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Optimization of dry-peeling method for plums using infrared radiation heating with response surface methodology and evaluation of physicochemical characteristics in compare of lye peeling method

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ABSTRACT

Peeling is a key stage from post-harvest processing for plum fruit, which traditional methods (using lye solution) meets to some challenges such as a high peeling loss, low efficiency of process, high consumption of water and energy, chemical wase water production that finally led to reduction of product quality. This study investigates the feasibility and optimization of dry-peeling for plums using infrared radiation heating as a sustainable alternative to conventional lye peeling. A laboratory-scale system including a ceramic IR emitter and the rotating fruit rollers for plum processing was designed. The effects of IR emitter power (350-1000 W), heating time (90-150 s), and emitter distance (20-70 mm) on physicochemical properties and peeling performance (moisture loss, peel thickness, surface temperature, color properties, and Ascorbic acid) were evaluated using Response Surface Methodology (RSM). The results showed that optimal conditions (797.48 W, 70 mm, 107 s) achieved 0.30% moisture loss, 0.12 mm peel thickness, 40°C surface temperature, 13.5 ΔE color change, and 14 mg/100 g ascorbic acid retention. In compare with conventional lye peeling method (10% NaOH, 85°C, 100 s), IR peeling significantly reduced moisture loss (0.30% vs. 9.56%), preserved bright yellow hue (Hue angle 82 vs. 55°), and enhanced ascorbic acid retention (14 vs. 10.5 mg/100 g), while eliminating chemical wastewater. These findings proved the high potential of infrared radiation heating as a green method, effective with high quality for plum processing.

1-Introduction

Potato (*Prunus domestica L.*.) is a globally important fruit grown in temperate and Mediterranean climates. According to the Food and Agriculture Organization (FAO)[1]), global plum production reaches 12.5 million tons annually, with Iran ranking sixth with a production of 376,000 tons. Plums are rich in vitamins A and C, potassium, copper, dietary fiber, and various bioactive compounds, which enable their use in juices, purees, and pharmaceutical formulations..Peeling improves texture and reduces tannins, while preserving essential nutrients and increasing the processing potential of plums [1].

Fruits and vegetables require processing to increase their shelf life due to their high humidity and short harvest season. The outer structure of the fruit consists of a layer called the pericarp (skin) covered by a waxy layer called the cuticle. This layer has multiple physiological functions, including acting as a barrier against pathogens, mechanical damage, and water loss [2]. The waxy epidermis of the fruit prevents moisture transfer during drying, making it necessary to remove the skin. Peeling is also essential for the production of value-added products such as purees and juices, as the skin of plums contains tannins and insoluble fibers that reduce the clarity of the juice and cause gassiness and texture problems [3].

Peeling is a significant step in the post-harvest processing of fruits or vegetables. Conventional methods for peeling plums, including the alkaline method and the steam method, despite their widespread use, have significant limitations. The alkaline method produces a large volume of saline-alkaline wastewater and damages the fruit tissue by hydrolyzing pectins, while the steam method, although free of chemicals, often causes discoloration, surface hardening, and uneven peeling [4]. These shortcomings necessitate the development of sustainable alternative methods such as dry peeling.[2](without using water) using infrared heating[3](IR) reveals [2, 5 and 6].

In recent years, significant progress has been made in the application of infrared technology in fruit and vegetable processing. Wu et al. (2024) showed that catalytic infrared systems[4](CIR) that operate on natural or liquid gas have higher thermal efficiency than traditional electric emitters and significantly reduce energy consumption [7]. From a mechanistic perspective, Niu et al. (2024) stated that infrared heating reduces the adhesive force between the skin and flesh by accelerating the local degradation of the pectin and hemicellulose matrix in the outer layer (exocarp) without damaging the inner layer (mesocarp) [8]. Furthermore, recent economic-environmental analyses by Eslami et al. (2024) show that infrared technology reduces water and energy consumption, reduces solid waste by 52%, and has a life cycle assessment of 100% [8].[5](LCA) performs much better than steam or alkaline methods [9].

Despite the promising applications of infrared heating dry peeling as an emerging technology for various fruits and vegetables, no published study has investigated its application to plums, which have a waxy and delicate epidermis. Therefore, this study aimed to develop and optimize an infrared dry peeling system for plums and evaluate its feasibility compared to the conventional alkaline method. Infrared peeling is a sustainable alternative to conventional alkaline peeling by eliminating chemical waste, reducing water and energy consumption, and preserving heat-sensitive nutrients (such as ascorbic acid) [5, 6]. The specific objectives of this research are: (1) To determine the optimal operating parameters of infrared heating (IR) using the response surface methodology[6](RSM) to achieve high efficiency and desirable quality in plum peeling; (2) to compare the peeling process performance and physicochemical properties of IR-treated plums compared to the conventional alkaline method to evaluate product stability and quality. By achieving these objectives, the present research contributes to the development of more sustainable and efficient fruit processing technologies with potential for industrial application.

2-Materials and methods

1.2- Preparation of samples

The required plums were obtained from the Sabzevar orchards of Khorasan Razavi province and were of the Santa Rosa variety in 1400 and were transported to the laboratory at a temperature of 4 degrees Celsius. The plums were graded after thorough washing and those with visible defects or outside the desired size were removed from among them. Then, plums of the same size were randomly selected for this experiment.

2-2- Infrared peeling system

The peeling system developed for plum processing in this study is a laboratory-scale infrared dry peeling

1- Food and agriculture organization

2- Dry peeling

3- Infrared heating

4-Catalytic infrared

5- Life cycle assessment

6- Response surface methodology

system consisting of two main units: (1) an infrared heating unit with a ceramic infrared emitter and (2) a plum fruit rotating roller unit (Figure 1). This system is designed to uniformly heat the surface of the plum, loosen the adhesion between the skin and the fruit flesh (mesocarp), and create surface cracks on the plum fruit skin through rapid heating. The infrared heating unit used a curved ceramic emitter (60 × 240 mm, RCH0624, Taiwan) with a power of 1000 W (Figure 1), which was installed on the ceiling of the chamber and emitted radiation at wavelengths of 2.5 to 6 µm. Below the emitter, two galvanized rotating rollers were installed in the same direction to rotate the plum samples in the middle of the chamber. The rollers were driven using a belt and pulley system connected to a three-phase electric motor and an inverter to set the speed to 3 rpm.

