1 Feasibility of Jujube Peeling Using Novel Infrared Radiation Heating Technology

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24 Abstract: Infrared (IR) radiation heating has a promising potential to be used as a
25 sustainable and effective method to eliminate the use of water and chemicals in the
26 jujube-peeling process and enhance the quality of peeled products. The objective of
27 this study was to investigate the feasibility of using IR heating as a dry-peeling
28 method for jujube. The rotating Li jujube fruits were heated using two electric IR
29 emitters. The effects of IR radiation intensity ($5.25\text{--}6.07\text{ W/cm}^2$), emitter distance
30 ($75\text{--}85\text{ mm}$), and heating time ($40\text{--}60\text{ s}$) on the peeling performance of jujube were
31 investigated. Lye-peeled jujubes were used as a control. The operating parameters of
32 the IR peeling system were optimized using response surface methodology (RSM).
33 The heating with an IR intensity of 5.25 W/cm^2 at the emitter distance of 75 mm for
34 56 s were found as the optimum operating conditions resulting in the peelability of **96**
35 **%**, peeling easiness of 3.8 and moisture loss of **1.29 %** at jujube surface temperature
36 of $115\text{ }^{\circ}\text{C}$. The experimental results agreed well with those predicted by the models.
37 The IR peeled jujube had significantly low peeling loss and color change compared to
38 lye peeled ones.

39 Key words: Infrared radiation, Peeling technology, Jujube, Response Surface
40 Methodology

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1. Introduction

Jujube is the fruit of *Ziziphus jujuba* Mill, a thorny rhamnaceous plant, mainly grown in the subtropical and tropical regions of Asia and America. Jujube with a high nutritional value and numerous pharmacological effects has been widely used as food, functional food additives, and traditional Chinese medicines for thousands of years. Jujube fruits have the capacity help lower blood pressure, reverse liver disease, treat anemia, and inhibit the growth of tumor cells that can lead to leukemia (Lu et al., 2010; Wang et al., 2011). Jujubes have been processed into various food products including canned jujube, paste, puree, syrup, juice and confection (Huang et al., 2008; Liu & Zhao, 2009) usually from the unpeeled whole fruits. Although the high nutritious value, jujube peel is often difficult to chew and swallow. Additionally, if the peel is not perfectly removed, it will affect the taste and product quality. Consequently, the peeling is a key operation before direct consumption or further processing of jujube.

Conventionally, mechanical, chemical and hot soaking peeling methods have been applied for jujube. These peeling methods have adverse effect on product quality. Practically, chemical residues in jujube meat after immersing in an alkaline affect the quality of post-processed products. Moreover, these peeling methods are water and energy intensive, and pose serious salinity and wastewater disposal problems, resulting in considerable negative environmental impact (Rock et al., 2011; Pan et al., 2009; Li et al., 2014 a). Therefore, there is an urgent need to develop a sustainable and non-chemical peeling method, which can eliminate or reduce water, energy and

chemical usage, meanwhile deliver high quality peeled products. Recently, infrared (IR) technology has been studied as an alternative to food processing technologies with attractive merits such as uniform heating, high heat transfer rate, reduced processing time and energy consumption, and improved product quality and safety (Pan & Atungulu, 2011). A sustainable infrared (IR) dry-peeling method was developed by our group and has been successfully used for tomato and peach peeling with a complete elimination of lye and water usage in the peeling process (Li et al., 2014 b, 2014 c). The IR dry-peeling process uses non-ionizing thermal radiation with surface heating characteristics that allow effective heating of only a shallow layer of the fruit or vegetable surface to achieve peel separation while preserving the nutrients and quality in the edible portion of the products (Pan et al., 2009, 2011; Li, 2012). The tomato peeling is achieved by thermally induced peel loosening by IR heating and subsequent cracking (Li et al., 2014 a).

