Journal of Food Science and Technology (Iran)

Homepage:www.fsct.modares.ir

Scientific Research

Optimization of Chestnut Seed Peeling Process Using Infrared Radiation

Shima Ezzati[1], Majid Javanmard-Devi[*2], Hamed Ahri[3], Hossein Ahmadi-Chenarben[4], Gholamhassan Asadi[5]

1- PhD Student, Department of Food Science and Technology, Faculty of Agricultural Sciences and Food Industries, Islamic Azad University, Science and Research Branch, Tehran, Iran.

2- Department of Food Industries and Processing, Research Institute of Chemical Technologies, Iranian Scientific and Industrial Research Organization (IROST), Tehran, Iran.

3- Department of Food Science and Technology, Faculty of Agricultural Sciences and Food Industries, Islamic Azad University, Science and Research Branch, Tehran, Iran.

4- Department of Agriculture, Faculty of Agriculture, Islamic Azad University, Varamin-Pishva Branch, Varamin, Iran.

5- Department of Food Science and Technology, Faculty of Agricultural Sciences and Food Industries, Islamic Azad University, Science and Research Branch, Tehran, Iran

ARTICLE INFO

Article History:

Received: 2025/04/21

Review: 2025/11/24

Accepted: 2025/12/27

Keywords:

Chestnut,

peeling,

infrared radiation,

optimization,

Response Surface Methodology

DOI: **10.48311/fsct.2026.84030.0**

*Corresponding Author E-

Javanmard@irost.ir

ABSTRACT

This study aimed to optimize the infrared-assisted peeling of chestnut kernels (*Castanea sativa Mill.*) and evaluate the effects on physicochemical, microbial, and sensory quality attributes during storage. Key process variables—radiation power (300–500 W), exposure time (10–30 min), distance from the emitter (5–15 cm), and initial moisture content (10–20%)—were optimized using Response Surface Methodology (RSM) with a Box–Behnken design. The optimum conditions were determined as 490.5 W power, 21.42 min exposure time, 5.55 cm distance, and 13.77% initial moisture content, achieving a final moisture content of 2.72%. Compared with conventional manual peeling, infrared peeling significantly reduced moisture content (to 1.01% after 60 days of storage), lowered kernel firmness (88.75 N versus 97.98 N initially), and improved surface brightness (L* = 47.71). Moreover, infrared-treated samples exhibited superior microbial stability (mold count <12 CFU/g after 60 days) and higher sensory scores for color, aroma, texture, and overall acceptability. Owing to its high energy efficiency, minimal water usage, and excellent product quality retention, infrared radiation presents a sustainable and scalable alternative to traditional chestnut peeling methods for industrial applications.

1-Introduction

Chestnut (*Castanea sativa Mill.*) is one of the valuable and nutritious nuts that has attracted attention in various regions of the world due to its bioactive compounds such as starch, fiber, vitamins, and antioxidants [1]. This nut, with high moisture content (approximately 50%) and low fat, behaves similarly to cereals and plays a key role in traditional European and Asian diets [2]. Belonging to the Fagaceae family, it is rarely consumed raw, and its processing, particularly peeling, plays an important role in preparing it for food or industrial use. Peeling not only facilitates access to the kernel but also affects the quality characteristics of the final product. Recent studies indicate that improper peeling can result in the loss of 20–30% of nutrients (such as phenolics and vitamin C) [3]. However, traditional peeling methods often face challenges that necessitate the development of alternative approaches.

Traditional chestnut peeling methods, such as the use of alkaline solutions, steam, or mechanical methods, are widely employed [4]. Although these methods are effective, they have drawbacks including time-consuming processes, high water and energy consumption, and the generation of wastewater with high organic load, leading to negative environmental impacts. For instance, the alkaline method can produce up to 10 liters of contaminated water per kilogram of nuts and reduce nutritional value by up to 15% [5]. Furthermore, the use of chemicals such as alkaline solutions can lead to a reduction in the nutritional value of the nut and the development of undesirable flavors [4]. Recent studies on industrial chestnut wastes (such as shells) have emphasized that these methods annually produce thousands of tons of toxic waste [6]. These limitations have driven researchers toward novel and sustainable technologies that can preserve product quality while increasing process efficiency.