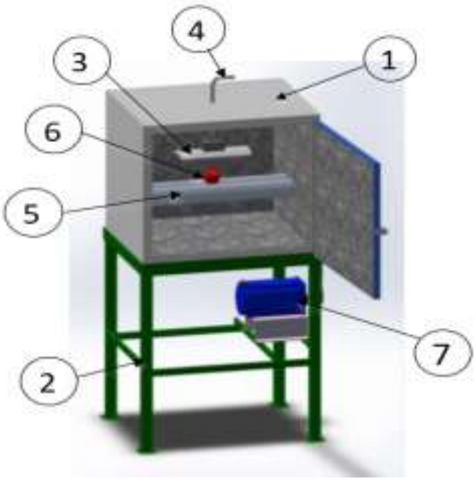


Fig. 1. Schematic diagram of the laboratory-scale infrared (IR) dry-peeling system for plums. (1) Chamber, (2) Chassis, (3) Ceramic IR emitter, (4) Screw mechanism for adjusting the distance, (5) Rotating rollers, (6) Plum sample, (7) Electric motor and belt drive assembly.

3.2- Infrared peeling test method

In this study, experiments were conducted to evaluate the performance of the infrared (IR) dry peeling system by considering the power supply power, irradiation time, and emitter-to-sample distance at three levels as independent parameters according to (Table 1) and the response surface method for plum fruit. To achieve different levels of electrical power supply for the infrared emitter, a dimmer device was installed on the incoming municipal power line. The power intensity was monitored and controlled using a power analyzer (LUTRON DW-6090). The infrared heating time was adjusted by a stopwatch, and the distance of the infrared emitter to the sample surface was determined using the height adjustment screw No. 4 (Figure 1). The electrical diagram of the system used in this study is shown in Figure 2.

Table 1. Actual and coded levels of independent variables in the central composite design (CCD) for infrared dry-peeling of plums

Variable	Low (-1)	Center (0)	High (+1)
IR emitter power (W)	350	675	1000
Irradiation duration (s)	90	120	150
Emitter distance to sample (mm)	20	45	70

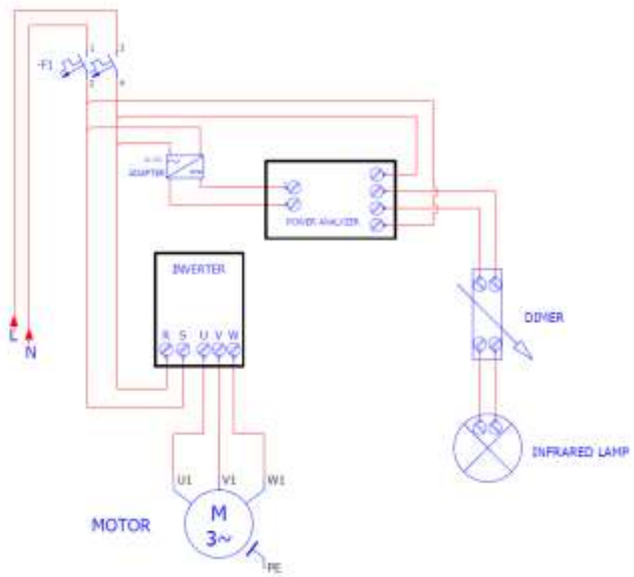


Fig. 2. Electrical circuit diagram of the infrared peeling chamber including power supply, dimmer, motor drive, and IR emitter connections

4.2- Peeling plums with alkaline solution

Alkaline peeling, a conventional method, was used as a control treatment for comparison with the infrared dry peeling method. Hot alkaline peeling was performed using a 10% w/v sodium hydroxide (NaOH) solution (100 g/L) at 85°C, which was determined from preliminary experiments and reference standards [10]. It was performed to ensure effective peeling and quality retention (e.g. vitamin C, color) of plums. Immersion time was factorially tested in a completely randomized design.[7](CRD) was determined at three times of 70, 100 and 120 seconds with three replicates. After alkaline treatment, plums were washed in water at 25°C for 30 seconds and alkali neutralization was confirmed with 1% phenolphthalein. Then, the samples were peeled manually. Performance parameters including moisture loss, skin thickness and color characteristics were measured. These parameters were used as a basis for comparison with the infrared peeling method.

5.2- Peeling performance parameters

The dependent variables used to evaluate infrared peeling performance and plum quality were moisture loss, thickness of peeled skin, color characteristics, and ascorbic acid content.

1-5-2- Skin thickness

Reducing the peeled thickness makes the final product more complete and reduces processing waste. The peeled thickness of each treatment was measured by digital caliper with an accuracy of 0.01 mm at three points on the peeled surface and the average of the measured values was recorded.

2-5-2- Moisture loss

Moisture loss represents the weight loss of the sample due to moisture evaporation during infrared heating. This parameter is determined by measuring the change in mass of the plum sample before ($M1$(and then)$M2$) from heat treatment and was calculated using equation (1).

$$Moisture\ loss\ \% = \frac{M1 - M2}{M1} \times 100 \quad (1)$$

3-5-2- Plum surface temperature

The surface temperature of the plums treated with infrared radiation was measured immediately after the heating treatment at three different points (two ends and the middle of the fruit) using a non-contact infrared thermometer (Testo 830-T2) and the average of the measured values was recorded. For peeling with alkaline solution, the surface temperature of the plum was considered equal to the temperature of the alkaline solution.

4-5-2- Color feature

The change in color characteristics of peeled plums is an important parameter for assessing the degree of tissue damage, quality and acceptance criteria. Image processing method was used to determine the color change of plums treated with infrared. Images of the samples after peeling were taken with a digital camera (Canon, Powershot G12, 10 megapixels). The camera

7-Completely randomized design

was fixed on a box with dimensions of 45 × 45 × 45 cm, equipped with four white fluorescent lamps (32 W, 2630 lux). Image processing was written in openCV-Python and the program was entered in the RGB color space, then the values of L* (lightness), a* (redness) and b* (yellowness) were calculated. The image characteristics for each treatment were compared with the reference image and the color change (ΔE) was determined by (Equation 2).

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (2)$$

For samples peeled from the alkaline control treatment and comparing the infrared peeling method with the alkaline method, the Hue angle color index was calculated using (Equation 3).

$$Hue\ angle = tan^{-1}(\frac{b^*}{a^*}) \quad (3)$$

5-5-2- Ascorbic acid

Plum fruit is rich in antioxidants, including ascorbic acid or vitamin C. This vitamin is sensitive to various processing conditions, so the stability of this vitamin after peeling can be considered an indicator of the quality of the process and the product. Due to the high sensitivity of ascorbic acid to heat, it may be destroyed during heat treatment, reducing the quality of the product. Although ascorbic acid acts as a stabilizer and prevents browning reactions, it can have the opposite effect and accelerate browning reactions with heat.The standard method AOAC Official Method 967.21 was used to measure the ascorbic acid content [11].