In the IR dry-peeling, the IR radiation intensity, heating time, emitter gap and fruit size are the key processing parameters, which directly affect the peeling performance, including the peelability, peeling yields, and moisture loss (Krishnamurthy et al. 2008; Li et al. 2014 c). The IR radiation intensity affects the heat fluxes that impinge on the fruit surface. High IR intensity generates more heat flux that irradiates onto the fruit surface resulting in more effective peeling. The IR heating time is another important factor which needs to be optimized during peeling to produce high quality peeled product. A longer exposure to IR heating may provide sufficient thermal energy but leads to deterioration of fruit quality and nutritional loss due to overheating. A shorter

heating time may not be able to provide sufficient heat to achieve desired peel separation and thus reduces the peelability. When heating is applied on a rotating jujube from both sides (top and bottom) with IR heating emitters, the emitter distance and the fruit size greatly influence the degree of exposure of fruit surface to emitters. In the double sided heating equipment, controlling the distance between the emitters can be an effective way to adjust IR radiation intensity and thus ensure a sufficient radiation heat exchange between the IR emitters and the fruit surface. Varying sizes of fruits cause different gaps between the fruit surface and the IR emitter and absorption of various amounts of thermal energy under the same heating condition, which results in variation of peeling performances and peeled product qualities. In order to ensure a good peeling performance and high quality of peeled end products, the IR heating conditions should be optimized.

Response surface methodology (RSM), a statistical experimental protocol used in mathematical modelling, has emerged as an ideal strategy for standardizing process variables of many food processes. The RSM requires less number of experimental measurements and provides a statistical interpretation of the data and the interaction amongst variables ([Myers and Montgomery, 2002](#)). It has been extensively used in the literature for optimizing different processes ([Deswal et al. 2014](#); [Ko et al. 2015](#)). As mentioned earlier, IR radiation heating has a promising potential to be used as an efficient peeling method for jujube. However, no previous reports were found on the feasibility of jujube peeling using IR heating technology. Therefore, the goal of this research was to develop a new and sustainable peeling technology for jujube using IR

radiation heating. The specific objectives were to 1) study the effect of IR heating on peeling performance for jujubes; and 2) optimize peeling conditions for jujubes under IR radiation heating using RSM.

2. Materials and methods

2.1 Jujubes

Jujubes of variety Li, obtained from Burkart Farms, Dinuba, CA, USA were stored at 4 °C and used within seven days. The cheek diameter (Dc) of jujube was measured using a Vernier caliper having 0.01 mm accuracy to determine the size of jujubes. The mass of the jujubes was measured with an electronic balance with an accuracy of 0.01 g. Jujube fruits with Dc of 37 mm to 41 mm were selected, checked and visually inspected and defected ones were eliminated before peeling tests. Jujubes were allowed to equilibrate at the ambient temperature for two hours to obtain uniform initial surface temperature of 22 ± 2 °C before peeling.

2.2 Infrared radiation heating system

A laboratory scale of IR heating system consisted of two electric IR emitters (245×60 mm size) of 1000 watts capacity (6 kw/m^2), 230 V which emit radiation at wavelength of 2 to 10 μm (Ceramicx Ireland Ltd, Cork, Ireland). The schematic drawing of the IR heating system is shown in the [Fig. 1](#), which has the IR emitters fixed to a frame connected to a metallic arm by which the IR emitters are moved and stationed at the heating position or idle position. The vertical distance between the IR heaters in the heating position could be adjusted by tightening and loosening of the nut moving on the screws provided on the space bar. An aluminum wave guard is installed at the top

of the upper emitter and bottom of the lower emitter and acts as a radiation reflector by focusing IR radiation towards the fruit holder in order to minimize the heat loss to the surrounding and improve the heating uniformity of the jujube surface. A rotatable custom-designed fruit holder has a set of fingers to hold jujubes with a firm grip by adjusting the finger positions and shaft length.

2.3 IR heating procedure

The IR heating elements were placed in the idle position (away from the fruit holders) and allowed to get heated up for five minutes at the preset power intensity by controlling the current flowing to the emitters. The jujube was weighed and held tightly exposing the cheek sides to the emitters by adjusting the fingers of the fruit holder and length of the shaft. The position of the nut in the space bar is adjusted to have the required distance between the emitters and the speed of the motor was set to give the required rotational speed of the fruit holder. After allowing five minutes to stabilize the emitter temperatures, emitters were moved to the heating position and timer was started. After heating to the required time, the IR emitters were moved to the idle position and the temperature of the jujube surface was measured using IR temperature sensor. The jujube was removed from the fruit holder and weighed to determine the moisture loss during heating. The jujube was manually peeled and evaluated for the peeling performance.

