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Research on Jujube-Fruit-Yield-Increasing Technology Based on Local Thermal Damage of Jujube Bark

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Abstract: Girdling is an important means of improving the yield and quality of jujube trees, but this measure can easily cause injury, or even death, to jujube trees. A technology for increasing yield and improving quality, based on local thermal damage of jujube bark, is proposed to address a series of issues in current jujube-tree-girdling technology. First, we measured the thermophysical parameters of jujube bark and established a heat-transfer model for jujube bark. Then, in order to investigate the impact of local thermal damage on jujube-tree yield and fruit quality, local heating experiments were conducted on jujube-tree bark, using the heat-transfer model. The experimental results indicated that heating the jujube bark at a certain temperature for an appropriate time can effectively improve the yield and quality of jujube fruit. Compared with traditional girdling techniques, this method has less impact on the health of jujube trees and does not form permanent wounds on them. The research results provide new ideas for exploring sustainable yield-increase methods for fruit trees.

Keywords: fruit trees; thermal damage; heat-transfer model; bark; girdling; yield; jujube-fruit quality

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1. Introduction

Girdling is an important method for increasing the yield and improving the fruit quality of fruit trees, and this technology has been widely applied in various regions of China [1]. Practice has shown that girdling can promote the accumulation of sugar in fruits, improve skin color, and promote fruit ripening. Numerous research results have shown that many fruit trees, such as jujube, citrus, apple, cherry, and blueberry trees, can improve the quality and the yield of their fruits, to a certain extent, through appropriate girdling [1,2]. Girdling usually refers to the use of tools to girdle the trunk or the main branches of a fruit tree in a reasonable manner, inhibiting the transportation of nutrients generated by the leaves through the phloem to the roots and allocating as many nutrients as possible to the fruit, in order to improve the yield and the quality of the fruit tree [3].

However, fruit tree girdling also has numerous defects. First, the most direct impact of girdling on trees is physical damage to them. An unhealed girdling wound increases the risk of insects and pathogens invading the tree, making it susceptible to pests and diseases. Second, continuous girdling for many years can affect the distribution balance of the photosynthetic products in the tree, resulting in insufficient supply of root nutrients. This leads to weakened tree vigor and undermines the sustainable productivity of an orchard. More seriously, according to statistics from farmers and from our team over the years, the annual continuous girdling of jujube trees in jujube orchards, for about 7 years, leads directly to about 8% of the trees dying each year thereafter [4]. In addition, years of continuous girdling have led to a decrease in the quality of fruits, resulting in reduced sugar content and a sour taste. Related studies have shown that after girdling until the formation of new phloem tissue, continuous girdling treatment affects both the water transport in the xylem and the normal physiological activities of the fruit trees [5]. This, in turn, leads to a weakened physiological function of the roots and a reduced ability to absorb various ions from the soil. At the same time, the accumulation of cytokinins in the roots inhibits the development of lateral root elongation [6]. In an experiment, Schepper [7] found that a decrease in the sap flow rate can be observed shortly after girdling. In addition, some other studies suggested that long-term girdling hinders the synthesis and transportation of endogenous hormones in trees, limits overall plant-nutrient absorption, and hinders the growth of branches, roots, and trunks, ultimately leading to a decrease in tree vitality [8]. In short, girdling has a significant destructive effect on the regulation of tree bodies, and this damage accumulates with increases in girdling frequency over time.

In order to eliminate these negative effects caused by traditional fruit-tree girdling, researchers have made continuous attempts at new methods related to girdling. First, plastic or metal wires have been used to ligate fruit trees to inhibit the transport of nutrients to the roots during the fruiting period. However, when using plastic rolling strips, it is easy for the strips to relax under the action of the preload, so the effect is not as good as that of iron wire. Moreover, both methods are cumbersome to operate, and ultimately the plastic bag or the metal wire needs to be removed, which requires a large amount of manual investment. In addition, researchers have also attempted to use the method of locally heating the fruit bark at high temperatures to achieve the goal of inhibiting the transportation of photosynthetic products from the phloem to the roots during specific periods. Research has shown that heating the phloem of peach trees at a certain temperature for a certain period of time reduces the ability of the phloem to transport starch toward the root, resulting in a better inhibitory effect on the nutritional growth of the peach trees and promoting their reproductive ability [9]. However, there is very little existing research on these methods, and no quantitative analysis has been conducted on the impact of locally heating the fruit bark on fruit-tree yield and fruit quality; there is also no relevant heat-transfer model available to guide specific heating experiments.

Unlike girdling, quantitative heating does not require peeling the bark, thereby avoiding the numerous adverse effects caused by exposure of the wood. Additionally, unlike the tightening methods such as the use of iron wire, quantitative heating does not require the subsequent removal of a rolling strip, making the process simpler. In addition, theoretically speaking, by establishing a heat-transfer model for bark, reasonable control of the heating temperature and the time can be achieved to accurately control the degree of bark-cell death during heating. This is expected to improve the yield and the quality of fruit trees without causing significant damage to the tree body. Therefore, the use of this method to replace the traditional girdling method in achieving the goal of increasing fruit-tree yield may be comparatively ideal. By heating the main branches (with the diameter of 15–20 mm) of jujube trees with a 1 mm diameter electric wire at 200 °C for 1 min, our team studied the effect of this treatment on jujube tree yield, in 2021. The preliminary research results indicated that the jujube fruit yield of jujube tree branches treated with this method was significantly higher than that of jujube tree branches untreated. However, this study did not consider that the heating time of bark with different thicknesses should vary, and quantitative research was not conducted on the heating time of bark with different thicknesses. Therefore, in order to further explore the impact of this method on jujube yield and establish a feasible jujube bark heating model, further research is needed.

This study proposes the hypothesis that heating the bark of jujube trees can cause heat damage, making it impossible for nutrients to be transported through the phloem to the roots for a period of time, promoting jujube-fruit growth and, ultimately, achieving the goal of increasing yield and improving jujube-fruit quality. In order to verify the correctness of this hypothesis, we carried out the following work. First, we measured the thermophysical properties and other parameters of jujube bark. Then, we established a heat-transfer model for jujube bark to provide a basis for decision making on the heating temperatures and times for jujube bark. Finally, based on the constructed heat-transfer model of jujube bark, jujube-bark-heating experiments were conducted to study the specific impact of the local heating of jujube bark on the quality and the yield of jujube fruit. Through this study, the feasibility of using thermal-damage-based methods to increase jujube yield and improve jujube-fruit quality was explored, and theoretical guidance and basic data are provided for the design of specialized heating devices in the future.