6.2- Designing experiments and analyzing data

In this study, experiments were designed to optimize the performance parameters of the plum infrared peeling system using the response surface methodology (RSM) in a central composite design.[8](CCD) was performed with six center point replicates (Table 2). The independent variables were infrared peeling system, emitter electrical power supply (X_1) at three levels of 350, 675 and 1000 watts, the distance of the lamp from the sample (X_2) at three levels of 20, 45 and 70 mm, the heating time (X_3) at three levels of 90, 120 and 150 seconds. The dependent variable is the moisture loss (Y_1, %), shell thickness (Y_2, mm), color property (Y_3) and surface temperature (Y_4, °C). (Table 2) shows the 20 experiments determined by Design-Expert Version 13.0 software and the results. The experimental data obtained for each response were fitted to a full second-order polynomial model and the regression coefficients were calculated. The significance of the model coefficients for each response was determined using analysis of variance.[9](ANOVA) was determined from the calculations and the corresponding F-value judgment. For the validation process, the infrared peeling treatment was carried out under the optimal operating conditions of the infrared heating system and the response values were determined. Then, the predicted values from the model were compared with the experimental values. The mean and standard deviation values of the responses at the central point (6 replicates, 675 W, 45 mm, 120 s) were as follows: Moisture loss 0.18±0.38%, skin thickness 0.01±0.14 mm, color difference 260± 75/13 ΔE = , and the surface temperature is 2/3±38.5 degrees Celsius.

Table 2. Central composite design (CCD) matrix and experimental results for infrared dry-peeling of plums

Treatment No.	Run	Independent variables			Response variables			
		X_1	X_2	X_3	AND_1	AND_2	AND_3	AND_4
		IR emitter power (W)	Distance (mm)	Irradiation time (s)	Moisture loss (%)	Peel thickness (mm)	Color difference (ΔE)	Surface temp. (◦C)
6	1	1000	20	150	3.5	0.033	16.27	90
18	2	675	45	120	0.8	0.13	13.55	40.5
1	3	350	20	90	0.2	0.180	9.79	35
10	4	1000	45	120	1	0.04	16.20	72
8	5	1000	70	150	1	0.035	15.5	70
14	6	675	45	150	0.2	0.168	13.56	50
11	7	675	20	120	1.9	0.163	14.64	34.5
7	8	350	70	150	0	0.188	11.02	36
4	9	1000	70	90	1	0.043	15.23	42.5
3	10	350	70	90	0.1	0.168	9.81	34.5

8- Central composite design

9- Analysis of variance

13	11	675	45	90	1	0.147	13.5	38.5
19	12	675	45	120	0.3	0.132	13.54	34
12	13	350	45	120	0.3	0.135	13.40	36
2	14	1000	20	90	2.8	0.086	16.30	45.5
9	15	350	45	120	0	0.135	10.11	34.5
20	16	675	45	120	0.3	0.137	14.23	41.5
5	17	350	20	150	0.1	0.175	9.83	50
16	18	675	45	120	0.3	0.160	13.70	41
15	19	675	45	120	0.3	0.134	13.95	40
17	20	675	45	120	0.3	0.155	14.12	40

CCD with 6 center point replicates (675 W, 45 mm, 120 s). For mean ± SD values of center point, see text above. Non-center points were performed once according to standard CCD design.

3-Results and Discussion

1.3- Evaluating the fit of response surface models

Table 3 shows the results of the regression analysis of the full second-order polynomial models. These models were fitted to evaluate the fit of the response surface models in infrared peeling of plums and for each response variable. The models developed by the RSM method showed significant fit (p-value < 0.0003), while the lack of fit was not significant (p-value > 0.0508). The coefficients of determination (R^2) and adjusted coefficients of determination (Adjusted R^2) of the second-order polynomial models were more than 92% and more than 84%, respectively. These results confirm that the regression model is significant at the 1% (0.01) probability level and can predict and optimize the peeling performance under the operating parameters of infrared heating. The coefficient of variation (C.V.) also varied in the range of 2.06 to 22.89%. Low values of the coefficient of variation indicate insignificant variations and high stability of the model. The value of sufficient accuracy was more than 9.91 (desirable signal-to-noise ratio S/N > 4) [12]. Therefore, the fitted models can be used to optimize the infrared heating variables in plum peeling.

Table 3. Statistical evaluation of quadratic models for response variables in IR dry-peeling of plums

Evaluation metrics	Response variables			
	Peel thickness (mm)	Moisture loss (%)	Surface temp. (◦C)	Color difference (ΔE)
Model (p-value)	> 0.0001**	**> 0.0001	> 0.0001**	> 0.0001**
Lack of fit (p-value)	0.29 ns	0.06 ns	0.05 ns	0.55 ns
R^2	0.96	0.94	0.93	0.99
Adj. R^2	0.93	0.89	0.87	0.98
Coefficient of variation (%)	10.02	22.31	11.77	2.23
Adequate precision	18.63	15.76	14.90	32.09

2.3- The effect of infrared operating variables on peeling performance

Table 4 shows the regression coefficients and significance levels of the full second-order polynomial model (derived from RSM and ANOVA) for evaluating the effects of power (X_1), heating time (X_2) and emitter distance (X_3) on plum peeling parameters (skin thickness, moisture loss, surface temperature and ΔE). This model includes width from origin, linear effects, interaction effects (X_1X_2، X_1X_3، X_2X_3) and quadratic effects (X_1^2، X_2^2، X_3^2). Significant levels are based on CCD and at two 5% levels (*,p< 0.05) and 1% (**,p< 0.01). Regression coefficients indicate the extent and direction of the effect of each variable on the response, and the values*p*They confirm statistical significance.