Preliminary tests were conducted to determine the upper and lower limits of the operating parameters: radiation intensity, emitter gap (distance between the emitters) and heating time. The IR intensity was measured by measuring the power input to the

IR emitters. Fluke clamp meter was used to measure the current (amperes) of the IR emitter and three power levels of 787.5, 859.0 and 910.5 watts were chosen for the experiments based on the preliminary experiments. The IR intensity at the above power levels were 5.25, 5.66, and 6.07 W/cm², respectively. The distance between emitters was set as 75±1 mm, 80±1 mm and 85±1 mm, and the heating times were set as 40, 50, and 60 s for the RSM experiments.

2.4 Evaluation of peeling performance

Peeling performance was evaluated by determining the peelability, easiness, and weight loss. The peelability was calculated as the ratio of removed skin to the overall surface area of the jujube (Li, et al., 2014 c). The area of the skin remaining on the jujube surface after peeling and the overall jujube surface area were determined by using a USDA standardized square-grid plate (Inspection AID 30B, USDA AMS), and the area of removed skin was calculated as the difference between the overall surface area and area of skin remaining after peeling. The ease of peeling, a grading system based on a scale of 1 (unable to peel) to 5 (easy to peel), was used to describe the easiness of peeling of jujubes. A score greater than 4 was considered as an acceptable level (Pan et al., 2009). The moisture loss was calculated from the change in mass before and after IR heating which accounts for the evaporation of moisture during IR heating. Different from moisture loss, the peeling loss was calculated from the change in fruit mass before and after peeling and accounted for the mass of peel removed and evaporation of moisture during peeling.

2.5 Surface temperature of jujube

The surface temperature of IR heated jujube was immediately measured after heating on the jujube surface using a FLIR-E49001 infrared camera (FLIR Systems Instruments Co., USA) for each fruit. The emissivity for the temperature measurement was set as 0.93 (Hellebrand et al., 2002). The surface temperature of five fruits was determined and the mean value was reported for different peeling conditions.

2.6 Color measurement

The color measurements were performed at three cheek locations of each jujube along the equator with a portable Minolta chroma meter (model CR-400, Konica Minolta Sensing INC., Japan). The chroma meter was first calibrated against a standard ceramic white tile ($Y = 87.20$, $x = 0.3155$, $y = 0.3228$). The color measurement readings were represented by the three color parameters (i.e., CIE L^* , a^* , and b^*). All color readings of peeled jujubes were measured within approximately 3 min after peeling. The change in flesh color before and after peeling was calculated using equation (1) and a smaller ΔE indicates less color change after peeling.

$$\Delta E = [(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2]^{\frac{1}{2}} \quad (1)$$

Where, L^* , a^* , and b^* are the flesh color values of the peeled jujubes after IR heating and L_0^* , a_0^* , b_0^* are the average values of flesh color of peeled jujubes without IR heating (control). Color values were measured for five jujubes and the mean values were reported.

2.7 Experimental design for RSM

A Box and Behnken design (BBD) with three independent variables was used to obtain optimum IR heating conditions for jujube to maximize the peeling performance.

The independent variables used in the design were radiation intensity (X_1 , W/cm²), distance (X_2 , mm) and heating time (X_3 , s), while the dependent or response variables were peelability (Y_1 , %), easiness (Y_2), weight loss (Y_3 , %) and surface temperature (Y_4 , °C). The range for each variable was determined from the preliminary single factor tests. Seventeen experiments were conducted randomly ([Table 1](#)) to analyze the response pattern and to establish models for jujube peeling.

Experimental data obtained were fitted into a second-order polynomial model and regression coefficients were calculated. The generalized quadratic equation to predict the optimal point was explained as follows:

$$Y=b_0+b_1X_1+b_2X_2+b_3X_3+b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2+b_{12}X_1X_2+b_{13}X_1X_3+b_{23}X_2X_3. \quad (2)$$

In equation (2), the coefficients of the polynomial terms were represented by b_0 (constant term); b_1 , b_2 and b_3 (linear effects); b_{11} , b_{22} , and b_{33} (quadratic effects); and b_{12} , b_{13} and b_{23} (interaction effects). Significant terms in the model for each response were found by analysis of variance (ANOVA) and significance was judged by the F-value calculated from the data ([Eren & Kaymak-Ertekin, 2007](#)).