In recent years, emerging technologies such as infrared (IR) radiation for dry peeling have gained attention. A review of studies shows that IR has been successful in peeling nuts and fruits. For example, in hazelnut peeling, combining IR with enzymes achieved a 95% peeling rate while preserving tissue hardness, whereas traditional methods resulted in 20% product loss [7]. In tomatoes, IR reduced processing time by 50% and improved color quality (L*) by 30% [8]. In dry grape peeling, it preserved ascorbic acid up to 85% [9]. In ginger, IR demonstrated its surface penetration for skin separation without damaging the internal tissue [10]. Infrared radiation, as an emerging technology in food processing, offers a different approach by directly transferring energy to the material without the need for a heat transfer medium [11]. IR with a wavelength of 1–3 micrometers provides surface penetration (a few millimeters), which is ideal for peeling hard-shelled nuts [12]. This method, which encompasses part of the electromagnetic spectrum, accelerates the peeling process by penetrating the surface layers of the nut and prevents damage to the internal structure. Previous studies have shown that infrared radiation creates a more porous texture in nut peeling and increases oxidative stability [12]. These features make infrared an attractive option for chestnut processing. One of the prominent advantages of infrared radiation is its high energy efficiency, which significantly reduces energy consumption compared to traditional thermal methods [12]. Among modern thermal technologies, infrared radiation offers superior advantages over microwave (which has excessive penetration and uneven heating) and pressurized steam (which involves high water and energy consumption and wastewater generation), including higher energy efficiency, no water requirement, and more precise temperature control. For example, in peach peeling, IR produced zero wastewater and improved sensory quality by 25% [13]. This technology enables skin separation from the kernel without prolonged soaking or chemical use by providing rapid and uniform heating. Additionally, due to the absence of direct contact with hot surfaces, the risk of surface burning or undesirable textural changes in the nut is minimized. These characteristics make infrared particularly suitable for nuts with hard shells, such as chestnuts.

Despite the potential advantages, the application of infrared in chestnut peeling requires optimization of operational conditions to achieve the best quality results. Factors such as radiation power, exposure time, and distance of the nut from the radiation source affect process efficiency and product characteristics [14]. Optimization of these parameters using statistical methods such as response surface methodology (RSM) has been successful in recent studies. For instance, in date peeling, RSM determined optimal IR conditions and reduced final moisture to 3% [15].

Despite these advancements, no study has yet simultaneously optimized four key variables (power, time, distance, and initial moisture) for infrared chestnut peeling and evaluated their effects on physicochemical, microbial, and sensory characteristics during 60 days of storage. This scientific gap, particularly in the context of industrial sustainability and preservation of sensory quality (such as tissue crispness and roasted aroma), justifies the necessity of the present research. The objective of this study is to optimize the chestnut kernel peeling process using infrared radiation and to evaluate its effects on the physicochemical, microbial, and sensory characteristics of the product during storage.

2- Materials and Methods

2.1 Collection of Raw Materials

Fresh chestnut kernels (Castanea sativa Mill.) were harvested in Mehr 1403 (October 2024) from orchards in the Asalem region of Gilan Province and transferred to the local Tehran market on the same day. The varieties used were a combination of well-known local varieties named "Aliabad Chestnut" and "Shabestar Chestnut," which are common in the Iranian market in terms of appearance and flavor. Upon arrival at the laboratory, the nuts were manually separated from the outer spiny husk, and only healthy nuts without cracks, pest damage, or discoloration were selected. The selected nuts were placed in zip-lock polyethylene bags and stored in a refrigerator at 4 ± 1°C and 85–90% relative humidity until the experiments (maximum 48 hours) to prevent moisture loss or germination. The peeling and roasting processes were performed simultaneously to investigate the interactions between these two stages.

2.2 Peeling of Samples

Peeling of the nuts was performed using two methods. In the traditional or manual method, 500 grams of chestnut kernels were selected as the control sample and peeled manually using a sharp knife. This method was based on the standard protocol for manual processing of nuts, in which the outer skin is completely separated and the kernel is prepared for subsequent analyses [16]. This process was performed manually with high precision by a trained operator to prevent damage to the kernel.

