the hardness and SSC detection performances of fragrant pears were assessed according to the coefficient of determination (R^2) and root-mean-square error (RMSE). The greater the R^2, the lower the RMSE and the higher the accuracy of the prediction model. The calculation formulas of R^2 and RMSE are as follows:

$$R^2 = 1 - \frac{\sum \left(M_j - T_j\right)^2}{\sum M_j^2 - \frac{\left(\sum M_j\right)^2}{n}} \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\sum_{i}^{N} \frac{\left(M_j - T_j\right)^2}{N}} \tag{3}$$

where M_j and T_j are measured values, the prediction value of the data j. n refers to the number of measured values, and N is the total number of data.

3. Results and Discussion

3.1. Quality Variation Laws of Damaged Korla Fragrant Pears during the Storage Period

3.1.1. Variation Laws of Hardness

Hardness is one of the important measuring indexes of fruit commodities, and it is an essential index for recognising quality characteristics [28]. It is vital for fruit edibility, supply period, and commodity value. It can be seen from Figure 5 that the hardness of fragrant pears gradually decreases as storage time increases. Given the same storage time, the hardness of fragrant pears decreases with an increase in the degree of the damage. The average hardness of fragrant pears with different damage degrees decreased from 7.25 $kg \cdot cm^{-2}$ to 5.33 $kg \cdot cm^{-2}$ at 40 days. Fragrant pears have strong physiological activity in the storage environment under room temperature. The hydrolase causes the major components of the cell wall, such as cellulose and polysaccharides (including protopectin), to progressively decompose, causing damage to the cell's organisational structure [29]. Therefore, the hardness changes of fragrant pears decrease gradually as storage time increases. Additionally, the degradation of polysaccharides in the cell wall of fruits requires the participation of carbohydrate enzymes. Mechanical damages may influence the activity of enzymes in fruit, thus increasing the activity of pectin methylesterase and polygalacturonase, accelerating the degradation of pectin and polysaccharide, and accelerating softening of fruits [30,31]. Therefore, the hardness of fruits is negatively related to the damage degree under the same storage time. During the storage period, no significant difference ($p > 0.05$) was found in the hardness of fragrant pears when the damaged area was 0 mm^2, 77.71 mm^2, and 296.91 mm^2, while no significant difference ($p > 0.05$) was observed in the hardness of fragrant pears when the damaged area was 900.77 mm^2, 952.30 mm^2, and 993.42 mm^2. However, a significant difference ($p < 0.05$) was noticed in the hardness of fragrant pears when the damaged area was less than 296.91 mm^2 and greater than 900.77 mm^2. When the damaged area is 77.71 mm^2, there is no damage to the pericarp of fragrant pears and no visible damage, but there is mild damage in the pulp after peeling (Figure 6). During the storage period, the hardness variation laws of fruits are similar to those of non-damaged fragrant pears, indicating that low degrees of damage and the non-breakage of the pericarp slightly influence the physiological activity of fruits. When the damaged area is greater than 77.71 mm^2, the higher damage degree significantly influences the physiological activity of fragrant pears.

3.1.2. Variation Laws of SSC

SSC is an important sensory quality of fruits and an essential index that reflects the internal quality of Korla fragrant pears [32]. The SSC of Korla fragrant pears determines the degree of sweet and brittle taste. The higher the SSC, the sweeter the taste of fragrant pears. It can be seen from Figure 7 that the SSC of fragrant pears decreases gradually with increasing storage time. Given the same storage time, the SSC of fragrant pears declines gradually as the degree of damage increases. The average SSC of fragrant pears with different damage degrees decreased from 12.10% to 11.25% at 40 days. The reasons for this can be described as follows: there is exuberant cellular respiration of fragrant pears in the storage environment at room temperature, and aerobic respiration may consume internal organic matter, such as glucose in fruits, thus decreasing SSC with the increase in storage time [33]. After mechanical damage to fruits, nutrients are consumed with the rise in respiration rate, resulting in a significant decrease in SSC. Under this circumstance, nutrients from surrounding perfect tissues will be supplied to the damaged position quickly, increasing nutrients at the site of damage and strengthening self-repair ability [34]. The respiration intensity of fruits is positively related to the degree of damage. Therefore, the SSC of fragrant pears decreases with increasing degrees of damage when the storage time is fixed. When the storage time is less than 25 days, there is no significant difference ($p > 0.05$) in SSC, regardless of the damaged area. When the storage time exceeds 30 days, there is no significant difference ($p > 0.05$) in the SSC of fragrant pears when the damaged area is less than 296.91 mm^2 and when the damaged area is greater than 900.77 mm^2. However, there is a significant difference ($p < 0.05$) in the SSC of fragrant pears when the damaged area is less than 296.91 mm^2 and when it is greater than 900.77 mm^2. Thus, the SSC of fragrant pears with different damage degrees is significantly affected by extending the storage time. When the damaged area of fragrant pears is 77.71 mm^2, the variation laws of the SSC of damaged fruits during storage are similar to those of undamaged fruits. This supports the notion that, when the damage degree is low and the pericarp is not broken, the respiration intensity of fruits is slightly influenced. When the damaged area is greater than 77.71 mm^2, the respiration intensity of fruits is influenced more by the increase in damage degree.