Table 4. Regression coefficients and statistical significance of independent variables affecting IR peeling performance

Response variables	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
Peel thickness (mm)	14.0	06.0- **0001.0 <	002.0- 5490.0<	005.0- 2612.0<	009.0- 0612.0<	005.0- 2711.0<	008.0- 0809.0 <	056.0- **0001.0 <	014.0- 0939.0<	016.0 0680.0<
Moisture loss (%)	43.0	89.0	03.0- 7840.0<	61.0-	11.0 3671.0<	50.0-	09.0-	01.0- 9652.0<	09.0 6640.0<	59.0

		**0001.0 <		**0002.0 <		**0016.0 <	4794.0 <			*0156.0 <
Surface temp. (◦C)	80.39	00.13 **0001.0 <	00.10 **0001.0 <	20.3- 0870.0<	49.6 **0043.0 <	06.1- 5855.0<	81.3- 0708.0 <	00.12 **0039.0 <	00.3 3729.0<	00.4- 2420.0<
Color differenc e (ΔE)	82.13	89/2 **0001.0 <	15.0 1330.0<	11.0- 2529.0<	12.0- 2610.0<	38.0- **0049.0 <	18.0 1136.0 <	81.0- **0012.0 <	43.0- *0383.0 <	41.0 *0429.0 <

1-2-3- Skin thickness

Peel thickness is a key indicator in evaluating the performance of infrared peeling system, which directly affects the yield and economic value of the product. Excessive removal of mesocarp can compromise the quality and marketability. The results of analysis of variance showed that infrared (IR) emitting power had highly significant linear and quadratic effects on peel thickness ($p< 0.0001$) (Table 4). In contrast, the linear and quadratic effects of emitter distance and heating duration, as well as all interaction effects, were nonsignificant ($p> 0.05$). Based on the significant regression coefficients (Table 4), the simplified prediction model for skin thickness is as described by equation (4).

$$Peel\ thickness = 0.14 - 0.06X_1 - 0.056X_1^2 \quad (4)$$

In which,X_1, infrared emitting power(IN)It is.

As shown in Figure 3, increasing the emitter power from 350 to 1000 W reduced the skin thickness from 0.188 to 0.033 mm. This reduction is attributed to the superficial penetration (0.1–1 mm) of infrared radiation (2.5–6 µm), which weakens the skin-flesh adhesion by creating cracks and vapor pressure in the pectin-hemicellulose matrix [14,13,4]. Shen et al. (2020) confirmed that this precision minimizes mesocarp (fruit flesh) loss [14]. These findings are consistent with studies conducted on peach and kiwifruit [15,6].

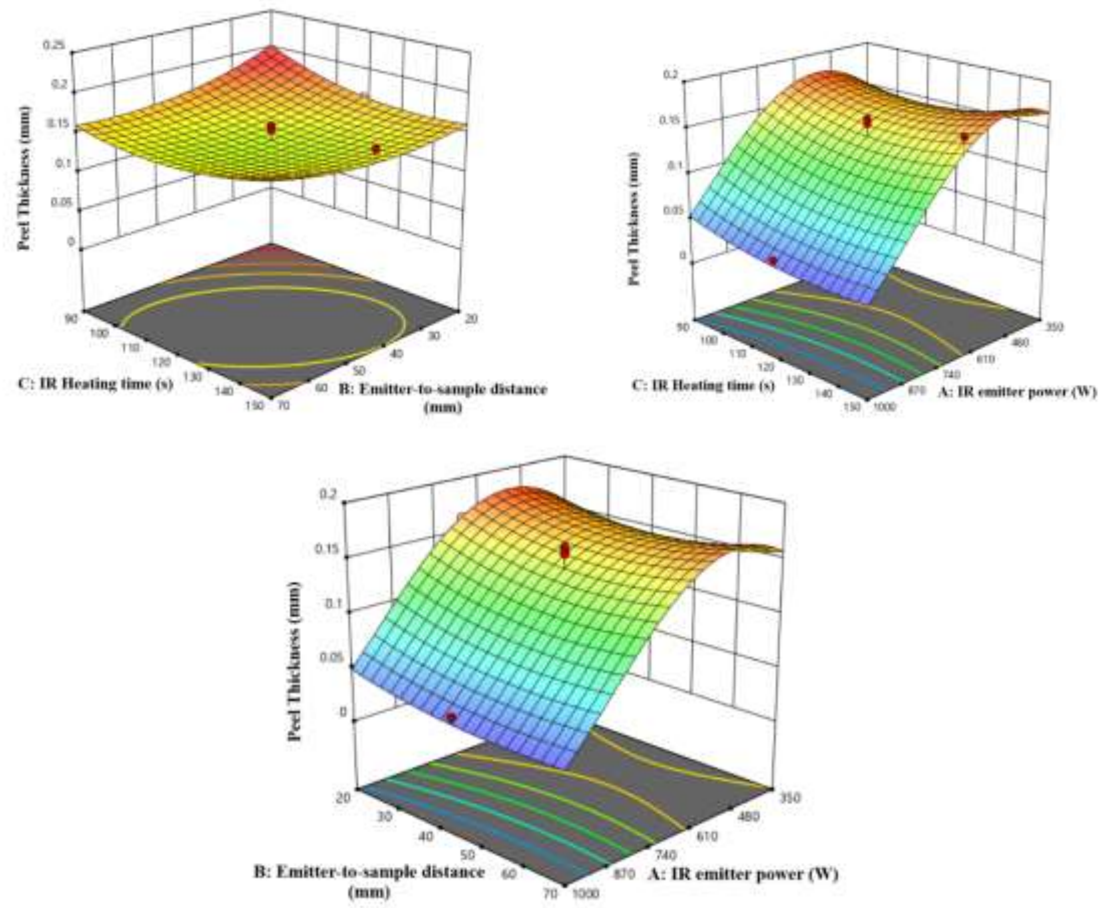


Fig. 3. The effect of infrared peeling operating parameters on peel thickness

2-2-3- Moisture loss

Moisture loss is a key indicator in IR peeling performance that affects the quality, shelf life and sustainability of plum processing. ANOVA showed that emitting power, distance, the interaction of power × distance and the square term of distance had a significant effect on moisture loss (*p*< 0.05) while heating time and its interaction effects were not significant (*p*> 0.05). Based on the significant regression coefficients, a simplified quadratic model for moisture loss is presented in equation (5).

$$Moisture\ loss = 0.43 + 0.89X_1 - 0.61X_3 - 0.50X_1X_3 + 0.59X_3^2 \quad (5)$$

In which, X_1, infrared emitting power(IN)، X_3The emitter distance is (millimeters).

Figure 4 shows that increasing IR power and decreasing emitter distance increased moisture loss. The highest value (15.3%) was observed at 1000 W power and 20 mm distance and the lowest value (0.05%) was observed at 350 W power and 70 mm distance. This trend is attributed to the increase in energy flux at higher power and shorter distances, which causes microcracks and fissures in the waxy epidermis of plum and facilitates moisture evaporation [4]. The significant interaction of power × distance indicates that the combined effect of power and distance exacerbates the amount of moisture loss, because higher radiation intensity at closer distances accelerates the increase in surface vapor pressure [16]. Surface penetration (0.1–1 mm) of IR radiation, by targeting the exocarp, preserves the integrity of the mesocarp and limits moisture loss [4]. These findings are consistent with IR peeling studies for tomato, kiwi, ginger, and hazelnut [19,18,15,4].