2. Materials and Methods

2.1. Materials and Instruments

The jujube trees used in the experiment are located in a jujube garden in Alar City, Xinjiang. The jujube trees are 8 years old and the Hui jujube variety, as shown in Figure 1. In addition, all experiments were conducted during the jujube-tree-girdling period, on 18 June 2022. A CD-15APX digital display vernier caliper produced by Mitutoyo (with an error of ±0.02 m) was used to measure jujube-bark size parameters. An LU-920SERIES thermostat produced by Anthone Electronice Co., Ltd. (Xiamen, China) with an error of ±0.5 °C was used to control the heating temperature during the experiment. The outdoor power supply was the B7 type produced by Shenzhen Chuangwei Energy Technology Co., Ltd (Shenzhen, China). A WRNK191 thermocouple with 0.5 mm probe diameter produced by Shanghai Shenji Instrument Co., Ltd (Shanghai, China) was used to detect temperature. The heater had a 60 × 60 mm infrared arc with a built-in K-type thermocouple and heating wire material of Nice0Cr20; it was produced by Taizhou Dayi Electric Heating Appliance Co., Ltd (Taizhou, China). Furthermore, in order to measure the yield and quality of jujube fruits, the jujube samples from the trees with different treatments were picked when jujube was in the full maturity stage, on 28 September 2022.

Figure 1. Jujube garden for the experiments.

2.2. Determination of Physical Parameters of Jujube Bark

The thickness of bark has a greater impact on the heat-transfer performance of bark compared to factors such as moisture content, density, and surface texture structure. Therefore, the trunk diameter can be used as an important indicator of the sensitivity of the corresponding phloem to heating. The bark of a jujube trunk is very thick, with a rough surface and wide and deep longitudinal cracks, which is not conducive to heat conduction. The bark of the main branch is relatively thin, with a narrow and shallow surface texture structure. Therefore, the main branch is chosen to reduce energy loss during the heating process and improve heating efficiency. In order to provide basic parameters for the construction of a heat-transfer model for jujube bark, some physical and heat-transfer-related parameters of jujube bark were measured.

Firstly, it is necessary to measure the thermal conductivity of jujube bark. Although the thermal conductivity of bark varies with the age of the tree, the moisture content of the bark, density, and other factors, it is generally considered constant in transient heat-transfer models [10]. In addition, due to its convenient use and relatively high accuracy, the Wenger formula [11] is often used to estimate the thermal-conductivity determination of tree bark. Therefore, the Wenger formula was also used in this study to calculate the thermal conductivity of jujube bark, as shown in Equation (1). The density of each jujube-bark sample was measured by the mass displacement of water method. Then, the density value was substituted into this equation to obtain its thermal conductivity.

$$k = (4.684\rho + 0.076) \times 10^{-4} \quad (1)$$

where k is the thermal conductivity coefficient, $\mathrm{Wm}^{-1}/\mathrm{K}$; ρ is the fresh jujube-bark density, $\mathrm{g/cm}^{-3}$.

Then, Equation (2) was used to calculate the specific heat capacity of jujube bark. Bark samples with volume of 2 cm^{-3} were collected using a sharp knife and their initial weight was immediately measured. Then, the samples were placed in a drying oven for 48 h at 60 °C to obtain their dry mass. The data obtained through the above experiment were used to calculate the ratio of moisture mass to dry mass of bark (M).

$$\begin{cases} c = 4186.8\left[0.264 + 0.00116T + \frac{Mc_w}{419+\Delta_c}\right] \\ c_w = 3.8 + 130 \div (371.85 - T) \end{cases} \quad (2)$$

where c is the specific heat capacity of jujube bark, J $\mathrm{kg}^{-1}/\mathrm{K}$; M is the ratio of moisture mass to dry mass of bark,%; c_w is the specific heat capacity of water, kJ $\mathrm{kg}^{-1}/\mathrm{K}$; T is the temperature, °C; Δ_c is an empirical correction for the effect of moisture on heat capacity, cal/(g °C); Δ_c is taken as 0.305 M for $M \leq 27\%$ or 0.0832 M for $M > 27\%$.

The thermal diffusion coefficient of bark is the rate at which heat is transferred from the outer surface of the bark to the inner surface through a given thickness of bark. It is a measure of the insulation capacity of tree bark and an important parameter in the heat-transfer model. Finally, based on the above measurement data, the thermal diffusion coefficient of jujube bark is calculated by Equation (3).

$$\begin{cases} \alpha = \frac{k}{\rho c} \\ \rho = \rho_b(1 + M_c) \end{cases} \quad (3)$$

where α is the thermal diffusion coefficient, $\mathrm{cm}^2/\mathrm{min}$; k is the thermal conductivity, W $\mathrm{m}^{-1}/\mathrm{K}$; ρ is the density of fresh jujube bark, $\mathrm{kg/m}^3$; c is the specific heat capacity, J $\mathrm{kg}^{-1}/\mathrm{K}$; ρ_b is the density of dried jujube bark, $\mathrm{kg/m}^3$; M_c is the moisture content of the bark, %.

2.3. Construction of Heat-Transfer Model for Jujube Bark

The heater is applied to the bark, and energy is mainly transmitted to the interior of the bark through thermal conduction [12]. High temperature causes damage to the phloem cells of jujube bark, leading to a decrease in the conductivity of the phloem, which can inhibit the normal transportation of photosynthetic products through the bark to the roots. Jujube bark is a complex biological material with a complex structure, being a typical anisotropic material. Therefore, its actual heat-transfer characteristics are also very complex. In order to establish a heat-transfer model that is convenient for practical application, it is necessary to make idealized assumptions about jujube bark. Peterson and Ryan [13] and Mantgem and Schwartz [14] established a bark heat-transfer model based on the standard one-dimensional heat-transfer equation. When using this method to describe the radial transfer of heat along the jujube-tree bark from the outer surface to the inner surface, it is assumed that the bark is a semi-infinite solid. The bark is not actually a semi-infinite object, and it is theoretically imperfect when viewed as a semi-infinite object. However, a large amount of practice has shown that the heat-transfer model of bark constructed by treating it as a semi-infinite object has practical value and significance when studying bark heat transfer. Therefore, this model is widely used for bark heat-transfer studies because of its convenient practical application [13] and this model was adopted in this study. Assuming that the outer surface temperature of the jujube bark reaches the temperature of the heater instantly when the heater contacts the jujube tree, then at a specific heating temperature, heat diffuses through the outer surface of the bark to the inner surface, so that the time required for the inner surface of the jujube bark to reach a specific temperature meets Equation (4).