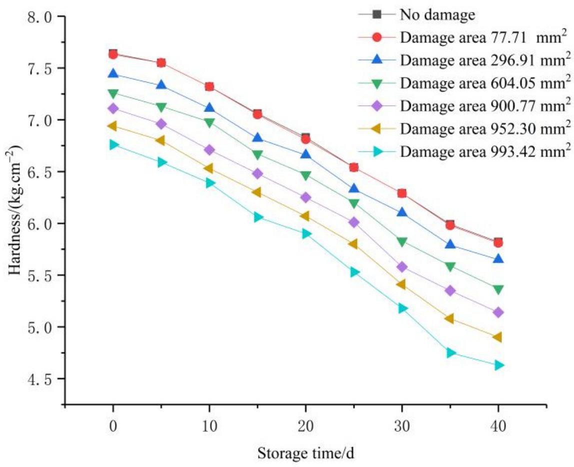
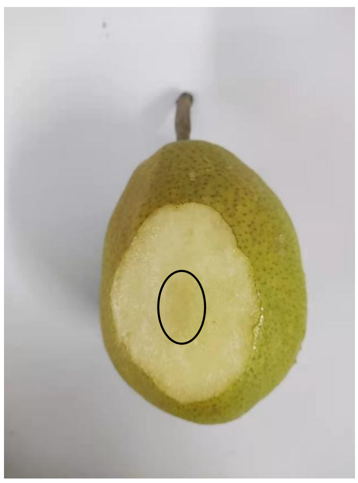


Figure 5. Variation laws of the hardness of fragrant pears during the storage period.

(**a**) The pericarp is undamaged



(**b**) The pulp has been mildly damaged

Figure 6. Damage characteristics of fragrant pears. Note: In this case, falling height was 30 cm, and the damaged area was 77.71 mm^2.

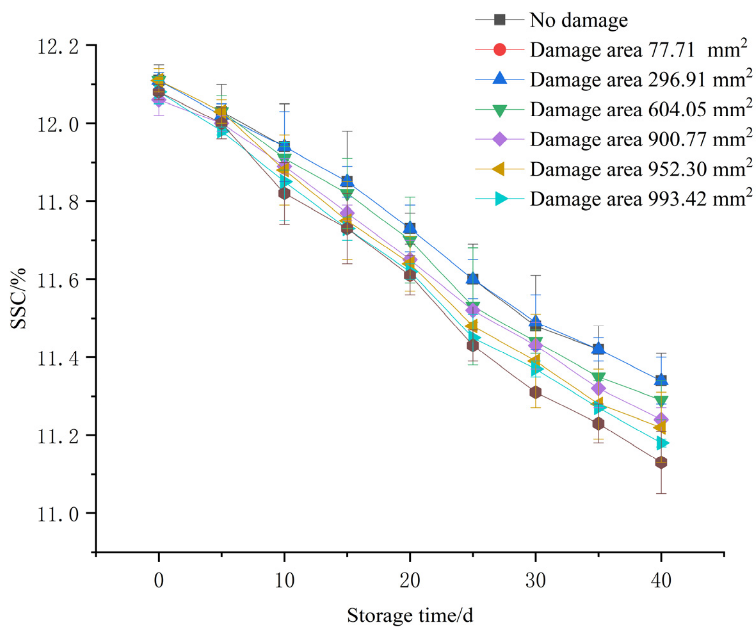


Figure 7. Variations in SSC of fragrant pears during the storage period.