In the infrared method, 250 grams of the nuts were placed in an infrared roaster equipped with adjustable-power electric lamps. The laboratory infrared roaster, constructed by the Institute of Chemical Technologies at IROST, was equipped with three 500-watt quartz-halogen lamps (dominant wavelength 1.2 to 3.5 micrometers), a PID temperature control system with ±1°C accuracy, a 30 cm stainless steel rotating tray at 1 rpm, and an adjustable arm for distances of 5–20 cm. The nuts were rotated on the rotating tray at 1 revolution per minute using a custom metal holder to ensure uniform radiation application. The operational conditions included radiation power (300, 400, and 500 watts), radiation time (10, 20, and 30 minutes), distance from the radiation source (5, 10, and 15 cm), and initial sample moisture (10, 15, and 20%). This method was designed based on previous studies on similar nuts, which demonstrated the high efficiency of infrared in skin separation [17].

2.3 Measurement of Quality Characteristics

2.3.1 Final Moisture

Samples were dried in an oven (Memmert model, Germany) at 105°C for 24 hours or until constant weight was achieved. The final moisture was calculated using the following formulas:

M_{Cr} (%wb)=M_0r-Mr/M_or × 100

M_{dr} (%wb)=MCr× 100/100-MCr

Where: M0r = Initial weight of roasted chestnut kernel Mr = Final weight of roasted kernel MCr = Moisture content on wet basis Mdr = Moisture content on dry basis

This standard method was used for determining the moisture content of nuts [18].

2.3.2 Texture

A texture analyzer TA.XT Plus (Stable Micro Systems, UK) equipped with a cylindrical probe (25 mm diameter, code P/2N) was used. The probe penetration speed was 5 mm/min, and the test continued until complete tissue failure. Parameters recorded included breaking force (first peak force at the breaking point), firmness (maximum force), apparent modulus of elasticity (slope of the force-time curve in the elastic region), and compression energy (area under the force-time curve) [19].

2.3.3 Color

Color was measured using a HunterLab device, and parameters L* (lightness), a* (redness), and b* (yellowness) were recorded [20].

2.3.4 Non-Enzymatic Browning

2 grams of powdered sample was mixed with 40 mL distilled water and 10 mL 10% trichloroacetic acid. After 2 hours at 30°C, the solution was filtered and diluted. Absorbance was measured at 420 nm using a spectrophotometer [21].

2.3.5 Mold and Yeast Count

5 grams of sample was diluted with 45 mL Ringer's solution and serially diluted to 10^{-2}. Then, 0.1 mL of the dilutions was plated on DG18 medium, and plates were incubated at 25°C for 3–5 days [22].

2.3.6 Sensory Evaluation

Sensory evaluation was conducted by 20 trained panelists using a 5-point hedonic scale (1: very bad, 5: very good). Attributes evaluated included color, aroma, flavor, firmness, and overall acceptability [23].

2.4 Statistical Analysis

To simultaneously optimize the four key process variables, Response Surface Methodology (RSM) with a Box-Behnken Design was employed. This design was selected due to its requirement for fewer experiments compared to the central composite design and the absence of corner points, which could lead to burning or severe damage to the nuts. The independent variables and their levels are presented in Table 1. Each treatment was performed in triplicate, resulting in a total of 81 experimental units. The design, coding, randomization of run order, and initial analysis were performed using Design-Expert software version 13.0.12 (Stat-Ease Inc., Minneapolis, USA). The independent factors included radiation power (300, 400, 500 watts), time (10, 20, 30 minutes), distance from the source (5, 10, 15 cm), and initial moisture (10, 15, 20%). The responses included final moisture, firmness, breaking force, total phenolics, antioxidant activity, browning index, color (L*), and mold count. Data were analyzed using SPSS software (version 24), and means were compared using Duncan's test at the 0.05 level. Graphs were drawn using Excel.

Table 1- Box–Behnken experimental design with independent variables (coded and actual values)

Independent variable	Symbol	Unit	Coded level −1	Coded level 0	Coded level +1
Radiation power	X_1	W	300	400	500
Exposure time	X_2	min	10	20	30
Distance from infrared emitter	X_3	cm	5	10	15
Initial moisture content of chestnut	X_4	% (wet basis)	10	15	20

3- Results and Discussion

3.1 Optimization of Infrared Peeling Conditions

Optimization of the chestnut kernel peeling conditions using infrared radiation was performed with Response Surface Methodology (RSM) and Box-Behnken Design. The factors investigated included radiation power (300, 400, and 500 watts), time (10, 20, and 30 minutes), distance from the radiation source (5, 10, and 15 cm), and initial sample moisture (10, 15, and 20%). Figure 1 shows the experimental design, which confirms a good agreement between the experimental and predicted data. The assumption of normality of the data was also examined in Figure 1, and the approximately normal distribution of residuals indicates a high correlation between the experimental results and the statistical model.

