Vibrational Bruise Prediction of Harvested Kiwifruits under Transportation based on the BP Neural Network

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Abstract

Vibrational bruise is one of the most common mechanical damages of fruit under transportation. Transportation vibrational bruise prediction can provide important theoretical basis for reducing the bruise and package design. However, there is no related research about the vibrational bruise prediction of fruits. In this study, a vibrational bruise prediction model based on BP neural network was established to predict the vibrational bruise of harvested kiwifruit. The inputs of the prediction model included the vibrational acceleration, vibrational frequency and time, and this network model was trained using adaptive learning rate method based on momentum gradient descent, the vibrational bruise deformation of kiwifruit could be predicted. The results showed that the neural network model has a good prediction effect of vibrational bruise deformation, and the average relative error of predicting vibrational bruise of kiwifruit is 1.32%, and the average absolute error was 0.01, and R^2 is 0. 9683. It can provide a weighable theoretical and data reference for the food storage and transportation.

Keywords: Kiwifruits, Vibrational bruise prediction, BP neural network, Transportation

1 Introduction

Transportation bruise of fruits and vegetables is one of the main problems in the transportation chain for the large economic loss [1]. In developing countries, the transportation bruised ratio of fresh fruits and vegetables are estimated to range from 2% for potatoes to 23% for strawberries, with an overall of 12% between the production and consumption sites, while the ratio is much higher than that in developed countries [2]. Mechanical damage will directly cause the destruction of fruit's cell structure, resulting in the loss of water and juice, and the rapid softening and browning of the pulp tissue. The bruise can also accelerate the microbial infection, causing the fruit to mold and lose its economic and edible value. Kiwifruits are some kind of easily bruised fruits and are highly sensible to mechanical injuries under transportation. For instant, the weight loss, soluble solids content, membrane permeability, respiratory intensity and ethylene production in kiwifruits during the vibration increased significantly and firmness decreased comparing to the non-vibrated samples [3].

Recent work by historians has established that transportation vibration is the main factor resulting in bruise of fresh fruits and vegetables [4-5]. Jarimopas measured and analyzed the vibrational forces of truck transportation and the damage of the citrus [6]; Berardinelli simulated the bruise of pears caused by transportation vibration based on the vibrational test and three-directional acceleration measurement [7]; Van Zeebroeck analyzed The influence of vibration frequency, acceleration amplitude, apple size and stacking height on the vibrational bruise of apples [8]; Soleimani measured the vibration of different suspension types, speeds and road conditions in fruit transportation [9]; Thompson tested the protection effects of pallet packaging on pears and avocados during transportation vibration [10]; Shahbazi analyzed the damage of watermelon caused by transportation based on the elastic modulus as the vibrational damage evaluation standard [11]. Zhou analyzed the mechanical bruise of Huanghua pears caused by vibration under various vibrational intensities [12-13]; Lu proposed a vibrational bruise model of fruit based on the fatigue damage theory [14]; Wu combined the visible and near-infrared spectroscopy of chemo metrics to analyze the transportation vibrational damage of tomato [15]. Zeng measured the influence of transportation vibration on the storage quality of melon [16]; Liu studied the relationship between vibrational parameters and vibrational damage characteristics [17].

To summarize the literatures above, there is no related research about the vibrational bruise prediction. Due to the randomness of vibrational forces and the vibrational bruises occurred with physiological changes and viscoelastic deformation, it is difficult to establish accurate traditional mathematical vibration bruise models under the complex conditions. Vibrational bruise prediction of fruits under transportation become the key to solving the problem.

As a kind of intelligent information processing system, artificial neural network does not need to determine the mathematical equation of the mapping relationship between input and output in advance [18-21]. It only learns certain rules through its own training, and gets the closest expected output value when given the inputs [22]. BP neural network is a multi-layer feed forward network trained by error back-propagation. It has excellent non-linear mapping ability, learning and adaptive ability, and good fault tolerance ability

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[23]. The underlying non-linear laws behind the factors affecting the degree of mining are used for mining and deep learning to predict the future bruise, and then corresponding prevention strategies could be formulated.