3.2. Storage Quality Prediction of Damaged Korla Fragrant Pears Based on ANFIS

3.2.1. Hardness Prediction

During model training and prediction, the correlations between the predicted hardness and observed hardness of fragrant pears during the storage period were obtained. Additionally, the RMSE and R^2 in the training and prediction stages are listed in Table 1. It can be seen from Table 1 and Figure S1 that, in the prediction stage, RMSE and R^2 are different among ANFIS models with different membership functions, with 0.1362 and 0.9752 in the ANFIS model with trimf; 0.2651 and 0.9129 in the ANFIS model with trapmf; 0.1750 and 0.9603 in the ANFIS model with gbellmf; 0.1653 and 0.9640 in the ANFIS model with gaussmf; 0.2293 and 0.9350 in the ANFIS model with gauss2mf; 0.2627 and 0.9143 in the ANFIS model with pimf; 0.2152 and 0.9384 in the ANFIS model with dsigmf; 0.2329 and 0.9284 in the ANFIS model with psigmf. In the prediction stage, the observed and predicted R^2 are higher than 0.91, proving that the trained ANFIS model can predict the hardness of fragrant pears during the storage period scientifically and effectively. Meanwhile, this analysis discovered that the ANFIS model with trimf has the highest R^2 and the lowest RMSE. This model clearly outperforms the other ANFIS models. As a result, the ANFIS model with trimf is the optimal model for predicting the hardness of Korla fragrant pears during storage.

Table 1. RMSE and R^2 for the prediction of hardness by the ANFIS model with different input MFs at the training and prediction phases.

Membership Functions	Training Stage		Prediction Stage	
	RMSE	R^2	RMSE	R^2
trimf	0.0865	0.9853	0.1362	0.9752
trapmf	0.1395	0.9609	0.2651	0.9129
gbellmf	0.0867	0.9852	0.1750	0.9603
gaussmf	0.0826	0.9866	0.1653	0.9640
gasuss2mf	0.1156	0.9735	0.2293	0.9350
pimf	0.1423	0.9593	0.2627	0.9143
dsigmf	0.1125	0.9749	0.2152	0.9384
psigmf	0.1129	0.9747	0.2329	0.9284

3.2.2. SSC Prediction

The method used for the SSC prediction of Korla fragrant pears based on the ANFIS model is consistent with the methods used to predict hardness. In the model training and prediction stages, the correlations between the predicted and observed SSC of fragrant pears during the storage period were obtained. In addition, the RMSE and R^2 in the model training and prediction stages are listed in Table 2. As shown in Table 2 and Figure S2, in the prediction stage, RMSE and R^2 are different among ANFIS models with different membership functions, which are 0.0315 and 0.9892 in the ANFIS model with trimf; 0.0866 and 0.9345 in the ANFIS model with trapmf; 0.0444 and 0.9836 in the ANFIS model with gbellmf; 0.0343 and 0.9897 in the ANFIS model with gaussmf; 0.0695 and 0.9606 in the ANFIS model with gauss2mf; 0.0865 and 0.9354 in the ANFIS model with pimf; 0.0803 and 0.9408 in the ANFIS model with dsigmf; 0.0810 and 0.9401 in the ANFIS model with psigmf. In the prediction stage, R^2 between the observed value and predicted values is higher than 0.91, proving that the trained ANFIS model can scientifically and effectively predict the SSC of fragrant pears during storage. Meanwhile, this study discovered that ANFIS models with trimf and gaussmf achieve the highest R^2, while the ANFIS model with trimf has the lowest RMSE and is superior to the other models in terms of performance. Therefore, the ANFIS model with trimf is the optimal model for predicting the SSC of fragrant pears during storage.

Table 2. RMSE and R^2 for the prediction of SSC by the ANFIS model with different input MFs at the training and prediction phases.