$$\begin{cases} \frac{T_i - T_1}{T_0 - T_1} = erf(\eta) = \frac{2}{\sqrt{\pi}} \int_0^{\eta} \mathrm{e}^{-\eta^2} d\eta \\ \eta = \frac{x}{2\sqrt{\alpha\tau}} \end{cases} \quad (4)$$

where T_i is the set temperature on the inner surface of the bark, °C; T_0 is the environmental temperature of the bark surface, °C; T_1 is the heater temperature, °C; x is the thickness of the bark, cm; α is the thermal diffusivity of the bark, cm^2/min; τ is the time required for the inner surface temperature of the bark to reach the set temperature, min; $erf(\eta)$ is the Gaussian error integral function.

It is generally believed that 60 °C is the lethal temperature for plant tissue cells, and the temperature of 60 °C for more than 1 min was used in some studies as a reference standard for plant-cell death [12]. However, studies also have shown that even within the range of 45–60 °C, plant cells still die as long as the temperature duration is long enough [15,16]. In this study, we assume that the death of jujube-bark cells occurs at a critical lethal temperature of 60 °C [17]. To ensure that the formation layer is not damaged, heating needs to be stopped quickly when the internal surface temperature of the jujube bark reaches 60 °C. Therefore, in the heating model, the internal surface temperature T_i of the bark is set to 60 °C. T_0 is the ambient temperature, and the heat-transfer model is not sensitive to this parameter. This study was conducted at an ambient temperature of approximately 25 °C. The thermal diffusion coefficient of jujube bark measured in the experiment varied slightly with the temperature of the heater, jujube-bark density, moisture content, and so on; but there were not significant differences. Therefore, in this study, the average value of the thermal diffusion coefficients of jujube-bark samples was used as the final α, which was taken as 0.057 cm^2/min.

The heating temperature T_1 of the heater was set to 200, 300, and 400 °C, respectively. The relationship between the thickness x of jujube bark and the heating time required for the inner surface of jujube bark to reach the set temperature can be obtained through Equation (4), as shown in Equation (5).

$$\begin{cases} \tau_2 = 5.42x^2 \\ \tau_3 = 3.77x^2 \\ \tau_4 = 3.10x^2 \end{cases} \quad (5)$$

where τ_2, τ_3, and τ_4 are the time required for the internal surface temperature of jujube bark to reach 60 °C at heating temperatures of 200, 300, and 400 °C, respectively, min; x is the thickness of jujube tree bark, cm.

2.4. Model Construction for the Relationship between Jujube Bark and Corresponding Diameter

From the results of the above heat-transfer-model construction, it can be seen that the heating time required for the inner surface of jujube bark to reach a certain temperature under a certain heat source temperature is a function of the bark thickness. Therefore, it is necessary to know the thickness of jujube bark when heating it. However, due to the complexity of the composition and structure of bark, there is currently no effective non-destructive rapid measurement method or related instrument for bark thickness. However, research has shown a correlation between bark and its corresponding diameter [18]. The research results indicated that by establishing a mathematical model of the relationship between tree diameter and bark thickness, bark thickness can be indirectly measured by measuring the diameter of the tree [19]. Therefore, this study also indirectly estimated the thickness of jujube bark in the heat-transfer model through this method. In order to construct a model for the relationship between jujube bark and corresponding diameter, 50 healthy jujube trees were randomly selected in the jujube orchard to measure the diameter of main branches and corresponding bark-thickness data. When measuring the diameter of jujube-tree branches and the corresponding thickness of jujube-tree bark, firstly, the bark with a width of 10 mm was removed from the randomly selected main branches of the jujube tree. Then, one location at the girdled opening of each branch was randomly selected to measure its diameter and corresponding bark thickness. After obtaining the data of jujube-bark thickness and corresponding diameter, the optimal mathematical model that jujube-bark thickness and corresponding diameter fulfilled was analyzed.

After obtaining the mathematical model, the accuracy of the model was tested by comparing the actual diameter of jujube-tree branches and the corresponding thickness of jujube bark with the predicted results of the model. Therefore, 30 main branch samples from different jujube trees were selected to verify the reliability of the model. After the accuracy of the bark thickness calculated by the model met the requirements, and the thickness of jujube-tree branches during the heating experiment based on the heating model was ultimately calculated using this mathematical model.

2.5. Accuracy Test of Heat-Transfer Model for Jujube Bark and Experimental Design of Two Different Treatments of Jujube-Tree Heating and Girdling

The accuracy testing of the jujube-bark heat-transfer model included two stages. In the first stage, experiments were conducted using measured jujube bark thickness data to verify the performance of the heat-transfer model itself. During the experiment, 30 jujube trees were randomly selected, and a main branch was randomly selected from each jujube tree for heating experiments. The experimental method is shown in Figure 2a. Firstly, the jujube-tree bark was girdled with a width of 8 mm, the thickness of it was measured, and a thermocouple inserted through the girdled part at the boundary between the jujube bark and the xylem. Then, to ensure the efficient heat transfer of the heater, the heater was tightly pressed on the jujube bark to start heating. Meanwhile, the theoretical and actual values of the heating time were recorded when the inner surface of the jujube bark reached 60 °C, respectively. In the second stage, after the jujube-bark thickness prediction model was substituted into the heat-transfer model, experiments on the heat-transfer model were conducted based on the predicted thickness data of the jujube bark. During the experiment, 30 jujube trees were randomly selected, and a main branch was randomly selected from each jujube tree for heating experiments. The heating and actual temperature measurement methods were consistent with the first-stage experimental method. The difference was that at this stage, the diameter of the jujube tree was a direct variable, and the thickness of the jujube-tree bark was predicted through the diameter.

(**a**) (**b**)

Figure 2. Experimental methods for heating jujube bark: (**a**) experimental method for initial heat transfer model; (**b**) heating experimental method for final heat transfer model with the function of the bark thickness prediction.