Therefore, the paper has been organized in the following way: (1) to establish the elastic deformation and its mathematical vibration bruise model based on the analysis of mechanical characteristics of bio rheological bruise of kiwifruit during transportation, (2) establish the bruise prediction model of kiwifruit based on the BP neural network, (3) train the model with the data collected, and (4) evaluate the predictive performance of the model.

2 Nonlinear Visco-elastoplastic Characteristics and Vibrational Deformation of Kiwifruit

2.1 Mechanical Model of the Kiwifruit

The kiwifruit is a multi-layered biological system comprising biomolecules, organelles, cells and even tissues [5]. The superficial flesh of kiwifruit can be approximated as linearly elastic under external forces, while the heart tissue is nonlinearly elastic. When the external force is greater than a certain amount, the surface layer is deformed plastically. Figure 1A shows the mechanical model of a single kiwifruit, where for different elements, K_1, K_s and K_v represent the elasticity of the surface fleshy, plasticity and viscosity element, respectively. And K_r means the non-linear elasticity of the cardiac tissue. K_v and K_r in parallel symbolizes the supporting effect of the microtubule bundle on the fleshy texture. And with increasing deformation, the tissue viscosity is always manifested with the deformation. For when $F_{K1} \geq F_s$, the tissue undergoes plastic deformation and is nonlinearly viscoelastic. For when $F_{K1} < F_s$, the tissue appears viscoelastic with creep characteristics [20].

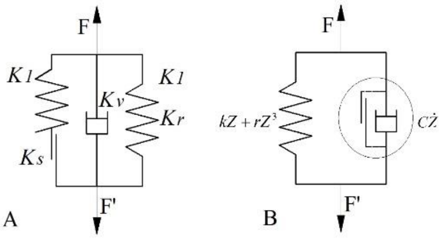

Figure 1. Mechanical model of the kiwifruit and its equivalent mechanical model

If the plastic force is equivalent to the viscosity term, as shown in Figure 1B, the deformation resistance F causing bruise for kiwifruit is [24]:

$$F = kZ + rZ^3 + C\dot{Z} \tag{1}$$

Where F is the deformation force; Z is the amount of deformation; k and r are the coefficient of elasticity; C is the equivalent viscosity coefficient.

2.2 The Relationship between Kiwifruit Deformation and Vibration Acceleration and Frequency

As kiwifruit are mostly transported in single-separated packages with minimal collisions with each other [3], the vibrational force situation can be simplified to a vibration model of a single kiwifruit on the bottom plate of the packaging material. In practice, the force and contact area of the base plate on each kiwifruit are difficult to determine and test, but the acceleration of the base plate's vibration caused by the unevenness of the road surface is easy to obtain. If the acceleration transfer rate at each point of the kiwifruit is approximately equal to 1, then the inertial force can be considered to be uniformly distributed with mass. Let the inertial force be concentrated on the kiwifruit plasmodesmata, and from the above analysis, the nonlinear differential equation of vibration of a single herbicide can be obtained [25] as

$$kZ + rZ^3 + C\dot{Z} + m\ddot{Z} = -mG_0 \sin \omega t \tag{2}$$

Where G_0 is the amplitude of vibration acceleration; m is the quality of kiwifruits; ω is the vibration frequency.

2.3 The Relationship between Kiwifruit Deformation and Vibration Time

Tissue deformation of kiwifruit is affected by their quality and shape. After a kiwifruit tissue is damaged, its texture and physical parameters change accordingly. So the stress-strain relationship after the damage can be detected to evaluate the severity of the bruise. Based on the visco-elastoplastic theory, the deformation of kiwifruit tissue can be written as [26]:

$$\varepsilon = \left(\frac{\sigma_A}{E} + \frac{\sigma_A - \sigma_S}{B} \right) \left(1 - e^{-\frac{t}{\tau}} \right) \tag{3}$$

Where $\tau = \frac{\eta(E+B)}{EB}$ means the characteristic relaxation time of vibrational bruise deformation; σ_A is the constant stress. σ_S is the plastic yield limit, B is the coefficient of intensification, and η is the coefficient of viscosity, t is the vibrational time, and E is the modulus of elasticity.

Based on the Equation (3), it can be seen that the shorter the vibrational time t, the smaller the deformation under constant stress. Under the experimental conditions of simulated transportation, vibration experiments were designed with different levels of vibrational frequency, vibrational intensity and time. The expressions of vibration damage deformation of kiwifruit were obtained by statistical analysis of the data from several experiments.