Membership Functions	Training Stage		Prediction Stage	
	RMSE	R^2	RMSE	R^2
trimf	0.0178	0.9961	0.0315	0.9892
trapmf	0.0686	0.9441	0.0866	0.9345
gbellmf	0.0322	0.9877	0.0444	0.9836
gaussmf	0.0236	0.9934	0.0343	0.9897
gasuss2mf	0.0526	0.9672	0.0695	0.9606
pimf	0.0677	0.9456	0.0865	0.9354
dsigmf	0.0646	0.9505	0.0803	0.9408
psigmf	0.0647	0.9504	0.0810	0.9401

3.3. Comparative Analysis between the Optimal Internal Quality Assessment Models for Korla Fragrant Pears and Traditional Regression Model

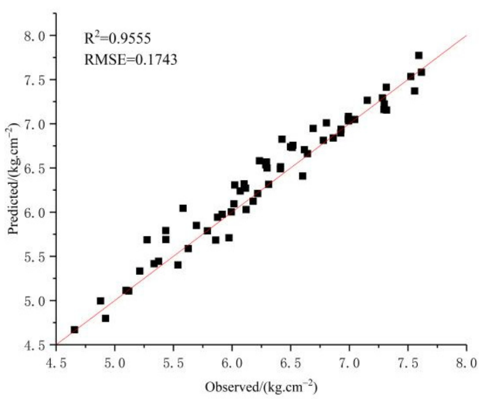
Multiple linear regression analysis and partial least squares regression analysis are traditional modelling methods. Because of their ability to improve the accuracy of predictions through the collaborative effect of multiple indicators, they have been widely utilised to predict the quality of fruits such as citrus [35], mango [36], and apple [37]. They achieved relatively good predictions. Therefore, the ANFIS with the input membership function trimf was compared with the traditional modelling methods of multiple linear regression analysis and partial least squares regression analysis to determine their relative quality prediction efficacy for damaged Korla fragrant pears. The results are shown in Table 3. The results demonstrated that, during the prediction of the hardness and SSC of fragrant pears, the R^2 of the multiple linear regression model were 0.9720 and 0.9880, and the RMSE were 0.1434 and 0.0873, respectively. The R^2 of the partial least squares regression model were 0.8301 and 0.9782, and the RMSE were 0.2985 and 0.0465, respectively. The R^2 of the ANFIS model with trimf were 0.9752 and 0.9892, while the RMSE were 0.1362 and 0.0315, respectively. The ANFIS with trimf as the input membership function has higher R^2 and lower RMSE values. To achieve better performances in predicting the internal quality of the damaged fragrant pears, the ANFIS model with trimf is recommended, as the ANFIS model with trimf had the best prediction performance.

Table 3. Comparison between optimal prediction models and traditional models.

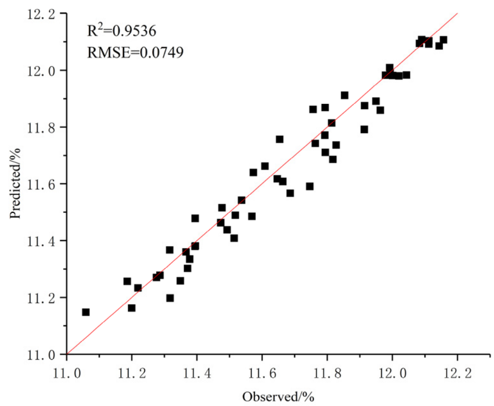
Project	Hardness	SSC
R^2 value of multiple linear regression model	0.9720	0.9880
R^2 value of partial least squares regression model	0.8301	0.9782
R^2 value of ANFIS model	0.9752	0.9892
RMSE value of multiple linear regression model	0.1434	0.0873
RMSE value of partial least squares regression model	0.2985	0.0465
RMSE value of ANFIS model	0.1362	0.0315

3.4. Model Verification

On 10 September 2022, during the autumn, a storage experiment was conducted on fragrant pears to verify the reliability and practicability of the optimal prediction model. Korla fragrant pear samples were collected from 12-year-old pear trees in Rice Farm Fragrant Garden (80°6′ E, 41°12′ N, elevation: 1131 m), Akesu City, Xinjiang, China. Pears with different damage degrees were obtained by the impact test, and the corresponding damaged areas were determined as 77.71 mm^2, 296.91 mm^2, 604.05 mm^2, 900.77 mm^2, 952.30 mm^2, and 993.42 mm^2, respectively. Fragrant pears were stored for 0, 5, 10, 15, 20, 25, 30, 35, and 40 days, and their hardness and SSC were evaluated. Linear fitting of the values measured in the experiment and the predicted values of the ANFIS model with trimf was carried out. The results are shown in Figure 8.