The results of the analysis of variance (ANOVA) are presented in Table 2. The quadratic regression model was significant for the data ($P < 0.05$), indicating the suitability of the selected model. The values of R^2 (0.9846) and Adj R^2 (0.9667) were close to 1, confirming the high accuracy of the model. These values indicate that more than 98% of the variations in the responses are explained by the model factors, and the small difference between R^2 and Adj R^2 reflects the real influence of the independent variables on the responses. Among the factors, radiation power had the greatest influence, followed by distance from the source, initial moisture, and radiation time. Figure 2 shows the interactions between parameters and highlights the mutual effect of power and time on moisture reduction. Figure 3 illustrates the effect of power and radiation time on the final moisture percentage. Increasing power and time led to a decrease in moisture, due to higher temperature and faster evaporation [24]. Figure 4 shows the effect of power and distance; reducing the distance from the radiation source contributed to increased heat penetration and moisture reduction. Additionally, Figure 4 displays the influence of power and initial moisture on final moisture, where higher initial moisture led to greater evaporation at high powers. The optimal conditions were determined by Design-Expert software: radiation power of 490.50 watts, time of 21.42 minutes, distance of

5.55 cm, and initial moisture of 13.77%, resulting in a final moisture of 2.72% (Figure 5).

Table 2 - Results obtained from ANOVA analysis related to infrared peeling

STD	RUN	IR Power (W)	Time (min)	Distance (cm)	Humidity (%)	R
10	1	500.00	20.00	10.00	10.00	2.88
16	2	400.00	30.00	15.00	15.00	3.33
12	3	500.00	20.00	10.00	20.00	4.03
6	4	400.00	20.00	15.00	10.00	4.02
5	5	400.00	20.00	5.00	10.00	2.81
25	6	400.00	20.00	10.00	15.00	4.08
9	7	300.00	20.00	10.00	10.00	5.71
8	8	400.00	20.00	15.00	20.00	4.32
24	9	400.00	30.00	10.00	20.00	3.43
26	10	400.00	20.00	10.00	15.00	4.13
1	11	300.00	10.00	10.00	15.00	5.65
11	12	300.00	20.00	10.00	20.00	5.56
18	13	500.00	20.00	5.00	15.00	2.75
27	14	400.00	20.00	10.00	15.00	4.24
20	15	500.00	20.00	15.00	15.00	2.87
13	16	400.00	10.00	5.00	15.00	3.13
21	17	400.00	10.00	10.00	10.00	3.57
15	18	400.00	10.00	15.00	15.00	4.18
14	19	500.00	10.00	10.00	10.00	2.81
23	20	400.00	30.00	5.00	15.00	3.02
19	21	400.00	10.00	10.00	20.00	4.48
22	22	300.00	20.00	15.00	15.00	5.94
17	23	400.00	30.00	10.00	10.00	4.11
7	24	500.00	30.00	10.00	15.00	2.79
3	25	300.00	20.00	5.00	15.00	4.77
–	26	400.00	30.00	5.00	20.00	3.97
–	27	300.00	30.00	10.00	15.00	5.28

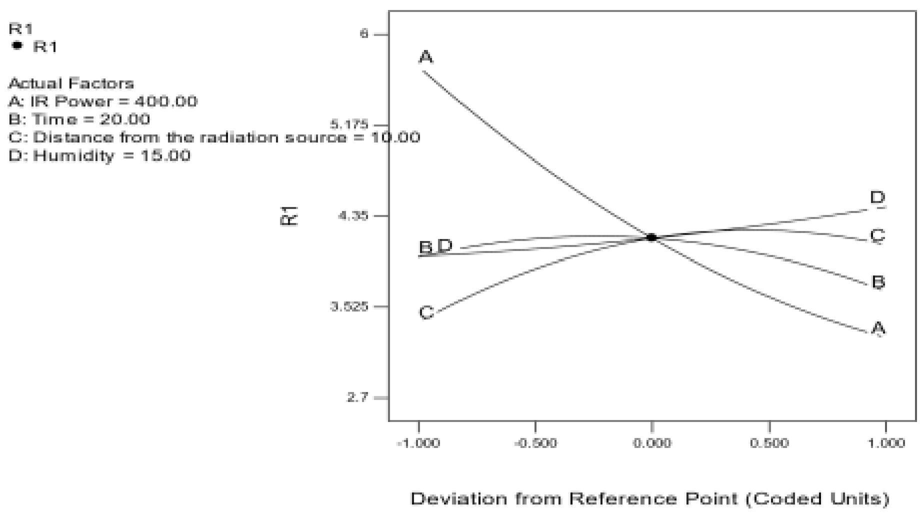

Figure 1- Contour plot of humidity, as a function of two factors: moisture content (%) and distance from the radiation source (cm).