The above analysis shows that the mathematical model of vibrational bruise and deformation resistance of kiwifruit is a nonlinear function, which is difficult to resolve accurately. The research and application of neural networks provide a powerful tool for establishing an accurate mathematical model of the evolution of vibration damage in kiwifruit.

3 Principle Establishment of Kiwifruits Vibrational Bruise Prediction Model based on BP Neural Network

Artificial neural networks have received attention in many fields for its self-learning, self-organization, better fault tolerance, and excellent nonlinear approximation ability. The multilayer forward neural network based on the error back propagation algorithm (BP algorithm) is the most widely used neural network learning algorithm, which has a wide range of applications in function approximation, pattern recognition, and data compression [27].

A typical BP neural network generally consists of an input layer, an output layer, and multiple hidden layers (or intermediate layers), while a neuron is the most basic unit of a neural network, which is a simplification and simulation of a biological neuron. Figure 2 shows a three-layer BP neural network structure containing a hidden layer. To construct a BP neural network, various aspects such as the number of layers, the number of neurons and the transfer function need to be determined.

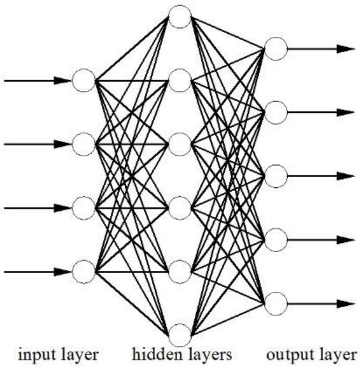

Figure 2. The Three-layer BP network model structure

3.1 The Number of Neural Network Layers

The hidden layer in which the neuron transfer function is tangential (tanh) is called the S-type hidden layer. Theoretically, it has been shown that a network with deviation b and at least one S-type hidden layer plus a linear output layer (three-layer network) can approximate any nonlinear function with finite discontinuity. Increasing the number of layers can further reduce the error and improve the accuracy, but it also complicates the network and increases the training time for the network weights. For this study, a three-layer BP neural network can meet the requirements [27].

3.2 The Number of Neurons

The number of neurons in the input and output layers of a neural network depends on the actual problem to be solved. For the specific problem studied in this paper, the input factors are vibrational frequency, vibrational accelerate and time, the input layer contains 3 neurons. The output factor is the deformation of the kiwifruit, so the output layer contains 1 neuron. Through several training comparisons, it was determined that the number of neurons in the hidden layer is 10-15 that can achieve good results.

3.3 The Neuron Transfer Function

The transfer function f in the BP neural network model is usually chosen as a differentiable monotonically increasing function. Combined with the specific problem of this paper, the transfer function of the hidden layer neurons is chosen as the tangent Sigmoid function (for the equation is $f(x)=\tanh(x)$), and the transfer function of the output layer neurons is chosen as the linear function (for the equation is $f(x) = kx$) (Figure 3).