(**a**) Hardness



(**b**) SSC

Figure 8. Scatter plots of the measured values versus the predicted values for hardness (**a**) and SSC (**b**).

According to the verification experiment, the ANFIS model based on trimf can achieve a relatively higher prediction accuracy for hardness (R^2 = 0.9555, RMSE = 0.1743), while the ANFIS model based on trimf can achieve a relatively higher prediction accuracy for SSC (R^2 = 0.9536, RMSE = 0.0749). These results suggest that the hardness and SSC of Korla pears during storage can be predicted by inputting data regarding damage degree and storage time into the optimal trained model.

Based on the above studies, the ANFIS model is suitable for predicting the internal quality of Korla fragrant pears during the storage period by collecting data on damage degree and storage time. Different membership functions have different performances in predicting the quality of fragrant pears, and the ANFIS model with trimf is the optimal model for predicting the hardness and SSC of Korla fragrant pears. Hardness and SSC are the most important internal quality attributes of fruits such as pears [9,10]. Other quality indexes of Korla fragrant pears, such as weight per fruit and colour, are of great significance to agricultural practitioners. ANFIS model can predict the hardness and SSC of Korla fragrant pears scientifically and effectively. The applicability of the model to predict other quality indices of fragrant Korla pears requires further investigation. This study reveals the variation laws of hardness and SSC of damaged Korla fragrant pears during storage and proposes a prediction method based on ANFIS. This study can provide references to develop methods for predicting other quality indexes of Korla fragrant pears and determining the storage quality of other fruits.

4. Conclusions

The hardness and SSC of fragrant pears decrease as the storage time increases. Given the same storage time, the hardness and SSC of fragrant pears negatively correlate with the degree of damage. When there is no damage to the pericarp of fragrant pears, the lower damage degree has little effect on fruit physiological activity. The ANFIS modelling technique is feasible for predicting the internal quality of fragrant pears during the storage period. The ANFIS with the input membership function of trimf showed the best prediction performances of hardness and SSC of fragrant pears (RMSE = 0.1362, R^2 = 0.9752; RMSE = 0.0315, R^2 = 0.9892).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9060666/s1, Figure S1: Correlation between observed value and predicted value of hardness in fragrant pears during storage in the training and prediction stages of ANFIS models with different membership functions; Figure S2: Correlation between observed value and predicted value of SSC in fragrant pears during storage in the training and prediction stages of ANFIS models with different membership functions.

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References

1. Liu, Y.; Wang, T.; Su, R.; Hu, C.; Chen, F.; Cheng, J. Quantitative evaluation of color, firmness, and soluble solid content of Korla fragrant pears via IRIV and LS-SVM. *Agriculture* **2021**, *11*, 731. [CrossRef]
2. Wang, Z.; Tang, Y.; Liu, Y.; Zhang, H.; Zhang, Y.; Lan, H. Inhibitory effect of $CaCl_2$ and carboxymethyl chitosan coating on the after-ripening of Korla fragrant pears in cold storage. *Int. J. Food Sci. Technol.* **2021**, *56*, 6777–6790. [CrossRef]
3. Jia, X.H.; Wang, W.H.; Du, Y.M.; Tong, W.; Wang, Z.-H.; Gul, H. Optimal storage temperature and 1-MCP treatment combinations for different marketing times of Korla Xiang pears. *J. Integr. Agric.* **2018**, *17*, 693–703. [CrossRef]
4. Liu, Y. Study on Mechanical Damage Mechanism and Effect Evaluation on Storage of Korla Fragrant Pear. Ph.D. Thesis, Northeast Agricultural University, Harbin, China, 2021.
5. *NY/T 585-2002*; Agricultural Industry Standard. Ministry of Agriculture of the PRC: Beijing, China, 2002; p. 3. Available online: http://www.csres.com/detail/71433.html (accessed on 20 December 2002).
6. Yu, S.; Lan, H.; Li, X.; Zhang, H.; Zeng, Y.; Niu, H.; Niu, X.; Xiao, A.; Liu, Y. Prediction method of shelf life of damaged Korla fragrant pears. *J. Food Process Eng.* **2021**, *44*, e13902. [CrossRef]
7. Shao, X. Study on Compression Damage and Quality Deterioration Mechanism of Citrus Reticulata Blanco. Master's Thesis, Huazhong Agricultural University, Wuhan, China, 2020.