Then, based on the prediction model of jujube-bark thickness, the heat-transfer model was used for heating experiments. One hectare of healthy jujube trees was randomly selected in the jujube garden and the main branches were heated. The test method is shown in Figure 2b, two heaters were used and tightly pressed on the jujube bark to simultaneously heat each jujube branch. The other jujube trees were all treated with traditional girdling as a control. Then, in the later stage of the experiment, jujube trees from different treatments were observed, and the conditions of trees from heating treatment and wound-healing conditions of the trees after girdling treatment were statistically analyzed.

2.6. Methods for Measuring Jujube Yield and Quality

To investigate the differences in the effects of heating and traditional girdling on the quality and yield of jujube fruit, the jujube-fruit yield and main quality indicators were measured during the jujube fruit harvest period under two different treatment methods. The indexes of jujube-fruit nutrients that were tested included the contents of soluble solids, water, total acid, protein, vitamin C, total sugar, reducing sugar, and sugar acid ratio. Moreover, the physical quality index of jujube tested in this study was single-fruit weight.

The national standard GB/T 5009.7-2008 was referenced to measure the total sugar content. In addition, the content of soluble solids was determined by a handheld refractometer [20]. During the soluble solids measurement, 15 jujubes were selected from each sample, and their juice was extracted by a juicer. Then, the juice was filtered by three layers of gauze, and an appropriate amount of fruit juice was taken to determine the content of soluble solids by an LH-B55 handheld refractometer (Luheng Environmental Technology Cable Co., Ltd., Shanghai, China). The content of vitamin C was determined by 2, 6-dichloroindophenol titration [21]. Total acid content was determined by the acid–base-titration method [22]. The content of reducing sugar was determined by ferin colorimetry. The moisture content of jujube was determined by normal atmospheric temperature and constant pressure drying method. The moisture content test samples of jujube were cut into 3 mm thick slices and dried in an oven at 105 °C to a constant mass. Then, the moisture content was measured by Equation (6).

$$M = \frac{W_1 - W_0}{W_1} \times 100\% \tag{6}$$

where M is the moisture content of jujube, %; W_1 is the weight of jujube before drying, g; and W_0 is the weight of jujube after drying, g.

In addition, the crude-protein content was determined by the Kjeldahl method. In the experiment of protein determination, the core of jujube was removed and jujube flesh was ground into powder after drying. A 0.300 g powder sample was taken, poured into a dry digestive tube, shaken well after 0.2 g copper sulfate and 6 g potassium sulfate were added, then 20 mL of concentrated sulfuric acid was added. It was heated at a low temperature until all the contents were carbonized, and the foaming in the digestive tube stopped; it was then heated at a low temperature to keep slightly boiling until the liquid was blue-green and clear. Then, heating continued for 30 min before cooling. Lastly, water was added up to a volume of 100 mL, which was the digestive liquid of the sample. According to the above method, copper sulfate, potassium sulfate, and concentrated sulfuric acid of the same amount as the sample used for digestion were taken for digestion. After cooling, it was diluted to 100 mL, which was the blank digestive solution. In total, 10 mL of sample digestion solution was taken in the digestive tube, put into a Kjeldahl nitrogen determinator for distillation for 7 min, then the liquid was titrated. At the same time, the 10.0 mL blank digestion solution was distilled according to the above method. All determinations were performed in triplicate. Finally, the protein content was calculated by Equation (7).

$$Y = \frac{c \times (V_1 - V_0) \times 14 \times F}{m \times 1000} \times 100\% \tag{7}$$

where Y is mass fraction of protein, %; c is concentration of hydrochloric acid standard solution, mol/L; V_0 is the volume of standard solution consumed in blank titration, mL; V_1 is the volume of standard solution consumed in sample titration, mL; 14 is the millimolar mass of nitrogen, g/mmol; F is the conversion coefficient of nitrogen to protein, 6.25; and m is sample weight, g.

2.7. Statistical Analysis

The means and standard deviations of the data related to this study were calculated by Microsoft Excel 2007 software. Bar graphs about nutrients in jujube and the significance of the data were analyzed by Origin 2022 (Origin Lab Corporation, Northampton, MA, USA). In addition, the non-parametric test method based on a Kruskal–Wallis test was used to analyze the significance of the difference between the predicted results of the model for jujube-tree-bark-thickness prediction and the actual measurement results. Additionally, the parameter test based on one-way ANOVA method was used to test the significance of the differences in the effects of jujube-tree-bark-girdling treatment and heating treatment on the yield and the quality of jujube of corresponding jujube trees. When performing the one-way ANOVA, a normality test of the experimental data was carried out according to Shapiro–Wilk, and the homogeneity test of variance was Levene's test.

3. Results

3.1. Construction of Jujube-Bark-Thickness-Prediction Model and Accuracy Test Results

The actual measurement results and linear fitting results of jujube-branch diameter and corresponding bark thickness are shown in Figure 3a. The linear fitting equation for the diameter of jujube branches and the corresponding bark thickness is shown in Equation (8). The determination coefficient of the fitting equation was 0.79, indicating a relatively high goodness of fit of the model.

$$\begin{cases} x = -0.516 + 0.073d \\ R^2 = 0.79 \end{cases} \tag{8}$$

where x is the thickness of the jujube-tree bark, mm; d is the diameter of the jujube tree, mm; R^2 is the determination coefficient.

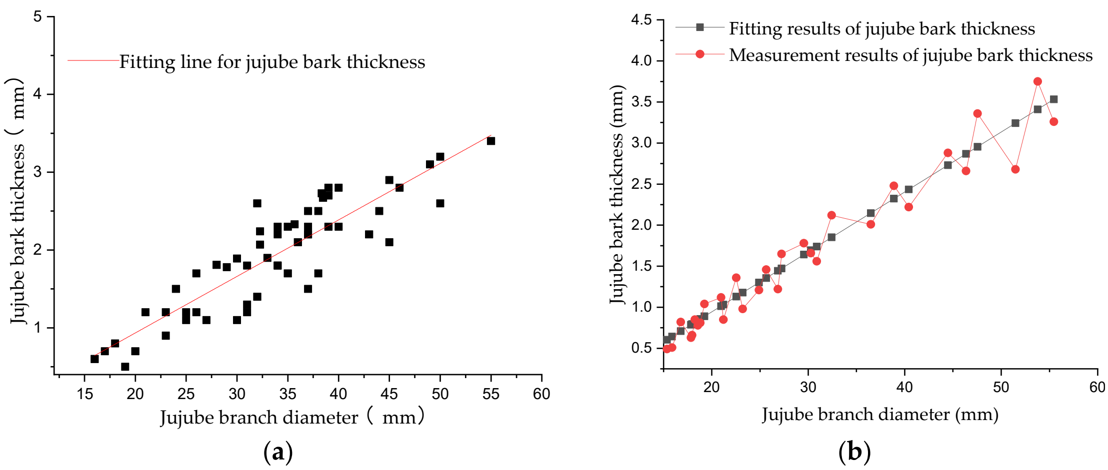

Figure 3. Construction and accuracy test results of the jujube-tree-bark-thickness-prediction model: (**a**) actual measurement results and linear fitting results of jujube tree branch diameter and corresponding bark thickness; (**b**) the thickness of jujube tree bark obtained through model calculation and the corresponding actual measurement results.