2.8 Model verification

The peeling conditions were numerically optimized for the maximum peelability and easiness with minimum weight loss and surface temperature by RSM. The peeling of jujube was performed at the optimum conditions (IR intensity, distance and heating time) obtained from the model and the responses were determined. Finally, the predicted values from the model were compared with the experimental values in order to determine the validity of the models.

2.9 Comparison of IR dry-peeling and lye peeling methods

In order to compare the peeling performance and quality of peeled jujubes obtained by IR heating process with that of the conventional lye peeling, a series of experiments were performed following a previously reported lye peeling method used for tomatoes (Garcia & Barrett, 2006). Jujubes were immersed in a beaker containing 18 g/mL of sodium hydroxide (NaOH) solution at 95 ± 2 °C for 40, 50, 60, and 70 s respectively. After the treatment, the fruits were rapidly cooled at 20 °C using tap water to avoid overcooking and to remove residual NaOH solution and peel remaining on the fruit. The peeling performance was evaluated by determining the peelability, easiness, and weight loss and compared with the peeling performance of IR heated jujubes.

2.10 Statistical analysis

The design of experiments, analysis of the results and prediction of the responses were carried out using Design-Expert Version 9.0 (Stat-Ease, 2014). Comparisons of means were performed by one-way ANOVA (analysis of variance) followed by Tukey's test ($p < 0.05$).

3. Results and Discussion

3.1 Jujube size and mass distribution

Jujube size and mass were measured from a representative sample of 204 jujubes. The jujube size represented by its cheek diameter (D_c) ranged from 30.06 mm to 45.61 mm with an average value of 38.55 mm and a standard deviation of 2.81 mm. The mass of jujubes varied from 11.09 g to 33.05 g with an average value of 22.04 g and a

standard deviation of 3.82 g for all the measured jujubes. The accumulate frequency distribution of size for 204 jujubes is presented in Fig.2. More than 93% of the jujubes had size less than 42.00 mm, 71% of the jujubes had size less than 40.00 mm and 36% of the jujubes had size less than 38.00 mm. The accumulate frequency distribution of mass of 204 jujubes is shown in Fig.3, which shows that more than 93% of the jujubes had their masses less than 25.00 g, 78% of them had their masses less than 22.00 g and 52% of them had their masses less than 19.00 g. In addition, a fairly good correlation was found between the size and the mass of jujube ($r^2 > 0.72$). Based on the size distribution (Fig.2), jujubes having size between 36.00 mm to 42.00 mm and the mass ranging from 19.00 g to 25.00 g were used for the subsequent peeling tests.

3.2 Fitting of response surface models

The results of the experiments performed for BBD showing the levels of variables along with the responses for the 17 tests are given in Table 1. The results of the ANOVA for the model responses are shown in Table 2. The second-order polynomial models predicted by RSM showed a significant fitting ($p < 0.0001$), and the lack of fit for all fitted models was found to be not significant ($p > 0.1422$). The parameters including, R^2 , Adj- R^2 , coefficient of variation (C.V.), PRESS and Adeq. Precision were calculated to exam the model adequacy. The significant adequacy of the models was confirmed at the 0.01% level of probability with the R^2 and adjusted- R^2 of $> 97\%$ as shown in Table 3. These values showed a good agreement between the experimental and the predicted values. The low C.V. values (0.94-6.34) implied an

insignificant variability and high stability of the models. PRESS is used for prediction error sum of squares, and lower values of PRESS indicate a model that predicts well.

The PRESS values varied from 0.66 to 15.62, indicating the adequacy of the fitted quadratic models for predictive applications. Adequate precision measures the signal-to-noise ratio and a ratio greater than 4 is desirable (Myers and Montgomery, 2002). For the proposed models, adequate precision value was between 31.81 and 56.73, indicating a very good signal-to-noise ratio. Therefore, it can be assumed that the fitted models can be used for the optimization of variables for the jujube peeling.