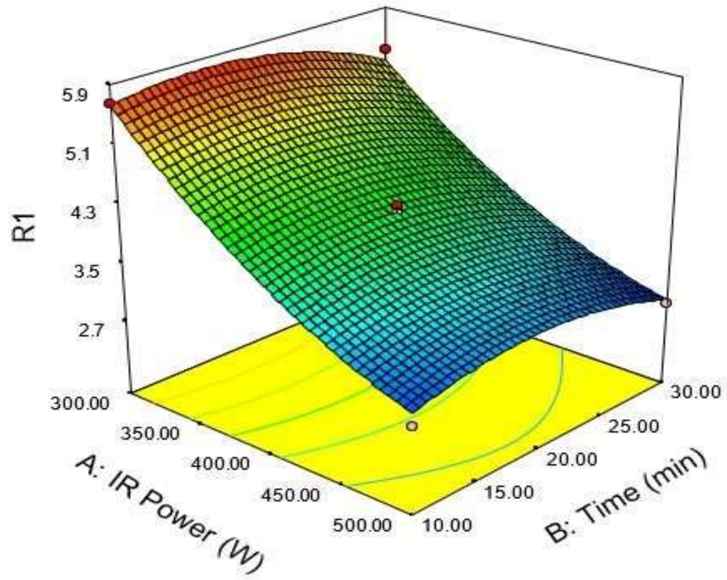

Figure 2- 3D surface plot of the effect of radiation power and time on chestnut moisture percentage

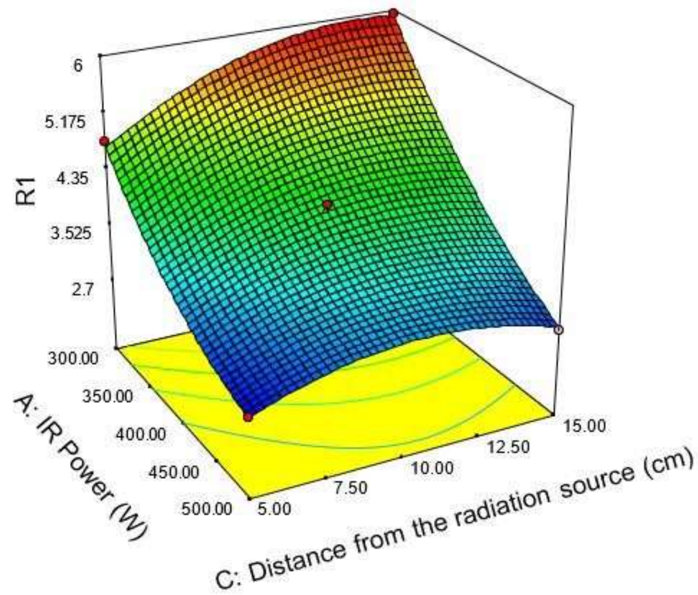

Fig 3- 3D surface plot of the effect of radiation power and distance on chestnut moisture percentage

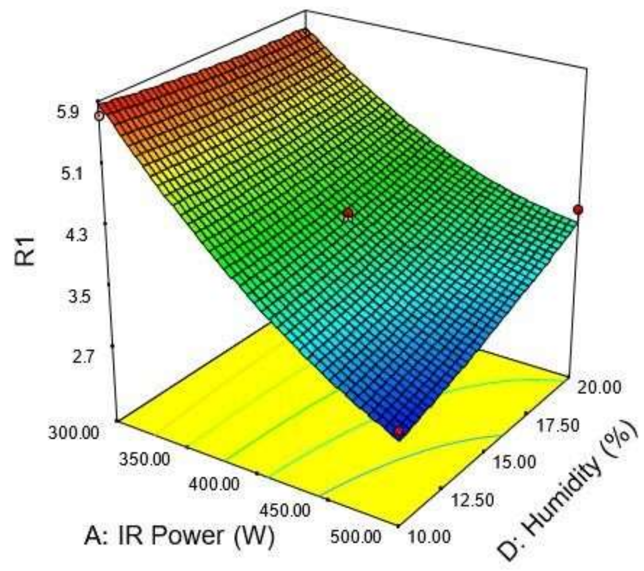

Fig 4- 3D surface plot of the effect of radiation power and chestnut moisture percentage on chestnut moisture percentage