The thickness of jujube-tree bark obtained through model calculation and the corresponding actual measurement results are shown in Figure 3b. The minimum error of bark thickness obtained through the two methods was 2.07%, and the maximum error was 26.13%. In addition, the non-parametric test results based on a Kruskal–Wallis test showed that there was no significant difference (p = 0.93) between the actual measurement results of jujube-bark thickness and the results calculated through the model at the 0.05 level.

3.2. Construction Results of Heat-Transfer Model for Jujube Bark

3.2.1. Construction of Initial Jujube-Bark Heat-Transfer Model and Accuracy Test Results

During the preliminary heating experiment of jujube bark, it was found that there was a significant pyrolysis phenomenon on the surface of jujube bark at temperatures of 300 and 400 °C, respectively. During the heating process, visible gas was generated from the jujube bark, and after the heating was completed, black charcoal was produced on the surface of the jujube bark. This indicated that heating the bark within this temperature range caused significant damage, which was not conducive to the health of jujube bark. However, under heating conditions of 200 °C, the above phenomenon did not occur. Therefore, in this study, the temperature for all subsequent experiments was set to 200 °C. Figure 4a shows the typical heat transfer curve of jujube bark with a thickness of 2.12 mm under 200 °C heating conditions. From Figure 4a, it was shown that when the temperature of the inner surface of jujube bark reached 60 °C and heating was stopped, the temperature of the inner surface of jujube bark would rapidly decrease. When the temperature dropped to about 40 °C, its rate of decline significantly decreased. Figure 4b shows the heat transfer prediction of the initial jujube-bark heat-transfer model and experimental results. In addition, the parameter test results based on one-way ANOVA showed that there was no significant difference (p = 0.59) between the heat transfer experimental results of jujube-tree bark and the prediction results of the initial bark heat-transfer model, at the 0.05 level.

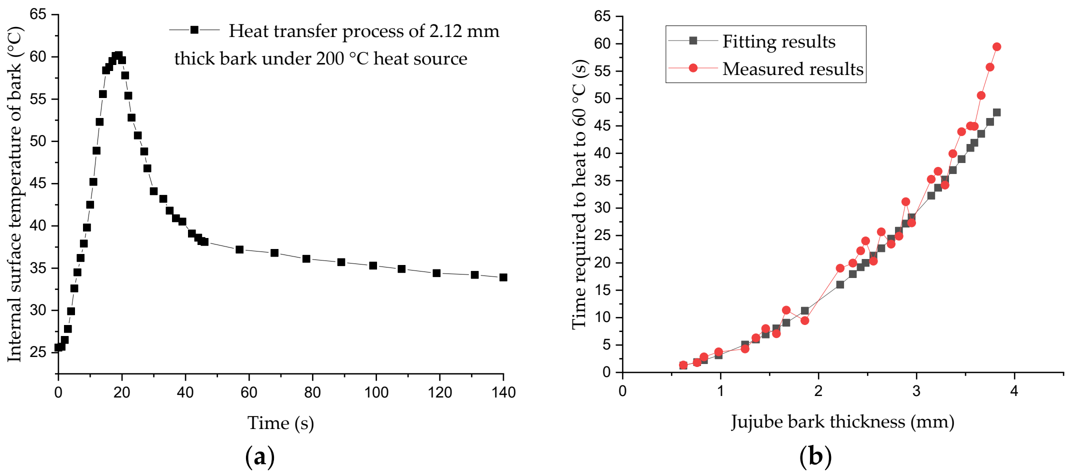

Figure 4. Construction of initial heat-transfer model for jujube bark and accuracy test results: (**a**) typical heat-transfer curve of jujube bark; (**b**) the heat-transfer prediction and experimental verification results of the initial jujube-bark heat-transfer model.

3.2.2. Construction and Accuracy Test Results of Heat-Transfer Model for Jujube Bark with Thickness Prediction

After incorporating the jujube-bark-thickness-prediction equation into the initial jujube-bark heat-transfer model, the relationship between jujube-branch diameter and the time required for heat transfer was obtained, as shown in Equation (9).

$$\tau'_2 = 325.20(-0.0516 + 0.0073d)^2 \tag{9}$$

where τ'_2 is the time required for the internal surface temperature of jujube bark to reach 60 °C when the heating temperature is 200 °C, s; d is the diameter of the jujube-tree branch, mm.

Figure 5 shows the predicted heating time of jujube bark by the heat-transfer model with bark-thickness-prediction function and actual measurement results. The parameter test results based on one-way ANOVA showed that there was no significant difference (p = 0.66) between predicted results by the heat-transfer model and actual measurement results, at the 0.05 level.

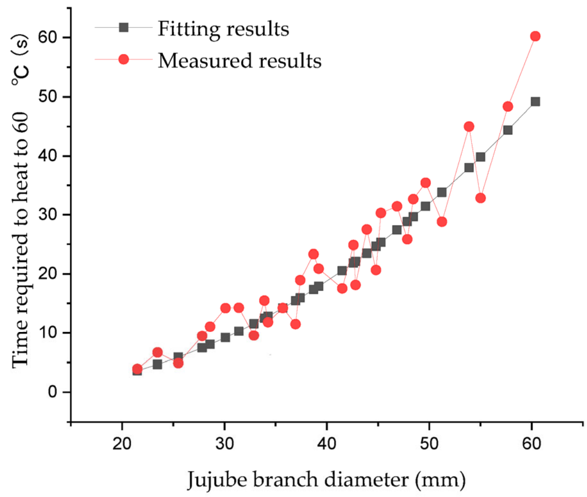

Figure 5. The heat-transfer prediction and experimental verification results of the heat-transfer model with bark-thickness-prediction function.