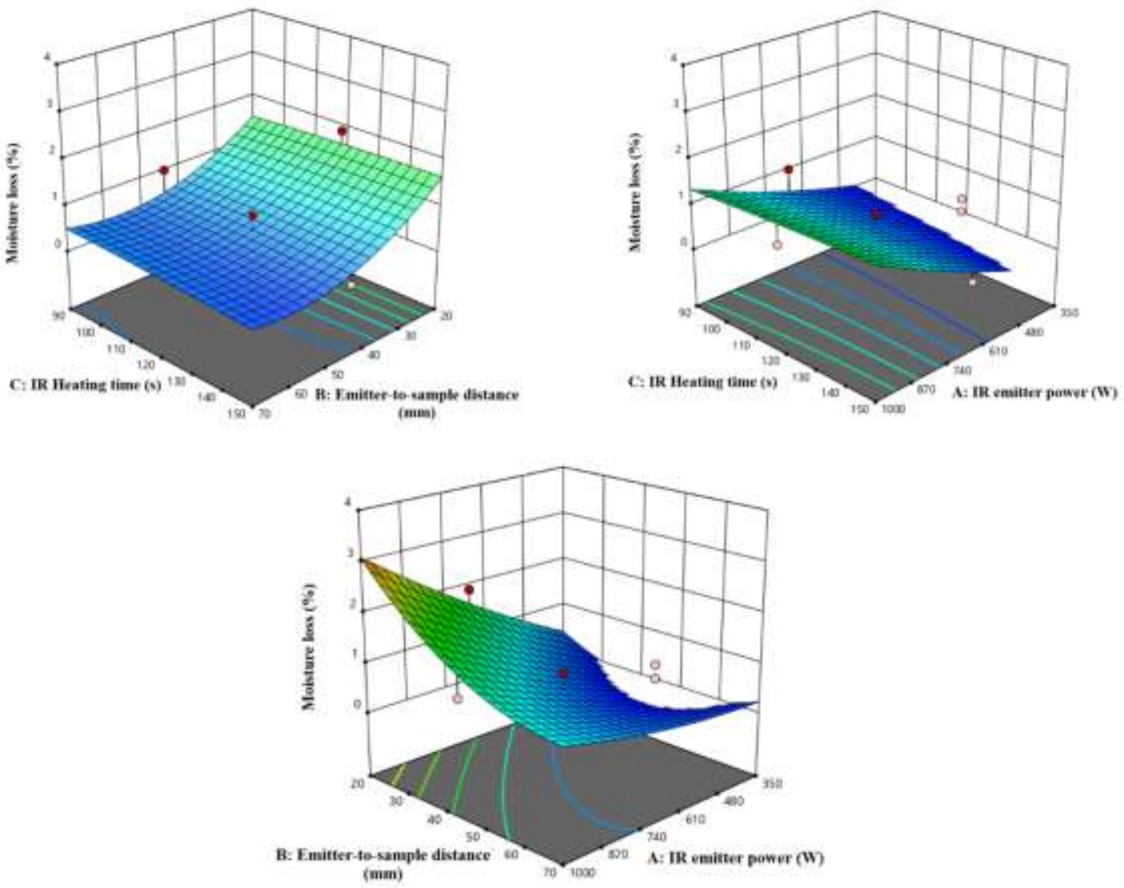


Fig. 4. The effect of infrared peeling operating parameters on moisture loss.

3-2-3- Surface temperature

According to Table 4, the linear effects of power and heating time inLevel 1% ($p< 0.01$) and alsoThe squared effect of power and the interaction effect of power × time at the 5% level($p < 0.05$)were significant on the surface temperature of plums. The simplified quadratic model of surface temperature after removing the meaningless terms is presented in equation (6).

$$Surface\ temperature = 39.80 + 13X_1 + 10X_2 + 6.49X_1X_2 + 12X_1^2 \quad (6)$$

Where:X_1Infrared emitting power(W)، X_2The heating time is (seconds).

As can be seen in Figure 5, the surface temperature increases with increasing power and heating time. The highest temperature (90°C) was recorded at a power of 1000 W, a distance of 20 mm, and a time of 150 seconds. RadiationANDWith a wavelength of 2.5–6 µm, it penetrates only to a depth of 0.1–1 mm and, by targeting the explant, prevents excessive heating of the explant [16,6]. This controlled heating, unlike the alkaline method (85°C), preserves ascorbic acid. A significant interaction of power and time indicates heat accumulation and is consistent with findings from studies of peach, kiwi, grape and jujube [21,20,15,6].