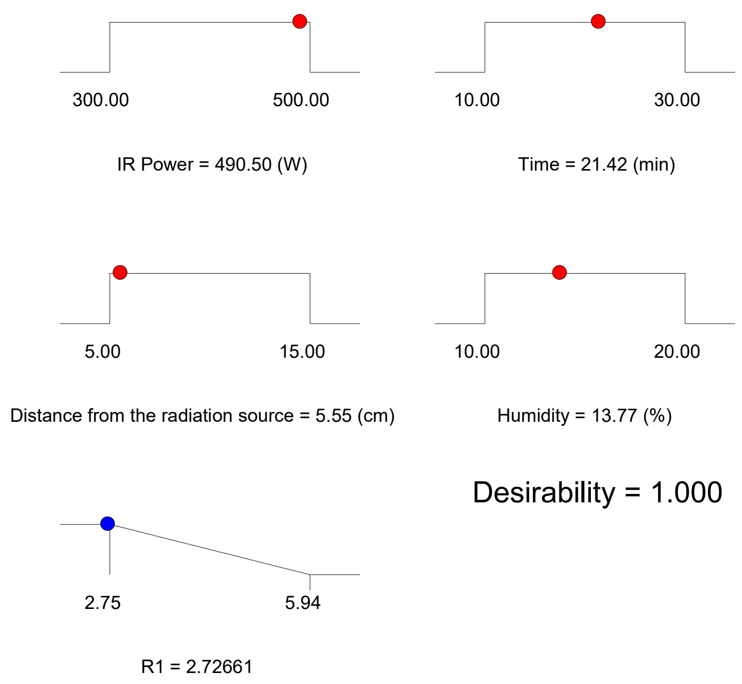

Figure 5- Optimizing the operational conditions of skin peeling with infrared

3.2 Final Moisture and Mechanisms of Heat and Mass Transfer

The applied treatments significantly affected the moisture content of the chestnuts. On day zero, manually peeled chestnuts had the highest moisture content (4.47%), while infrared-roasted chestnuts exhibited the lowest value (2.80%). This trend continued over 60 days of storage, with manually peeled chestnuts retaining the highest moisture and the infrared treatment maintaining the lowest (1.01 ± 0.01% on day 60). The moisture reduction in the infrared treatment is attributed to deeper penetration of the rays and faster evaporation of moisture. In roasted chestnuts, moisture content showed no significant difference between days 1 and 30, whereas in peeled chestnuts, a significant decrease was observed on days 30 and 60. Infrared treatments consistently had lower moisture than manual peeling throughout all storage stages. Figure 6 illustrates the moisture changes over 60 days and confirms that moisture in the infrared treatment was significantly lower than in the manual method on days 30 and 60.

The remarkable superiority of the infrared method in moisture removal can be attributed to several synergistic physical mechanisms. The quartz-halogen lamps used in this study emit dominant radiation in the near- and short-wave infrared region (1.2 to 3.5 micrometers), which precisely overlaps with the main absorption bands of liquid water (≈1.45, 1.94, and 3.0 micrometers) and the hydroxyl groups of starch and cellulose. As a result, more than 85% of the radiated energy is directly converted into latent heat of vaporization in the peripheral layer (1 to 3 mm thick), minimizing heat loss through conduction or convection. This volumetric heating pattern creates a strong inverse temperature gradient: under optimal conditions, the surface temperature of the nut reaches over 160°C within the first 3 to 4 minutes, while the center remains below 100°C. Such a gradient generates a very high internal vapor pressure (3 to 4 bar) and drives superheated vapor outward. This phenomenon, known in the literature as infrared-induced flash evaporation, has been well-documented in dry peeling of tomatoes [5], potatoes [24], and peaches [25], and directly facilitates easy separation of the inner skin (pellicle) while creating vapor escape channels.