3.3. Experimental Results of the Effect of Heating-and-Girdling Treatments on the Yield and Quality of Jujube Fruit

3.3.1. Experimental Results of the Effects of Two Different Treatments on Jujube Trees and Fruit Yield

The experimental results of the effects of two different treatments on jujube-fruit yield and single-fruit weight are shown in Figure 6a,b, respectively. The statistical results of the healing of jujube-tree-girdling wounds after girdling treatment showed that 14.5% of jujube trees had incomplete healing of jujube-tree-girdling wounds, and 8.6% of jujube trees were dead. Meanwhile, the heated jujube trees showed no visible wounds or tree death. In addition, the single-fruit-weight test results showed that the weight of the single jujube obtained from both treatments was within the range of 9–13 g. The average single-fruit weight of fresh jujube from trees treated with heating was 11.23 g, while that from the jujube trees treated with girdling was 11.18 g. The analysis of variance results showed that the two treatments had no significant impact on the weight of the single fruit ($p = 0.94$). In terms of yield, the yield per hectare of jujube trees treated with heating and girdling was 19.87 tons and 20.76 tons, respectively. The analysis of variance results showed that the two treatments had a significant impact on jujube-fruit yield ($p = 0.02$).

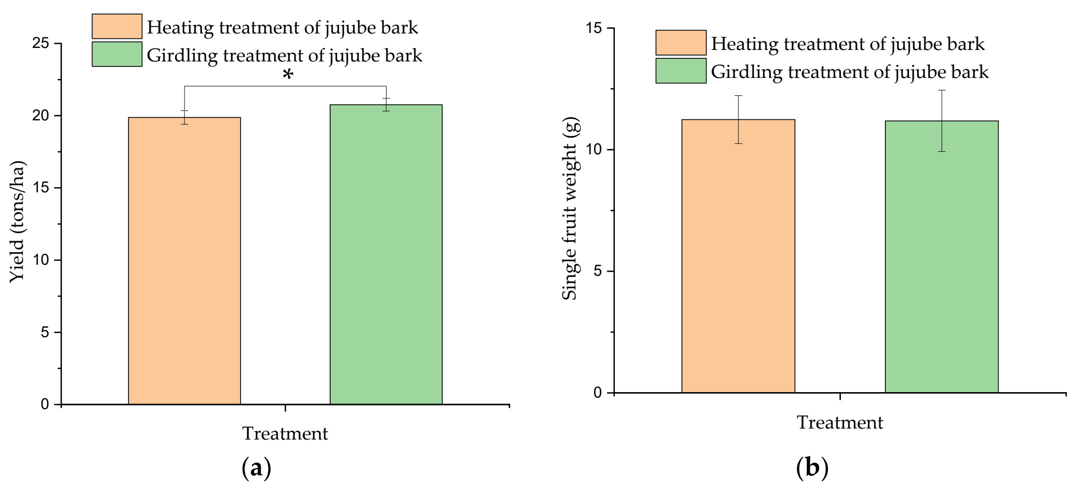

Figure 6. Experimental results of the effects of two different treatments on jujube-fruit yield and single-fruit weight: (**a**) effects of different treatments on jujube-fruit yield, (**b**) effects of different treatments on the single-fruit weight; * represents a significant difference (p values ≤ 0.05).

3.3.2. Experimental Results of the Effects of Two Different Treatments on the Quality of Jujube Fruit

The experimental results of the effects of two different treatments on Vc and protein content of jujube fruit are shown in Figure 7a,b, respectively. The average Vc content of fresh jujube fruits treated with heating and girdling was 3.302 mg/g and 3.384 mg/g, respectively. The analysis of variance results showed that the two treatments had no significant impact on the Vc content of jujube fruit ($p = 0.29$). The average protein content of fresh jujube fruits treated with heating and girdling was 2.23% and 2.31%, respectively. The analysis of variance results showed that the two treatments had no significant effect on the protein content of jujube fruit ($p = 0.14$). The experimental results of the effects of two different treatments on the content of reducing sugars and soluble solids in jujube fruit are shown in Figure 7c,d, respectively. The average reducing sugar content of fresh jujube fruits treated with heating and girdling was 16.06% and 16.89%, respectively. The analysis of variance results showed that the two treatments had no significant effect on the reducing sugar content of jujube fruit ($p = 0.24$). The average soluble solids content of fresh jujube fruits treated with heating and girdling was 47.36% and 48.08%, respectively. The analysis of variance results showed that the two treatments had no significant effect on the average soluble solids content of jujube fruit ($p = 0.12$). The experimental results of the effects of two different treatments on the water and acid content of jujube fruits are shown in Figure 7e,f, respectively. The average moisture content of fresh jujube fruits treated with heating and girdling was 56.44% and 53.26%, respectively. The analysis of variance results showed that the two treatments had a significant impact on the moisture content of jujube fruit ($p = 0.03$). The average content of fresh jujube acid of jujube trees treated with heating and girdling was 0.21% and 0.20%, respectively. The analysis of variance results showed that the two treatments had no significant impact on the average acid content of jujube fruit ($p = 0.28$). The experimental results of the effects of two different treatments on the sugar acid ratio and total sugar content of jujube fruit are shown in Figure 7g,h, respectively. The average sugar acid ratio of fresh jujube fruits treated with heating and girdling was 189.72% and 196.46%, respectively. The analysis of variance results showed that the two treatments had no significant effect on the sugar acid ratio of jujube fruit ($p = 0.41$). The average total sugar content of fresh jujube fruits treated with heating and girdling was 39.37% and 39.65%, respectively. The analysis of variance results showed that the two treatments had no significant effect on the average total sugar content of jujube fruit ($p = 0.80$).