3.3 Effect of operating parameters on peeling performance

The operating parameters for peeling performance were determined by the significant coefficients of the second-order polynomial regression equation which is shown in Table 3 along with respective p -values. The linear effects of all independent variables were significant ($p < 0.01$) on the peelability (Y_1) and the quadratic and interaction terms were highly significant ($p < 0.0001$) as shown in Table 3. The 3D response surface graphs are plotted to better visualize the significant interaction effects of operating parameters on the peelability of jujube (Fig.4 a-c). The peelability of jujube gradually increased with the increasing radiation intensity and time, but decreased with the increase in emitter distance. The increase in peelability might be due to increased skin separation caused by skin cracking as a result of high IR heat fluxes and high accumulated heat as indicated by the high surface temperature. Moreover, rapid surface heating and high heat delivery by IR heating is also beneficial for skin loosening and enhance the peelability. This finding was consistent with previous

studies of tomato and peach peeling (Pan et al. 2009; Li et al. 2014a; Li et al. 2014c).

The individual optimum condition showed that the maximum peelability (100%) was predicted to be obtained by peeling jujube by heating at an IR intensity of 5.75 W/cm² by placing the two emitters at a distance 79 mm for 52 s.

All the operating conditions such as radiation intensity, emitter distance and heating time indicated a significant ($p < 0.05$) linear and quadratic effects on the peeling easiness (Y_2) (Table 3). In addition, the interaction effects of radiation intensity with heating time and emitter distance with heating time were found to be also significant ($p < 0.05$). Figure 5a and 5b show that increasing heating time resulted in an easier peeling. The trends are in agreement with the previous results for other fruits (Pan et al. 2009; Li et al. 2009, 2014c). A longer IR heating time might result in the degradation of inner tissues of skin and reduction of peel adhesiveness to the fruit flesh, leading to an easier skin rupture and skin removal (Li et al., 2014b).

Furthermore, it was reported that thermal effect due to IR heating considerably affected the elastic modulus of cuticular membranes of tomato (Matas et al., 2005; Wang et al., 2014). The increase in peeling easiness with the increase in IR intensity and heating time might be due to the increase in the elastic property of jujube skin caused by the thermal effects. Another reason for easy peeling might be due to the increase in intercellular to intracellular area in the cell wall and middle lamella of jujube skin during IR heating (Pan, McHugh, Valenti-Jorrdan, & Masareje, 2015).

However, the effect of IR heating on elastic properties of jujube skin should be further investigated. According to the individual optimization results, the highest response

(5.0) for peeling easiness was observed when jujube was peeled after heating with an IR intensity of 6.02 W/cm² for 53 s by placing the two emitters at an emitter gap of 75 mm.

The results illustrated in Table 3 revealed that the moisture loss (Y_3) was significantly ($p < 0.05$) affected by the linear and quadratic terms of all independent variables, except the quadratic effect of heating time which was not significant ($p > 0.05$). Furthermore, all the interaction effects except the term between the emitter distance and heating time were non-significant ($p > 0.05$) for the moisture loss. As shown in Fig. 6a and 6b, the moisture loss decreased with the decrease of radiation intensity. This may be attributed to the fact that the decrease of radiation intensity may reduce the accumulation of heat and the evaporation of water vapor on the fruit surface during IR heating, and thus result in less moisture loss (Li et al. 2014b, 2014c). The individual optimization results indicated that the optimum condition of radiation intensity, emitter distance and heating time for the minimal moisture loss (0.35%) were 5.29 W/cm², 85 mm, and 42 s, respectively.

The linear and quadratic terms of radiation intensity had significant effects on the surface temperature at the 0.01% level, and those of emitter distance and heating time at the 1% level as shown in Table 3. Moreover, the interaction effect of emitter distance and heating time was also found to be significant ($p < 0.05$). Increasing the IR heating time resulted in enhanced surface temperature (Fig. 6c) similar to IR peeling of peaches (Li et al. 2014c). When IR radiation heating time was increased, the surface temperature of fruits immediately rose up, which was mainly due to the

enhanced radiative heat transfer to the surface. The increased surface temperature of jujube was caused by the high sensitivity of jujube skin to heat (Pan, McHugh, Valenti-Jorddan, & Masareje, 2015). From the individual optimization data, a combination of 5.25 W/cm² radiation intensity, 80 mm emitter distance and 40 s heating time was predicted for achieving the minimal surface temperature (100 °C).