8. Pathare, P.; Mai, A. Bruise damage and quality changes in impact-bruised, stored tomatoes. *Horticulturae* **2021**, *7*, 113. [CrossRef]
9. Guo, W.; Fang, L.; Liu, D.; Wang, Z. Determination of soluble solids content and firmness of pears during ripening by using dielectric spectroscopy. *Comput. Electron. Agric.* **2015**, *117*, 226–233. [CrossRef]
10. Nicolaï, B.; Verlinden, B.; Desmet, M.; Saevels, S.; Saeys, W.; Theron, K.; Cubeddu, R.; Pifferi, A.; Torricelli, A. Time-resolved and continuous wave NIR reflectance spectroscopy to predict soluble solids content and firmness of pear. *Postharvest Biol. Technol.* **2008**, *47*, 68–74. [CrossRef]
11. Yu, S.; Liu, Y.; Tang, Y.; Li, X.; Li, W.; Li, C.; Zhang, Y.; Lan, H. Non-destructive quality assessment method for Korla fragrant pears based on electrical properties and adaptive neural-fuzzy inference system. *Comput. Electron. Agric.* **2022**, *203*, 107492. [CrossRef]
12. Yu, Y.; Zhang, Q.; Huang, J.; Zhu, J.; Liu, J. Nondestructive determination of SSC in Korla fragrant pear using a portable near-infrared spectroscopy system. *Infrared Phys. Technol.* **2021**, *116*, 103785. [CrossRef]
13. Chen, J.; Feng, Z.; Wu, J.; Wang, Z.; Hu, X. Changes in the volatile compounds and physicochemical properties of Wujiuxiang pear fruits during storage. *Trans. Chin. Soc. Agric. Eng.* **2009**, *25*, 264–269.
14. AlDairi, M.; Pathare, P.B.; AlMahdouri, A. The contribution of impact damage to the quality changes of stored banana fruit. *Biol. Life Sci. Forum* **2022**, *16*, 3.
15. Zhang, F.; Li, B.; Yin, H.; Zou, J.; Ouyang, A. Study on the quantitative assessment of impact damage of yellow peaches using the combined hyperspectral technology and mechanical parameters. *J. Spectrosc.* **2022**, *2022*, 7526826. [CrossRef]
16. Cao, Y.; Zhang, Y.; Lin, M.; Wu, D.; Chen, K. Non-destructive detection of damaged strawberries after impact based on analyzing volatile organic compounds. *Sensors* **2022**, *22*, 427. [CrossRef]
17. Xu, F.; Fei, L.; Zhi, G.; Zhe, L. Influence of drop shock on physiological responses and genes expression of apple fruit. *Food Chem.* **2020**, *303*, 125424. [CrossRef]
18. Mencarelli, F.; Massantini, R. Influence of impact surface and temperature on the ripening response of kiwifruit. *Postharvest Biol. Tec.* **1996**, *8*, 165–177. [CrossRef]
19. Huang, Y.; Lan, Y.; Thomson, S.; Fang, A.; Hoffmann, W.; Lacey, R. Development of soft computing and applications in agricultural and biological engineering. *Comput. Electron. Agric.* **2010**, *71*, 107–127. [CrossRef]
20. Liu, Y.; Zhao, J.; Tang, Y.; Jiang, X.; Liao, J. Construction of a Chlorophyll Content Prediction Model for Predicting Chlorophyll Content in the Pericarp of Korla Fragrant Pears during the Storage Period. *Agriculture* **2022**, *12*, 1348. [CrossRef]
21. Niu, H.; Liu, Y.; Wang, Z.; Zhang, H.; Zhang, Y.; Lan, H. Effects of harvest maturity and storage time on storage quality of Korla fragrant pear based on GRNN and ANFIS models: Part I Firmness Study. *Food Sci. Technol. Res.* **2020**, *26*, 363–372. [CrossRef]
22. Liu, Y.; Zhang, Q.; Niu, H.; Zhang, H.; Lan, H.; Zeng, Y.; Jia, F. Prediction method for nutritional quality of Korla pear during storage. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 247–254. [CrossRef]
23. Jiang, Z.; Zheng, H.; Mantri, N.; Qi, Z.; Zhang, X.; Hou, Z.; Chang, J.; Liu, H.; Liang, Z. Prediction of relationship between surface area, temperature, storage time and ascorbic acid retention of fresh-cut pineapple using adaptive neuro-fuzzy inference system (ANFIS). *Postharvest Biol. Technol.* **2016**, *113*, 1–7. [CrossRef]