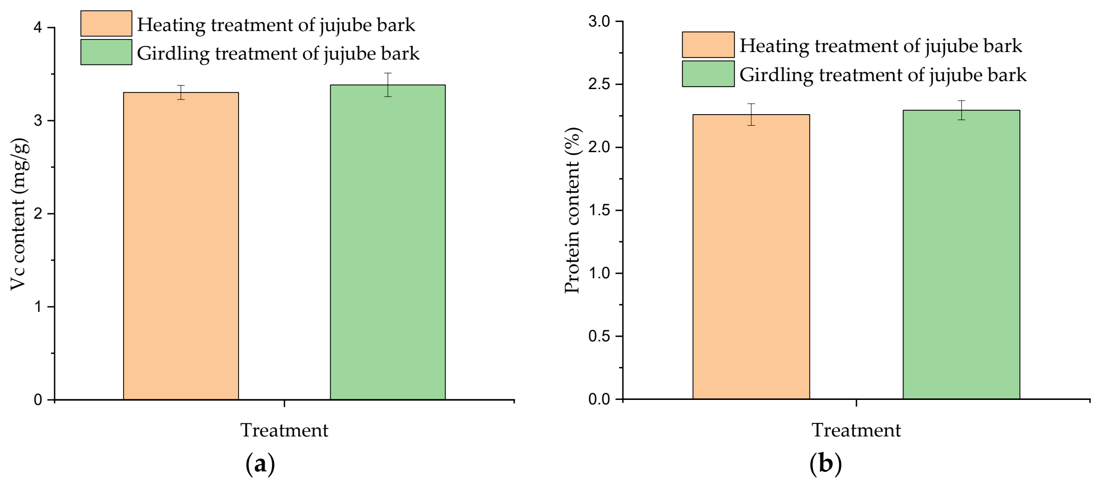

Figure 7. *Cont.*

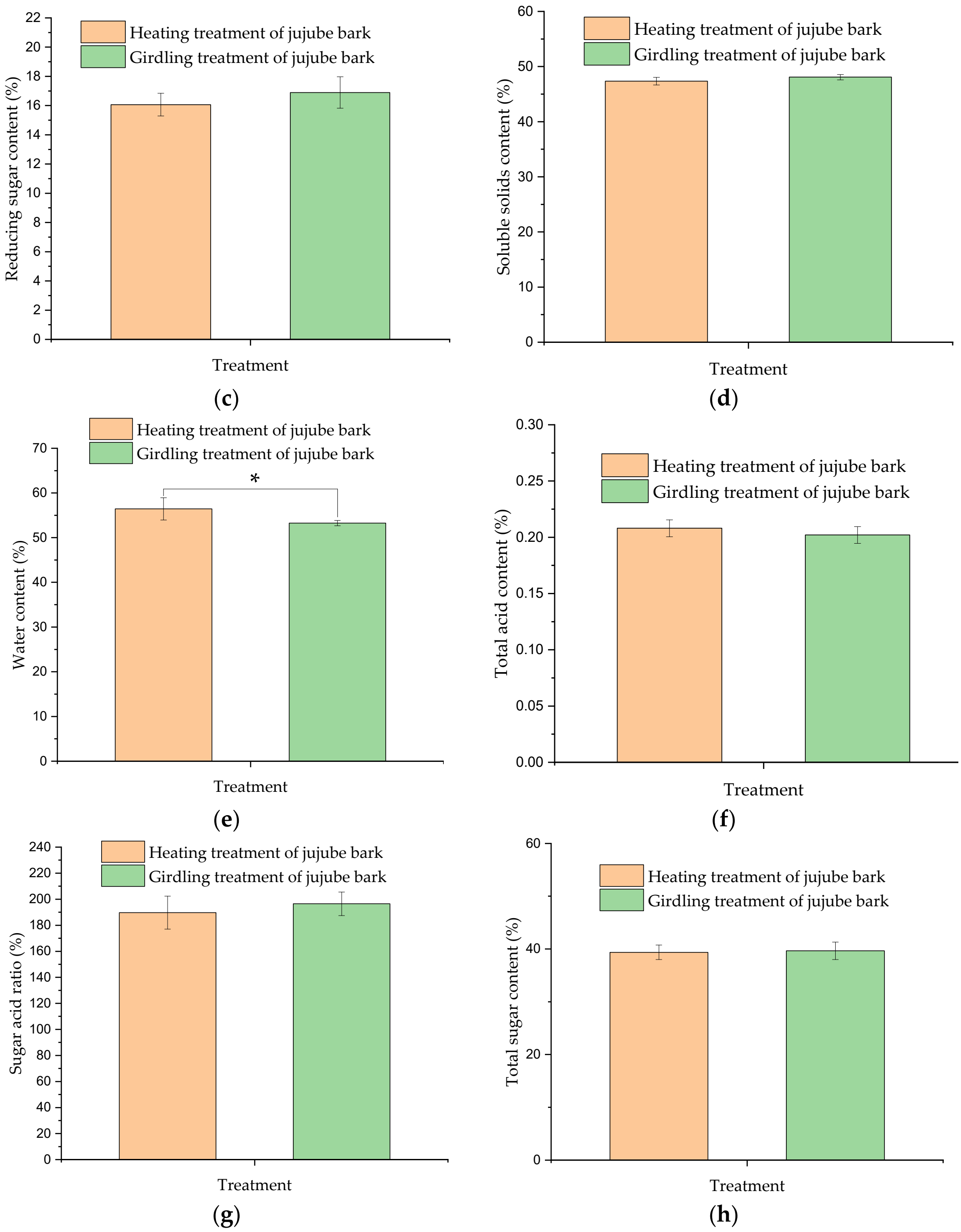

Figure 7. Experimental results of the effects of two different treatments on the quality of jujube fruit: (**a**) comparison of vitamin C content; (**b**) comparison of protein content; (**c**) comparison of reducing sugar content; (**d**) comparison of soluble solids content; (**e**) comparison of water content; (**f**) comparison of total acid content; (**g**) comparison of sugar acid ratio; (**h**) comparison of total sugar content; * represents a significant difference (p values ≤ 0.05).

4. Discussion

4.1. Prediction Model of Jujube-Bark Thickness Based on Jujube-Branch Diameter

Predicting the thickness of jujube bark is the foundation for precise heating of jujube bark. Therefore, in this study, a mathematical model of the diameter of jujube branches and the corresponding jujube-bark thickness was established, and the reliability of using this model to indirectly predict jujube-bark thickness was verified through experiments.

The fitting results of tree bark thickness indicated that there was a high linear positive correlation between branch bark thickness and its diameter, and the fitting model had a high degree of goodness of fit. The experimental analysis results indicated that there was no significant difference between the predicted results of jujube-bark thickness using this model and the actual measured data. This result was basically consistent with the relevant research conclusions on predicting bark thickness of other types of trees [23]. This indicated that the model is expected to become a simple and feasible method for predicting bark thickness before obtaining better methods for detecting it. Of course, we hope to explore faster and more accurate non-destructive testing methods for bark thickness, which is also one of the areas that we need to focus on in the future.