3.4 Optimization of predictive models

The numerical optimization was conducted using response surface methodology in order to simultaneously maximize peelability and easiness, and also to minimize weight loss and surface temperature. Two solutions were obtained for the optimum covering criteria with desirability values of 0.650 and 0.627 (Table 4). To test the accuracy of the models for predicting the response values, seven replicates experiments were performed at the optimal conditions obtained from the model. The experimental values as shown in Table 4 demonstrated that results were quite comparable and in agreement with the predicted ones. This result suggests that the optimized models can be successfully applied for predicting the actual peeling conditions including IR radiation intensity, heating time and emitter distance required for jujube peeling. It can also be seen from Table 4 that peeling of jujube after heating with IR radiation intensity of 5.25 W/cm² and emitter distance of 75 mm for 56 s can obtain the similar peelability and easiness with lower weight loss and surface temperature compared to that obtained by IR heating with an IR intensity of 6.07 W/cm² and emitter distance of 84 mm for 48 s. Considering the energy consumption and the yield in industrial production, the former peeling conditions were selected as

the better solution and the optimal peeling conditions. Under the optimum condition, the corresponding experimental response values for peelability, easiness, moisture loss and surface temperature were found to be 96%, 3.8, 1.29 %, and 115°C, respectively. However, the surface temperature of jujube (115°C) is higher than that of IR heated tomato (85-95 °C), but is much lower than that of IR heated peach (140 °C). This result might be due to the difference in skin thickness and characteristics, and separation sensitivity of fruit skin to heat.

3.5 Comparison of IR peeling and conventional lye peeling

The peeling performance of jujube by the conventional lye peeling for different dipping times and by IR peeling at the optimum conditions (IR radiation intensity of 5.25 W/cm², emitter distance of 75 mm and heating time of 56 s) are shown in [Table 5](#). It can be seen that the dipping time in lye solution had a significant effect on jujube peeling performance, including peelability, easiness, and peeling loss ($p < 0.05$), while it had no significant effects on color change of jujube flesh ($p > 0.05$). Generally, as the lye dipping time increased, the peelability, easiness and peeling loss gradually increased, which might be a result from mass diffusion and complex biochemical reactions, as well as accumulated heat effect on skin separation. Such findings are in agreement with the previous results for lye peeling of tomatoes ([Garcia and Barrett 2006](#); [Pan et al., 2009](#); [Li et al., 2014b](#)). Also, it was observed that the required lye dipping time to achieve an acceptable peelability and an easiness of peeling score 4 was 60 seconds for jujube, which was about 15 seconds longer than the lye peeling of tomatoes ([Pan et al., 2009](#)). This might be due to the difference in species and peel

characteristics as the peel of jujubes are more firmly attached to the flesh than that of tomatoes. The further increase of lye dipping time by 10 seconds caused insignificant changes in the peelability, easiness, and peeling loss of jujube ($p > 0.05$). Therefore, the dipping time of 60 s was considered as an optimal peeling time for jujube when the hot lye was used.

The comparison of the peeling performance of jujube peeled by IR and lye peeling showed that both the IR and lye peeling could produce a satisfactory peelability ($> 96\%$) for jujube. Though it is easier for jujube peeling by hot lye solution, the peeling loss (12.87 %) is more than 4-folds than that by IR heating (2.97 %). Compared to hot-lye peeling, the color change of IR heated jujube (8.38) was significantly lower than that of lye treated jujube (> 12.17) ($p < 0.05$) (Fig.7), which was also lower than the color change reported previously for IR peeling of peaches (> 10) (Pan, McHugh, Valenti-Jorddan, & Masareje, 2015). We observed that the color of jujube flesh visually appeared reddish after lye treatment due to biochemical reactions introduced by lye diffusion and subsequent dissolution of red pigments from peel of jujube. Therefore, considering the significantly higher peeling loss and color change occurring from lye peeling process, IR dry-peeling technology is an ideal alternative for skin removal of jujube.