24. Wu, J. Study on Dynamic Viscoelastic Property and Impact Bruise of Korla Pear. Ph.D. Thesis, Northwest A&F University, Yangling, China, 2011.
25. *NY/T 2009-2011*; Industry Standard—Agriculture. Fruit and Seedling Quality Supervision and Testing Center of Ministry of Agriculture: Beijing, China, 2011; p. 6. Available online: http://down.foodmate.net/standard/sort/5/33815.html (accessed on 20 December 2002).
26. Taghinezhad, E.; Kaveh, M.; Szumny, A. Optimization and prediction of the drying and quality of turnip slices by convective-infrared dryer under various pretreatments by RSM and ANFIS Methods. *Foods* **2021**, *10*, 284. [CrossRef]
27. Arabameri, M.; Nazari, R.; Abdolshahi, A.; Abdollahzadeh, M.; Mirzamohammadi, S.; Shariatifar, N.; Barba, F.; Mousavi, K. Oxidative stability of virgin olive oil: Evaluation and prediction with an adaptive neuro-fuzzy inference system (ANFIS). *J. Sci. Food Agric.* **2019**, *99*, 5358–5367. [CrossRef]
28. Wang, Z.; Tang, Y.; Jin, X.; Liu, Y.; Zhang, H.; Niu, H.; Lan, H. Comprehensive evaluation of Korla fragrant pears and optimization of plucking time during the harvest period. *Int. J. Agric. Biol. Eng.* **2022**, *15*, 242–250. [CrossRef]
29. Lan, H.; Zhang, Q.; Tang, Y.; Liu, Y.; Zhang, H.; Jia, F. Research of the maturity law and the evaluation method for the ripeness of the Korla fragrant pear based on the effective accumulated temperature. *Int. Agric. Eng. J.* **2016**, *25*, 10–19.
30. Linden, V.; Sila, D.; Duvetter, T.; Baerdemaeker, J.; Hendrickx, M. Effect of mechanical impact-bruising on polygalacturonase and pectinmethylesterase activity and pectic cell wall components in tomato fruit. *Postharvest Biol. Technol.* **2008**, *47*, 98–106. [CrossRef]
31. Manrique, G.; Lajolo, F. Cell-wall polysaccharide modifications during postharvest ripening of papaya fruit (*Carica papaya*). *Postharvest Biol. Technol.* **2004**, *12*, 1000–1016. [CrossRef]
32. Lan, H.; Wang, Z.; Niu, H.; Zhang, H.; Zhang, Y.; Tang, Y.; Liu, Y. A nondestructive testing method for soluble solid content in Korla fragrant pears based on electrical properties and artificial neural network. *Food Sci. Nutr.* **2020**, *8*, 5172–5181. [CrossRef]
33. Wang, Z.; Liu, Y.; Zhou, Y.; Zhang, H.; Niu, H.; Lan, H. Prediction method of changes in storage quality of Korla fragrant pear based on kinetic modeling. *Int. Agric. Eng. J.* **2020**, *29*, 245–254.
34. Yu, Y. Effects of Mechanical Damage on Postharvest Physiology and Biochemistry of DangShan Pear. Master's Thesis, Anhui Agricultural University, Hefei, China, 2011.

35. Al-Saif, A.M.; Abdel-Sattar, M.; Eshra, D.H.; Sas-Paszt, L.; Mattar, M.A. Predicting the chemical attributes of fresh citrus fruits using artificial neural network and linear regression models. *Horticulturae* **2022**, *8*, 1016. [CrossRef]
36. Mishra, P.; Woltering, E.; El Harchioui, N. Improved prediction of 'Kent' mango firmness during ripening by near-infrared spectroscopy supported by interval partial least square regression. *Infrared Phys. Technol.* **2020**, *110*, 103459. [CrossRef]
37. Zhang, Y.; Zhu, D.; Ren, X.; Shen, Y.; Cao, X.; Liu, H.; Li, J. Quality changes and shelf-life prediction model of postharvest apples using partial least squares and artificial neural network analysis. *Food Chem.* **2022**, *394*, 133526. [CrossRef] [PubMed]