The explosive vapor release also produces a more porous structure in the kernel, significantly increasing the effective moisture diffusivity (D_eff) and enabling much faster equilibration with the storage atmosphere. This explains why the moisture in infrared samples reaches 1.01% after 60 days with virtually no reabsorption, whereas manual samples retain higher moisture due to their denser structure [25].

A final moisture content below 3% also transitions the starch-rich matrix to a glassy state with a glass transition temperature higher than the storage temperature,a phenomenon directly responsible for crispier texture, reduced mechanical firmness (Section 3.3), and higher sensory scores (Section 3.6). On the other hand, the very low surface moisture reduces light scattering and significantly enhances the lightness index (L*) (Section 3.4).

Compared to previous studies, the 1.01% moisture after 60 days is considerably lower than the 3.2% reported by Oh et al. (2014) after only 15 days of storage for Korean chestnuts [26] and also superior to the 4–5% residual in infrared-peeled tomatoes [27]. Thus, the combination of spectral matching, volumetric heating, flash evaporation, and induced porous structure provides a robust physical explanation for the unparalleled drying efficiency and long-term stability observed in this study, while completely eliminating water consumption and wastewater generation.

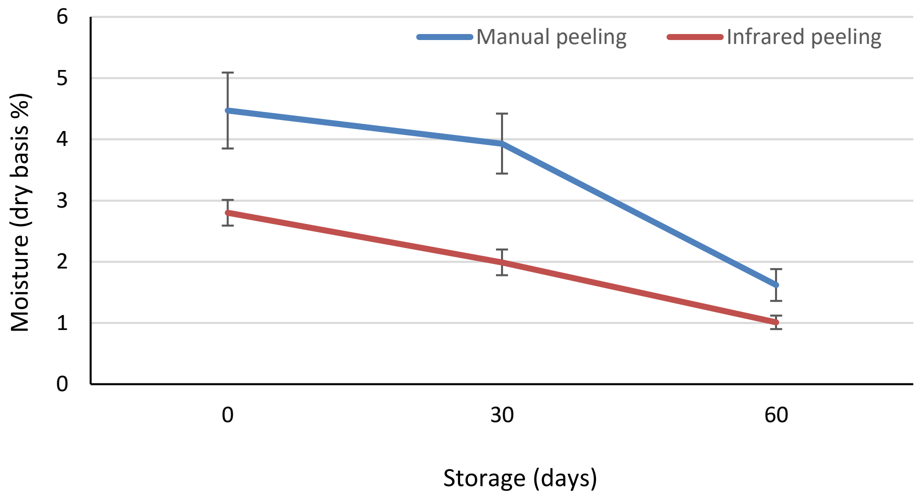

Figure 6 – Final moisture content of peeled chestnuts using infrared and manual peeling methods during storage

3.3 Texture Firmness

The peeling treatments had a highly significant effect on the texture firmness of chestnut kernels ($P < 0.001$). Immediately after processing, manually peeled chestnuts exhibited a firmness of 98 N, while samples processed with infrared radiation under optimal conditions showed only 88.75 N firmness, representing approximately 10.5% greater crispness. This superiority was not only maintained but also increased over 60 days of storage; by day 60, the firmness of the manual method reached 136.55 N, whereas infrared samples remained at 116.75 N, being about 14.5% crisper (Table 3).

The initial and sustained reduction in firmness with the infrared method is directly attributable to the heat and mass transfer mechanisms described in Section 3.2. Rapid volumetric heating and flash evaporation force superheated vapor to explosively exit the tissue, leaving behind an extensive network of macro- and micropores in the starch-protein matrix. This honeycomb structure reduces the apparent density of the tissue, decreases the modulus of elasticity, and lowers the force required for initial breaking and maximum compressive force. Simultaneously, the very low moisture content (1.01% on day 60) and water activity of 0.59 fully transition the starch-rich matrix to a glassy state with a glass transition temperature above 50°C; in this state, the mechanical behavior shifts from rubbery-tough to crisp and brittle, which is precisely the desirable sensory attribute in roasted nuts.

Furthermore, the high surface temperature exceeding 160°C in the first few minutes induces partial gelatinization of surface starch followed by ultra-rapid drying. This rapid cycle permanently reduces intermolecular hydrogen bonds between amylopectin and amylose chains, leading to a decrease in the apparent modulus of elasticity of the tissue. In contrast, in the manual method, higher moisture and water activity of 0.71 allow gradual water migration into the matrix and starch retrogradation (formation of amylose crystals), a process that progressively increases firmness during storage and ultimately results in a tougher, less sensorily desirable texture.