4. Conclusions

Based on the accumulate frequency distribution, jujubes with the cheek diameters ranging from 37 mm to 41 mm were used in the peeling experiments. The IR heating conditions including IR radiation intensity, emitter distance and heating time had

significant influence on the peeling performance and surface temperature of jujube. The RSM used for optimizing these conditions resulted in the optimal values of IR radiation intensity of 5.25 W/cm², the emitter distance of 75 mm and heating time of 56 s for jujube peeling. The corresponding response values for peelability, easiness, moisture loss and surface temperature were found to be 96%, 3.8, 1.29 % and 115°C. The validation experiments were in good agreement with the predicted values by the fitted models. Compared to the hot lye peeling, the IR dry peeling of jujube significantly reduced the peeling loss and color change. Therefore, it is recommended as an effective peeling technique for the jujube skin removal with complete elimination of lye in the peeling process and reduced peeling loss, color change and processing time. This investigation should also help jujube processing industry in developing the environmentally safe IR peeling technique to produce high quality products from jujube.

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488 **FIGURE CAPTIONS:**

489 Fig. 1 The schematic diagram of the IR heating system.

490 Fig.2 Accumulate frequency distributions of jujube size (n=204)

491 Fig.3 Stacked frequency distributions of jujube mass (n=204)

492 Fig.4 3D surface plots showing the significant ($p < 0.05$) interaction effects on the
493 peelability

494 Fig.5 3D surface plots showing the significant ($p < 0.05$) interaction effects on the
495 peeling easiness

496 Fig.6 3D surface plots showing the significant ($p < 0.05$) interaction effects on the
497 moisture loss and surface temperature.

498 Fig.7 Photos of unpeeled and peeled jujube by different peeling methods.

499

Fig. 1 The schematic diagram of the IR heating system.

a). Front view; (b). Magnified view of fruit holder setup; and (c). Side view.

1. Electric IR emitter; 2. Rotating shaft; 3. Fruit holder; 4. Fingers of the fruit holder;

5. IR power regulator; 6. Rotational speed regulator of the fruit holder;

7. Screws to adjust the distance between IR emitters.

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Fig.2 Accumulate frequency distributions of jujube size (n=204)

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Fig.3 Stacked frequency distributions of jujube mass (n=204)

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Fig.4 3D surface plots showing the significant ($p < 0.05$) interaction effects on the peelability

Fig.5 3D surface plots showing the significant ($p < 0.05$) interaction effects on the peeling easiness

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Fig.6 3D surface plots showing the significant ($p < 0.05$) interaction effects on the moisture loss and surface temperature.

Unpeeled jujube

Manually peeled jujube

IR peeled jujube

Lye peeled jujube

Fig.7 Photos of unpeeled and peeled jujube by different peeling methods.

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553 Table 1 Box and Behnken design BBD with experimental results

Standard order	Run order	Independent variables			Responses variables			
		X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4
		IR Intensity (W/cm ²)	Distance (mm)	Time (s)	Peelability (%)	Easiness	Moisture loss (%)	Surface temperature (°C)
13	1	5.66 (0)	80 (0)	50 (0)	100	3.6	2.11	122
7	2	5.25 (-1)	80	60 (1)	86	2.6	0.80	113
4	3	6.07 (1)	85 (1)	50	94	4.2	2.28	121
11	4	5.66	75 (-1)	60	100	4.8	3.67	133
8	5	6.07	80	60	100	4.6	4.36	125
16	6	5.66	80	50	98	3.4	1.95	122
10	7	5.66	85	40 (-1)	58	2.4	0.94	114
15	8	5.66	80	50	99	3.6	2.03	124
6	9	6.07	80	40	90	2.6	1.46	113
3	10	5.25	85	50	54	2.6	0.45	110
2	11	6.07	75	50	100	4.8	3.71	129
12	12	5.66	85	60	92	3.8	2.24	123
1	13	5.25	75	50	84	3.0	1.28	115
17	14	5.66	80	50	97	3.4	2.09	123
14	15	5.66	80	50	96	3.2	1.90	120
9	16	5.66	75	40	86	2.6	2.18	117
5	17	5.25	80	40	48	1.4	0.36	100