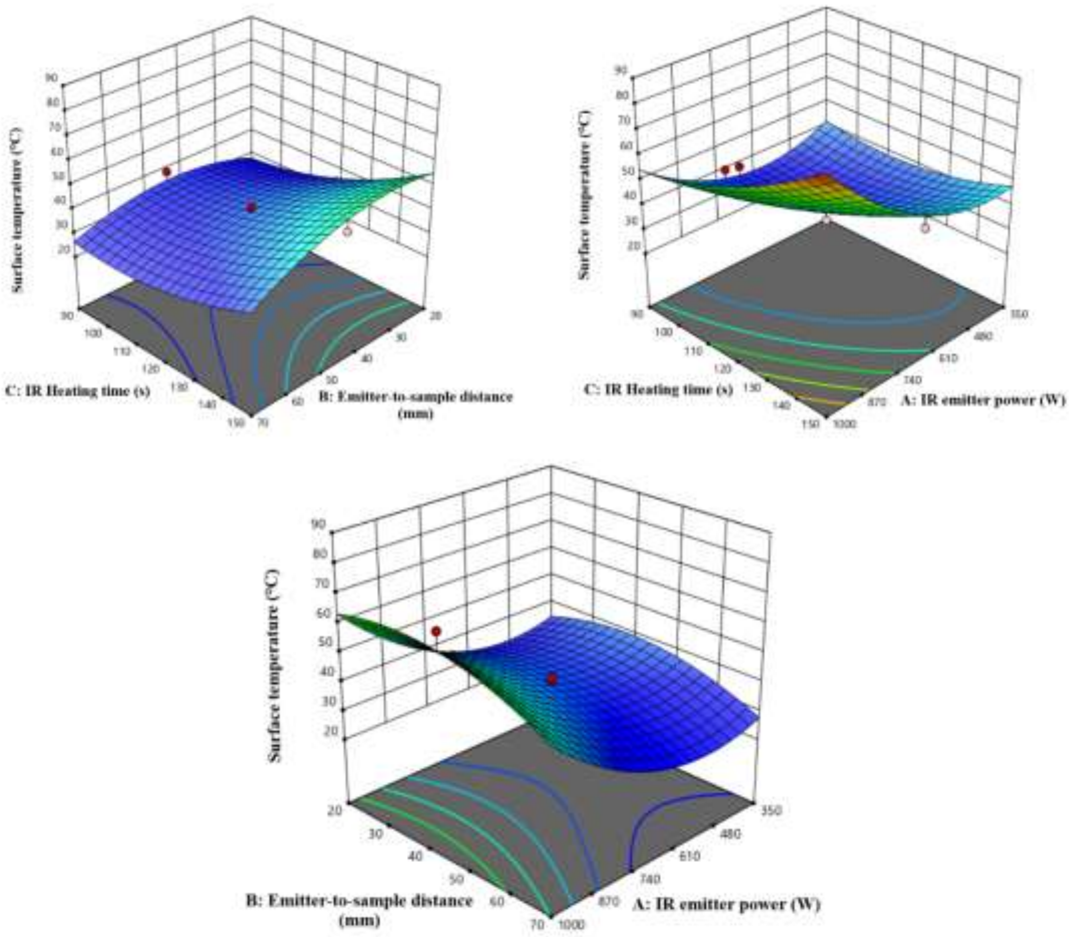


Fig. 5. The effect of infrared peeling operating parameters on surface temperature

6-2-3- Color feature

The color characteristic ΔE is a key indicator of peeled plum quality, reflecting textural changes and visual acceptability of the product. According to Table 4, ANOVA showed significant effects on ΔE: significant linear effects of power at the 0.01% level ($p < 0.0001$), quadratic effects of power, time and distance at the 1% level ($p < 0.01$) and the interaction effect of power and distance at the 5% level ($p < 0.05$). Other interaction effects as well as linear effects of time and distance were non-significant ($p > 0.05$). The simplified quadratic model for color difference is presented in equation (7).

$$Color\ difference\ \Delta E = 13.82 + 2.9X_1 - 0.38X_1X_3 - 0.80X_1^2 - 0.43X_2^2 + 0.41X_3^2 \quad (7)$$

Where: X_1 Infrared emitting power (IN)، X_2 Heating time (seconds), X_3 The emitter distance is (millimeters).

Figure 6 shows that ΔE increases with increasing IR power: from 9.79 at 350 W (20 mm, 60 s) to 16.27 at 1000 W (20 mm, 150 s), which is attributed to more intense browning of the tissue. Increasing the emitter distance at high powers reduces ΔE, while heating time has a negligible effect. The surface penetration of IR radiation (0.1–1 mm) maintains color stability by limiting thermal degradation and reducing Maillard reactions [16,4]. These findings are consistent with results from peeling peaches, kiwifruit, grapes, and jujubes [21,20,15,6].

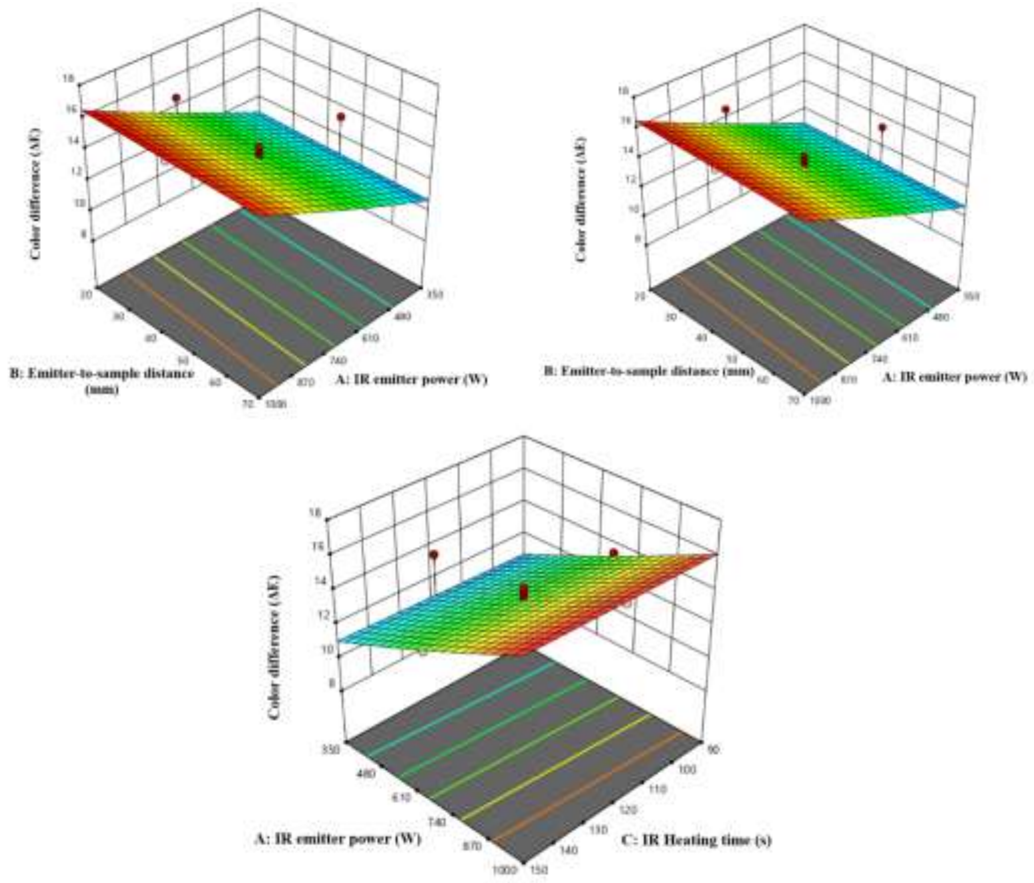


Fig. 6. The effect of infrared peeling operating parameters on color difference

3-3- Optimization of the infrared peeling system

The main objective of this study was to determine the optimal operating conditions for IR peeling of dried plums using RSM. Optimization was performed with a utility function approach with the aim of simultaneously minimizing moisture loss, skin thickness, surface temperature, and ΔE. The highest utility (0.55) was obtained at a power of 797.46 W, a distance of 70 mm, and a time of 107 s, which indicates a balance between effective skin loosening and minimal thermal damage to the flesh [4]. The relatively low utility (0.55) is due to the inherent conflict between the responses. In other words, the optimal conditions for reducing skin thickness (high power) do not fully correspond to the optimal conditions for maintaining color and reducing moisture (lower power). This phenomenon has also been reported in similar studies of tomato and peach peeling [4,6]. Despite the effectiveness of the RSM method in multi-response optimization, the limitations of quadratic models in fitting complex nonlinear relationships and the limited volume of experimental data (20 experiments) are factors affecting the resulting utility. For future studies, the use of hybrid approaches such as response surface methodology–Artificial neural network (RSM-ANN), applying cross-validation methods, and increasing the number of test points in the central composite design are proposed.For validation, three replicate experiments were performed under optimal conditions. Table 5 shows the high agreement between the predicted and experimental values (0.92R^2>) which indicates the robustness and reliability of quadratic models.