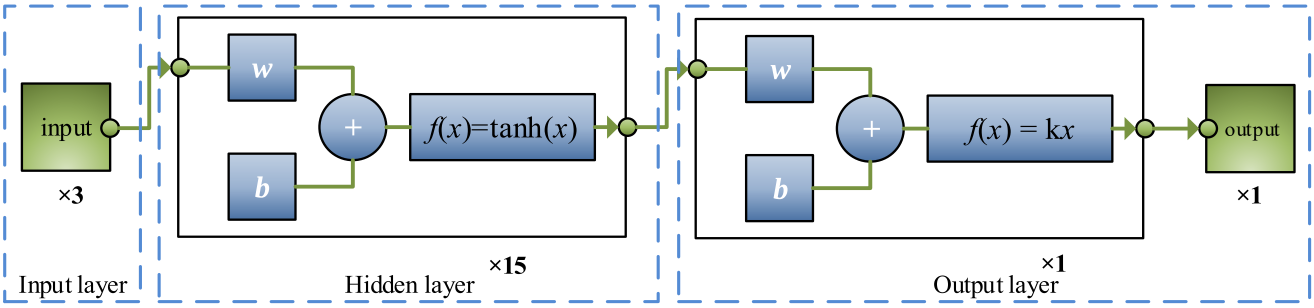

Figure 3. Schematic diagram of BP neural network structure

4 The Training of Kiwifruits Vibrational Bruise Prediction Model based on BP Neural Network

4.1 The Data Construction of Training Samples

The training samples was obtained by the vibrational bruise test of kiwifruits by the vibrational damage test systems. As shown in Figure 4, A single kiwifruit column vibration test was conducted using a 300 g weighted simulated ball to simulate the mass of multiple specimens on the top layer of a single kiwifruit fruit, while a 2.0 mm thick rubber sheet was bonded between the simulated ball and the kiwifruit sample to ensure that the viscoelastic properties of the rubber sheet were essentially the same as the viscoelastic properties of the kiwifruit flesh. According to the preliminary experimental exploration and related literature, the vibration damage test conditions for kiwifruit samples were: vibration treatment temperature at room temperature, vibration intensity 0.50, 0.75, 1, 1.25 gc (gc is the acceleration of gravity), vibration frequency 10, 20, 30, 40 Hz.

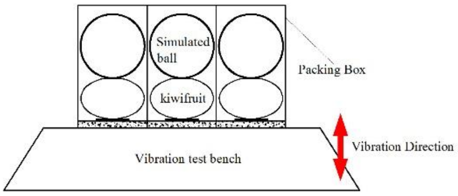

Figure 4. The vibrational damage test systems for fruits

4.2 Data Normalization

Neural networks are artificial intelligence theories of statistical induction followed by deductive simulation. The purpose of normalization is to unify the probabilities of statistical distributions of events on the affiliation of 0 to 1 gray clusters. According to the previous paper, BP neural network mainly uses S-type transfer function, which is often sensitive to the numbers between 0 and 1. In addition, the normalized preprocessing of the "input-target" sample set data can improve the training efficiency of the neural network.

Normalization consists of normalization and denormalization: normalization is performed before training and simulation (or prediction); denormalization is performed after simulation (or prediction), mainly to denormalize the output vector in order to bring it back to its normal value.

The normalization equation is as follows [27]:

$$P_n = 2\frac{P - P_{\min}}{P_{\max} - P_{\min}} - 1 \tag{4}$$

$$T_n = 2\frac{T - T_{\min}}{T_{\max} - T_{\min}} - 1 \tag{5}$$

Where: P is the original input data; P_n is the normalized input data; T is the original target data; T_n is the normalized target data; the subscripts "max" and "min" represent the maximum and minimum values, respectively. The "input-target" sample set used for neural network training needs to be normalized, and the input data before the simulation (or prediction) of the trained network also needs to be normalized. Note that Pmax and Pmin in the normalization equation should use the maximum and minimum values at the time of training.

Denormalization is to recover the normalized data. The main purpose here is to denormalize the target data T, which is given by:

$$P' = 0.5(P_n + 1)(P_{\max} - P_{\min}) + P_{\min} \tag{6}$$

$$T' = 0.5(T_n + 1)(T_{\max} - T_{\min}) + T_{\min} \tag{7}$$

4.3 The Training of Neural Network

The neural network learning is the learning algorithm used to train the BP neural network. For different problems, it is important to consider not only the performance of the algorithm itself, but also the complexity of the model, the size of the sample set, the size of the network, the network error target, and the type of problem being solved. In this paper, the problem of vibrational bruise prediction belongs to the "function fitting" type, and the Bayesian regularized learning algorithm is finally chosen after several training comparisons of various models. The network was initialized with the Newff function in the neural network toolbox in the Matlab 2019b software, and the trained model parameters were set to the maximum number of learning times of 10000, the network performance target error was 10-13, and the learning rate was 0.02. When the training process reached the set parameters, the training would stop automatically. The above BP neural network program is trained with the designed model samples. Figure 5 shows the convergence curve of the network training error, which shows that after 2564 training sessions, the final convergence accuracy is 0.05483.