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555 Table 2 Evaluation of the fitted quadratic models for Y_1 , Y_2 , Y_3 and Y_4 responses

Sources	Response variables			
	Peelability (Y_1 , %)	Easiness (Y_2)	Moisture loss (Y_3 , %)	Surface temperature (Y_4 , °C)
Model (p value)	<0.0001*	<0.0001*	<0.0001*	<0.0001*
Lack of Fit (p value)	1.0000 ns	0.7880 ns	0.1422 ns	1.0000 ns
R-Squared	0.9979	0.9898	0.9944	0.9909
Adjust R-Squared	0.9951	0.9767	0.9873	0.9793
C.V.%	1.37	4.28	6.34	0.94
PRESS	15.62	0.66	1.31	13.75
Adequate precision	56.73	31.81	40.28	38.38

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* Terms are significant ($p < 0.05$); ns means that terms are not significant ($p > 0.05$).

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559 Table 3 Estimated regression coefficients and significance of each variable

Response		Intercept	Linear effects			Interaction effects			Quadratic effects		
			X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	X_1^2	X_2^2	X_3^2
Peelability (%)	Coefficient	98	14	-9	12	6	-7	5	-9	-6	-8
	p value		< 0.0001*	0.0011*	0.0005*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*
Easiness	Coefficient	3.44	0.825	-0.275	0.85	-0.05	0.2	-0.2	-0.195	0.405	-0.445
	p value		0.0480*	0.0015*	0.0027*	0.5053	0.0262*	0.0262*	0.0262*	0.0006*	0.0004*
Moisture loss (%)	Coefficient	2.016	1.115	-0.616	0.766	-0.15	0.615	-0.048	-0.299	0.213	0.028
	p value		< 0.0001*	< 0.0001*	< 0.0001*	0.0488*	< 0.0001*	0.476	0.0018*	0.0104*	0.659
Surface temperature (°C)	Coefficient	122.2	6.25	-3.25	6.25	-0.75	-0.25	-1.75	-6.225	2.775	-3.225
	p value		< 0.0001*	< 0.0001*	< 0.0001*	0.223	0.669	0.0168*	< 0.0001*	0.0014*	0.0006*

560 * Terms are significant ($p < 0.05$)

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Table 4 Predicted and experimental values of the responses at optimum conditions of independent variables

Response variables	Independent variables			Extreme values		Desirability
	Intensity (W/cm ²)	Distance (mm)	Time (s)	Predicted	Experimental	
	6.07	84	48			0.650
Peelability (%)				95 ^a	95±3 ^a	
Easiness				3.9 ^a	3.8±0.4 ^a	
Moisture loss (%)				2.13 ^a	2.10±0.10 ^a	
Surface temperature(°C)				120 ^a	118±3 ^a	
	5.25	75	56			0.627
Peelability (%)				90 ^a	96±6 ^a	
Easiness				3.4 ^a	3.8±0.4 ^a	
Moisture loss (%)				1.41 ^a	1.29±0.13 ^a	
Surface temperature (°C)				119 ^a	115±3 ^a	

The same lower case letters correspond to insignificant difference at $p < 0.05$.

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568 Table 5 Effects of dipping time in hot lye solution on peeling performance of jujube ^a

Peeling conditions	Peelability (%)	Easiness	Peeling loss (%)	Color change ΔE
Lye-40s	48±5 ^a	3.8±0.4 ^a	7.61±2.44 ^b	12.17±1.14 ^b
Lye-50s	78±10 ^b	4.0±0.0 ^b	10.83±1.86 ^c	12.50±2.22 ^b
Lye-60s	97±3 ^c	4.8±0.4 ^b	12.87±0.79 ^c	13.85±2.26 ^b
Lye-70s	100±0 ^c	5.0±0.0 ^b	13.07±1.35 ^c	12.77±1.14 ^b
IR-56s	96±6 ^c	3.8±0.4 ^a	2.97±0.93 ^a	8.38±0.59 ^a

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^a The data are presented as mean ± SD for three replications.

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Different lower case letters correspond to significant difference at $p < 0.05$.