Table 5. Predicted versus experimental values of IR peeling performance parameters under optimal condition

Independent variable	Value	Response variable	Predicted	Experimental
IR emitter power (W)	46.797	Moisture loss (%)	0.60	0.30 ± 0.05
Irradiation duration (s)	107	Peel thickness (mm)	0.16	0.12 ± 0.01
Emitter distance to sample (mm)	70	Surface temp. (◦C)	35.53	40 ± 1
		Color difference (ΔE)	14.97	13.50 ± 0.5

4-3- The effect of alkaline method on plum yield and quality

Table 6 Effects of alkaline peeling using a 10% w/v solutionNaOH(100 g/l) at 85°C on yield and quality characteristics of plums. Effect of immersion time using one-way analysis of variance($p < 0.05$)was analyzed and showed significant differences in key parameters. The results show that moisture loss increases significantly with longer immersion time in alkaline solution (Table 6). Conversely, the Hue angle decreases with longer immersion, indicating a color change towards red. This color change is likely due to the combined effects of mass diffusion and complex biochemical reactions, including non-enzymatic browning processes such as the Maillard reaction and caramelization, which are accelerated by high temperature and alkaline environment.

Table 6. Analysis of variance (ANOVA) results for lye peeling performance parameters

Source of variations	degrees of freedom (df)	Mean squares	
		Moisture loss	Hue angle
Immersion time	2	*13.52	**28.3121
Error	6	39.0	51.0
Coefficient of variation (%)	-	71.6	65.1

Figure 7 shows the visual difference of plums peeled with hot alkali at different immersion times. At 70 s, peeling was difficult, but became significantly easier at 100 and 120 s. However, 120 s immersion caused significant color change (browning and surface redness), as confirmed by the sharp decrease in the Hue angle in Table 7. This phenomenon is attributed to the high temperature of the alkaline solution, which causes thermal stress in the mesocarp, ascorbic acid decomposition, and acceleration of non-enzymatic browning reactions (Maillard and caramelization). These findings are consistent with studies of alkaline peeling of kiwi, tomato, and jujube [22,21,10].

Table 7. Impact of immerse on time in hot lye on plum peeling performance metrics

Immersion time (s)	Moisture loss (%)	Hue angle (degree)
70	16.5 ± 0.44 c	81.79 ± 0.50 a
100	9.56 ± 0.35 b	55.50 ± 0.51 b
120	13.5 ± 0.29 a	23.46 ± 0.01 c

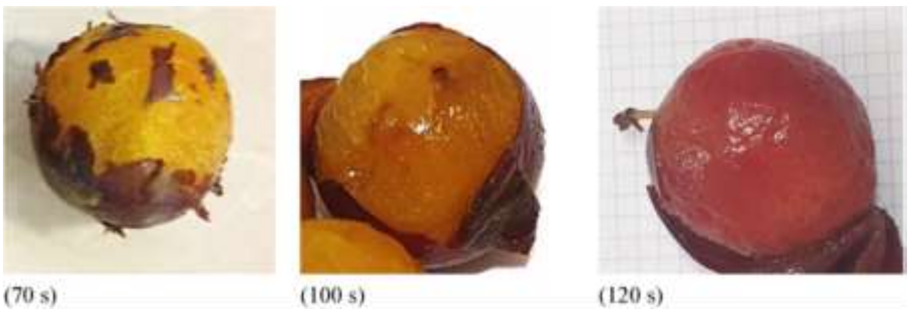


Fig. 7. Peeled plums after hot lye treatment at immersion times of 70 s, 100 s, and 120 s, illustrating changes in peelability and browning.

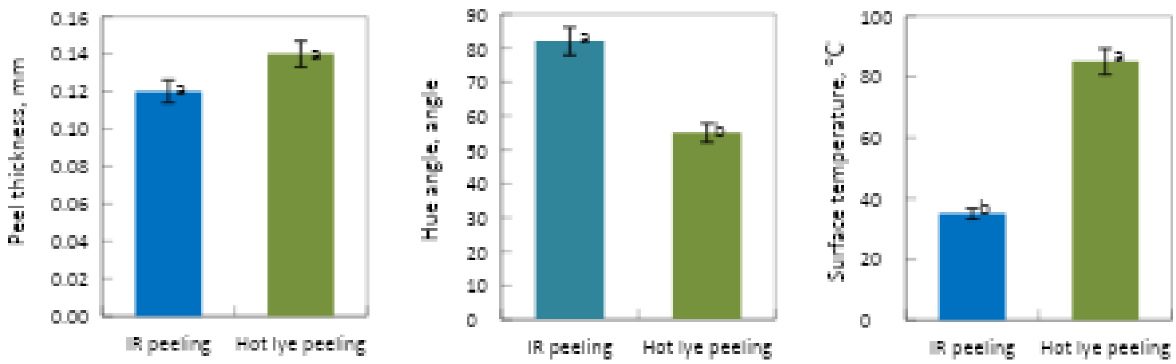
The optimal conditions for alkaline peeling of plums were determined to include 10% NaOH solution, temperature 85°C, and immersion time 100 seconds. Table 8 summarizes the yield and physicochemical properties of plums under these conditions. Although this method results in complete peeling (100%) due to chemical hydrolysis of the skin-flesh adhesion, it is associated with significant quality disadvantages: increased moisture loss (9.56%), removal of thicker skin (due to tissue hydrolysis), darker color (hue angle 55.5°), and reduced ascorbic acid content (10.5 mg/100 g).