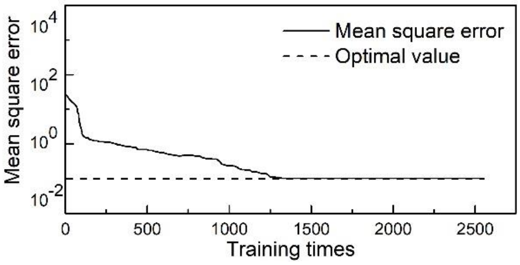

Figure 5. Training error convergence curve of the sample

5 Validation and Discussion of Prediction Results

To further verify the performance of this prediction model based on BP neural network, 18 sets of data not involved in the training were used as calibration samples to test the network. Figure 6 shows the learning results of the neural network model for vibrational bruise deformation of kiwifruit. The solid line is the output of the neural network model after training, and the dotted line is the fitted curve derived from the aforementioned vibration bruise deformation equation (4) of kiwifruit. Figure 5(a) shows the relationship between vibration bruise deformation and vibrational time of kiwifruit for different vibrational frequencies, Figure 6(b) shows the relationship between vibrational bruise deformation and vibrational time of kiwifruit for different vibrational intensities. As shown in Fig. 6, the calculated values of the neural network model are consistent with the actual values, and the prediction accuracy is higher than that of the fitted curve. The neural network model accurately reflects the evolution of vibration damage deformation of kiwifruit.

Figure 6(a) shows that the deformation of kiwifruit heart tissues was more damaged at high frequencies as the vibrational frequency increased. In addition, the deformation varied with time, and there were viscoelastic and cumulative damage effects. Figure 6(b) reflects that the compression deformation of kiwifruit internal tissues gradually increased under higher vibrational acceleration conditions, which is related to the cellular structure characteristics of kiwifruit. In conclusion, the prediction results show that the model has high accuracy, and the average relative error of predicting vibrational bruise of kiwifruit is 1.32%, and the average absolute error was 0.01, and R^2 is 0. 9683.

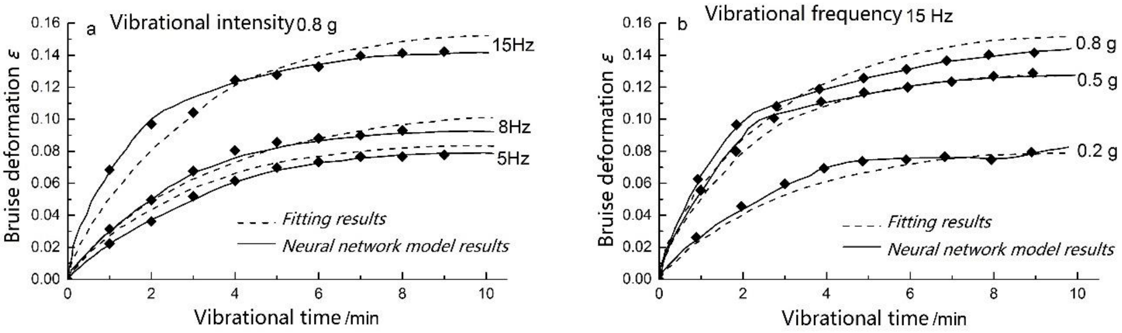

Figure 6. Neural network output results for vibrational deformation of kiwifruit

6 Conclusion

In this paper, mechanical characteristics of bio rheological bruise of kiwifruit during transportation was analyzed, and BP artificial neural network was applied to develop a model that can predict the vibrational bruise of kiwifruit by parameters such as vibrational frequency, vibrational accelerate and time. The prediction results show that the model has high accuracy, and the average relative error of predicting vibrational bruise of kiwifruit is 1.32%, and the average absolute error was 0.01, and R^2 is 0. 9683. In the actual process, since the parameters of vibrational frequency, vibrational accelerate and time can be easily measured, the vibrational bruise of kiwifruit can be predicted according to the BP neural network model, and the prediction is fast and easy to operate, so that it can provide a weighable theoretical and data reference for the food storage and transportation.

Since neural network modeling is a learning process through the intrinsic connection of data itself, it is an inductive way of thinking and can be a good solution to the nonlinear problem of vibration damage in kiwifruit. Further work can be done to apply neural network theory to control the occurrence and development of vibration damage in kiwifruit, and to predict the life span of kiwifruit, in order to solve the problem of vibration damage in kiwifruit.

Acknowledgements

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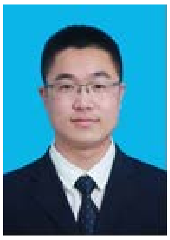

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