4.2. Heat-Transfer Characteristics and Model of Jujube Bark

Preliminary heating experiments on jujube bark have shown that temperatures above 300 °C can cause significant pyrolysis of jujube bark, which is consistent with existing wood pyrolysis experiments [24]. Due to the fact that high-temperature pyrolysis can cause numerous pores on the surface of wood [25], if high-temperature heating causes severe pyrolysis of jujube bark, it will directly damage the structure of jujube bark. In addition, the porous surface can easily provide breeding locations and habitat for insects, which will cause secondary damage to jujube trees. Therefore, this study conducted heating experiments on jujube bark at a temperature of 200 °C. The heating experiment of jujube-tree bark at a temperature of 200 °C showed that when the internal surface temperature of the main branch of the jujube tree reached 60 °C and heating was stopped, the time in which the internal surface temperature of the jujube-tree bark remained above 45 °C was approximately within the range of 20 to 40 s. Therefore, this heating condition is not sufficient to kill the cambium and the phloem cells near the inner surface of the jujube bark. However, when the inner surface temperature of jujube bark reached 60 °C, other phloem cells near the outer surface of the bark were all at temperatures higher than 60 °C. Therefore, overall, heating the jujube bark under this condition will not cause the death of all bark cells, let alone the death of cambium cells, but may cause the death of phloem cells near the outer surface of the bark. Therefore, this may damage the function of jujube bark to some extent, but it will not completely prevent the bark from transporting nutrients to the roots. That is to say, under this heating condition, it is expected that the bark will continuously transport a portion of the nutrients generated by photosynthesis to the root system, while maintaining the health of the tree to a greater extent and increasing yield. Therefore, as long as the parameters of thermal injury of jujube bark are selected appropriately, it can be used many times and not cause damage to the tree body. This is of great significance for promoting the sustainable development of jujube planting.

As a complex biological material [26], jujube bark has extremely complex structures and thermophysical properties in various aspects [27,28]. Therefore, in order to establish a feasible and convenient heat-transfer model, this study considered jujube bark as a semi-infinite solid, and then a jujube-bark heat-transfer model was established based on the standard one-dimensional heat-transfer equation. By solving the model, the initial heat-transfer equation of jujube bark was obtained. The time required for heat transfer in jujube bark under specific temperature parameters was a quadratic function of jujube-bark thickness. The analysis of variance on the experimental results showed that there was no significant difference between the predicted heat-transfer time of the model and the actual measured time. This indicated that the model is meaningful to be used to predict the heat-transfer time of jujube bark, and the idealization of jujube bark as a semi-infinite object did not significantly affect the effectiveness of the heat-transfer model. Then, the prediction model of jujube-bark thickness was incorporated into the initial heat transfer model to obtain a quadratic power function of heat-transfer time with respect to the diameter of jujube branches. The final experimental results also indicated that there was no significant difference between the predicted heat-transfer time by the model and the actual measured results. Therefore, using this model to predict the bark thickness and heat-transfer time of jujube branches simultaneously has certain reliability in guiding jujube-bark-heating experiments.

4.3. Effect of Heating Treatment on the Yield and Quality of Jujube Fruit

Through observation and statistics, it was found that 14.5% of jujube trees treated with traditional girdling methods did not fully heal, and 8.6% of jujube trees died. However, the heated jujube trees showed no visible wounds or tree death. Furthermore, there was no significant difference in single-fruit weight between two different treatments of jujube trees. Although there were significant differences in yield, the yield of jujube fruit obtained by heating treatment was only 4.28% lower than that obtained by girdling treatment, while it significantly increased compared with the yield of jujube trees without any treatment [29]. Because if the jujube tree is not subjected to any treatment such as no girdling, the ju-jube fruit will shed a large amount during the growth stage, resulting in extremely low yield. This result validates the correctness of the hypothesis proposed in this study, indicating that heating the jujube-tree bark can also increase production, and there is basically no permanent damage to the jujube tree. The detection and analysis of the main quality indicators of jujube fruit showed that there was no significant difference in the quality of jujube fruit between the two treatments, indicating that heating treatment also improved the quality of jujube fruit compared to untreated jujube trees.

As for the slight decrease in jujube-fruit yield caused by heating treatment compared to girdling treatment, there are many possible reasons. For example, it may be due to the fact that there is still a portion of jujube-tree bark around the heating treatment area that has not lost its function, allowing nutrients to be transported normally to the roots through this portion of the bark. Alternatively, the phloem that temporarily loses its function after heating can restore its ability to transport nutrients in a relatively short period of time. These reasons may to some extent lead to a relative decrease in the fruit-setting rate of jujube trees [1], thereby leading to a relative decrease in yield. Overall, heating treatment can greatly avoid damage to jujube trees while improving their yield and quality. This has positive significance for the healthy and sustainable development of jujube planting. In the future, quantitative research can be conducted on the relationship between the degree of damage to the bark and phloem of jujube trees and indicators such as jujube-fruit yield and quality; through the correction and optimization of heating model parameters, further improvements in the jujube-fruit yield of jujube trees are expected under heating treatment. In addition, in the research and development of heating-related equipment, automatic jujube bark thickness detection and automatic decision making of heating time can be studied to improve the automation and intelligence of heating equipment.

5. Conclusions

This study aimed to address a series of negative issues such as jujube-tree death caused by traditional methods of increasing yield through jujube-tree girdling. A method of heating the jujube-tree bark was proposed to cause local thermal damage to inhibit the transportation of photosynthetic products to the roots, thereby achieving the same goal of increasing yield as girdling treatment. The established heat-transfer model was used to predict the heating time required for jujube bark with different temperature parameters and thicknesses, and this was used to guide the development of heating experiments. The experimental results showed that heating treatment can increase yield and improve the quality of jujube fruit, and there is no significant damage to jujube trees. Therefore, as long as the degree of thermal damage to jujube bark is accurately controlled, this method can be applied for a long time without affecting the health of jujube trees. The research results provide innovative ideas for increasing fruit-tree production and are of great significance for the sustainable development of the fruit-tree-planting industry. Especially for fruit trees such as peach trees that may experience serious problems such as gum flow after girdling, adopting this method to increase fruit-tree yield and reduce fruit-tree damage is of great practical significance for the sustainable and healthy development of the fruit-tree-planting industry.

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