Table 8. Peeling performance and physicochemical properties of plums under selected hot lye peeling conditions

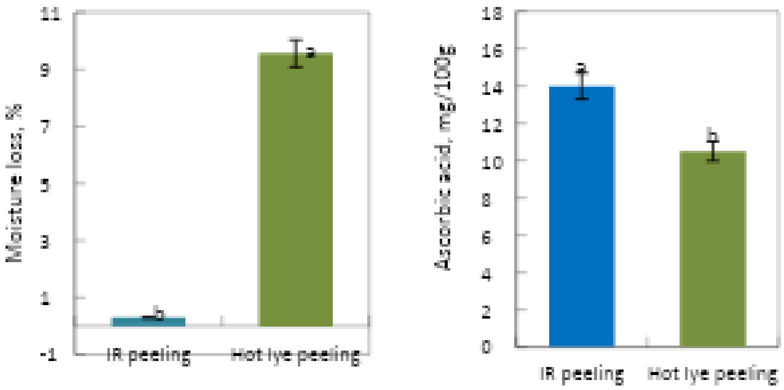
Peeling performance	Value	Physicochemical characteristics	Value
Moisture loss (%)	9.56	Hue angle (Degree)	55.50
Peel thickness (mm)	0.14	Ascorbic acid content (mg/100 g)	10.50

5-3- Comparison of dry peeling with infrared and alkaline method

The performance of the optimized IR method (797.46 W, 70 mm, 107 s) was compared with the conventional alkaline method (10% NaOH, 85 °C, 100 s). Key parameters were analyzed by one-way analysis of variance and Duncan's range test ($p< 0.05$). As can be seen in Figure 8, no significant difference in skin thickness was observed between the two methods (p < 0.01, respectively).±0.12 and 0.02±0.14 mm). However, the skin obtained by the IR method was uniform and intact, while the alkaline method resulted in a degraded and uneven skin, which is more suitable for the production of by-products such as fruit pulp [23]. Also, Figure 8 shows significant differences (*p*There was a significant difference (p < 0.01) in surface temperature, moisture loss and ascorbic acid between the two methods. The IR method had a lower surface temperature (1±40 vs. 2±85 degrees Celsius), less moisture loss (0.05±0.30% vs. 0.8±9.56%) and higher ascorbic acid retention (0.5±0.14 vs. 0.4±10.5 mg/100 g). These findings are consistent with previous studies on tomatoes [24] and plum drying [25]. The IR method is in line with the principles of circular economy by eliminating saline-alkaline wastewater [9]. Also, compared to steam peeling (which has been reported to cause 15–20% nutrient loss in peaches [6]), the IR method showed lower anthocyanin degradation (ΔE = 13.5 vs. 2.16) and higher ascorbic acid retention, confirming its effectiveness for heat-sensitive fruits such as plums.



(a) (b) (c)



(d) (and)

Fig. 8. Comparison of peeling performance parameters between dry-IR and lye methods: (a) Peel thickness, (b) Hue angle, (c) Surface temperature, (d) Moisture loss, (e) Ascorbic acid content.

4- Conclusion

This study confirmed the feasibility of dry infrared (IR) peeling as a sustainable alternative to the alkaline method in plum processing. The optimal conditions with the RSM method included an infrared emitting power of 797.46 W, a distance of 70 mm from the fruit, and a heating time of 107 s, which resulted in 0.30% moisture loss, 0.12 mm skin thickness, 40 °C surface temperature, and ΔE = 13.50 ($R^2 > 0.92$). Compared with the alkaline method (10% NaOH, 85 °C, 100 s), the IR method performed better in key indicators: lower moisture loss (0.30% vs. 9.56%), lower surface temperature (40 vs. 85 °C), and higher ascorbic acid retention (14% vs. 10.5 mg/100 g). The IR method also minimized environmental impacts by eliminating chemical wastewater. For industrial application, future studies should focus on optimizing the emitter array, increasing energy efficiency, and evaluating the capital and maintenance costs of the system. Overall, IR technology is introduced as a green and effective solution for fruit processing, in line with global trends of chemical-free food production.

Data access

Research data are available upon request from the authors. All data used in this study are presented throughout the text and in tables and figures.

Conflict of interest

There are no items to declare.

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Authors' Contributions

Dariush Shaterabadi: Writing the initial version, software, data analysis; Ali Mashaallah Kermani: Writing, reviewing and editing, idea generation, supervisor, methodology, data analysis, project manager, methodology; Hojjatollah Akbari: Methodology, data analysis, software.

5-Resources

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مقاله علمی_پژوهشی

بهینه‌سازی پوست‌گیری خشک آلو با گرمایش مادون قرمز تابشی به روش سطح پاسخ و ارزیابی ویژگی‌های فیزیکوشیمیایی در مقایسه با روش قلیایی

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چکیده

پوست‌گیری یکی از مراحل کلیدی فرآوری آلو است که روش‌های مرسوم استفاده از محلول قلیایی با چالش‌هایی نظیر تلفات بالای پوست‌گیری، راندمان پایین فرآیند و مصرف زیاد آب و انرژی، تولید فاضلاب شیمیایی و کاهش کیفیت محصول همراه است که در نهایت صرفه اقتصادی را کاهش می‌دهد. این پژوهش به بررسی امکان‌سنجی و بهینه‌سازی پوست‌گیری خشک آلو با استفاده از گرمایش تابشی مادون قرمز به عنوان جایگزین پایدار پرداخته است. سامانه آزمایشگاهی شامل ساطع‌کننده سرامیکی مادون قرمز و غلتک‌های چرخان طراحی شد. اثرات توان ساطع‌کننده (۳۵۰ – ۱۰۰۰ وات)، زمان گرمایش (۹۰ – ۱۵۰ ثانیه) و فاصله ساطع‌کننده (۲۰ – ۷۰ میلی‌متر) بر عملکرد پوست‌گیری و خصوصیات فیزیکوشیمیایی (تلفات رطوبت، ضخامت پوست، دمای سطح، ویژگی تغییر رنگ (ΔE) و محتوای اسید اسکوربیک) با روش سطح پاسخ و طرح مرکب مرکزی ارزیابی گردید. نتایج نشان داد که شرایط بهینه (توان ۷۹۷/۴۶ وات، فاصله ۷۰ میلی‌متر، زمان ۱۰۷ ثانیه) به از دست دادن رطوبت ۰/۳۰ درصد، ضخامت پوست ۰/۱۲ میلی‌متر، دمای سطح ۴۰ درجه سلسیوس، ΔE برابر ۱۳/۵ و محتوای اسید اسکوربیک ۱۴ میلی‌گرم در ۱۰۰ گرم منجر شد. در مقایسه با پوست‌گیری قلیایی مرسوم (سدیم هیدروکسید ۱۰ درصد، دمای ۸۵ درجه سلسیوس، مدت زمان غوطه‌وری ۱۰۰ ثانیه)، روش مادون قرمز اتلاف رطوبت را به طور چشمگیری کاهش داد (۰/۳۰ درصد در مقابل ۹/۵۶ درصد)، رنگ روشن‌تری (زاویه هیو ۸۲ درجه در مقابل ۵۵ درجه) حفظ کرد و محتوای اسید اسکوربیک را بیشتر نگه داشت (۱۴ در مقابل ۱۰/۵ میلی‌گرم در ۱۰۰ گرم)، ضمن حذف کامل فاضلاب شیمیایی. این یافته‌ها پتانسیل بالای فناوری گرمایش مادون قرمز را به عنوان روشی سبز، کارآمد و با کیفیت بالا برای فرآوری آلو تأیید می‌کند.