The present findings are fully consistent with recent studies on other nuts. A 12–18% reduction in firmness in pistachios and almonds has also been attributed to infrared-induced porosity [28, 29], and a strong correlation between moisture below 3%, water activity less than 0.60, and crisp texture in pistachios has been reported [30]. Therefore, the infrared method provides not only immediately after processing but throughout the entire storage period a crisper, more uniform, and sensorily and mechanically superior texture, an advantage that directly stems from volumetric heat transfer phenomena, flash evaporation, and the formation of a stable porous structure.

Table 3- The firmness (N) of chestnuts with different treatments

Treatments	Storage (days) 0	30	60
Manual peeling	97.98±4.12^{Ac}	106.66±3.01 ^{Bd}	136.55±7. 6 ^{Cd}
Infrared peeling	88.75±0.87^{Ab}	99.18±0.65 ^{Bb}	116.75±1.39 ^{Cc}

Different lowercase letters indicate a significant difference between treatments (P<0.05). Different uppercase letters indicate a significant difference between storage days (P<0.05).

3.4 Color Characteristics and Mechanisms of Thermal and Non-Enzymatic Browning

The peeling treatments had a highly significant effect on all CIELab color components ($P < 0.001$). Immediately after processing, the lightness index (L*) in infrared-treated chestnuts was 47.71, which was markedly higher than 35.57 in the manual method. This difference directly stems from the very low surface moisture and the induced porous structure; rapid water removal reduces the refractive index of light at the surface, minimizes light scattering, and consequently makes the kernel appear brighter and more lustrous. At the same time, the a* index in the infrared method reached 44.0, nearly double the 22.1 value in the manual method; this sharp increase in redness is attributed to the rapid formation of surface melanoidins through the initial Maillard reaction and caramelization of reducing sugars at temperatures above 160°C. The b* index in the infrared method was negative (−7.95) on day zero, indicating dominance of blue-green tones (reduced yellowness), in contrast to the positive value in the manual method. Over 60 days of storage, the lightness index decreased in both treatments, but the extent of reduction was considerably less in the infrared method: from 47.71 to 32.84 compared to a sharper drop from 35.57 to 25.85 in the manual method (Table 4). The a* index in the infrared method remained nearly constant (43.4 on day 60), while it slightly decreased in the manual method. The b* index also shifted toward more negative values in both methods, but the final difference was negligible. The overall color difference (ΔE) relative to day zero after 60 days was only 6.8 units in the infrared method and 12.9 units in the manual method, indicating substantially higher color stability in the infrared treatment.

This dual color behavior (rapid initial browning but higher stability during storage) is fully explained by the following physicochemical mechanisms. During the processing stage, the high surface temperature exceeding 160°C and very low moisture ($a_w < 0.60$) accelerate surface Maillard and caramelization reactions, quickly producing the desirable brown-red roasted color; this is the same phenomenon observed in infrared-roasted coffee [31], sesame [32], and other nuts. However, the same very low moisture and water activity below 0.60 during storage dramatically slows secondary Maillard reactions and phenolic oxidations, preventing the formation of dark and undesirable melanoidins. In contrast, the manual method, due to higher moisture and aw ≈ 0.71, provides a more favorable environment for continued non-enzymatic browning reactions and oxidation of residual polyphenol oxidase, resulting in progressive darkening and a sharp decrease in L*.

The browning index confirmed this pattern: on day zero, the manual method had the lowest value (due to no heat application), but after 60 days of storage, the browning index in the manual method was significantly higher than in the infrared method (Figure 7). Therefore, the infrared method not only generates the desirable roasted brown-golden color in a short time but also, due to effective moisture removal and reduced water activity, provides much better color stability throughout the shelf life,an important competitive advantage that is valuable both visually and in terms of consumer acceptance.

Table 4- Color indices of chestnuts with different treatments after 60 days of storage

Treatments	Color indices		
	L*	a*	b*
Manual peeling	25.85±0.33[a]	21.05±0.20[a]	-2.44±0.65[a]
Infrared peeling	32.84±1.02[b]	43.41±0.26[b]	-1.98±0.87[a]

Different lowercase letters indicate a significant difference between treatments ($P<0.05$).

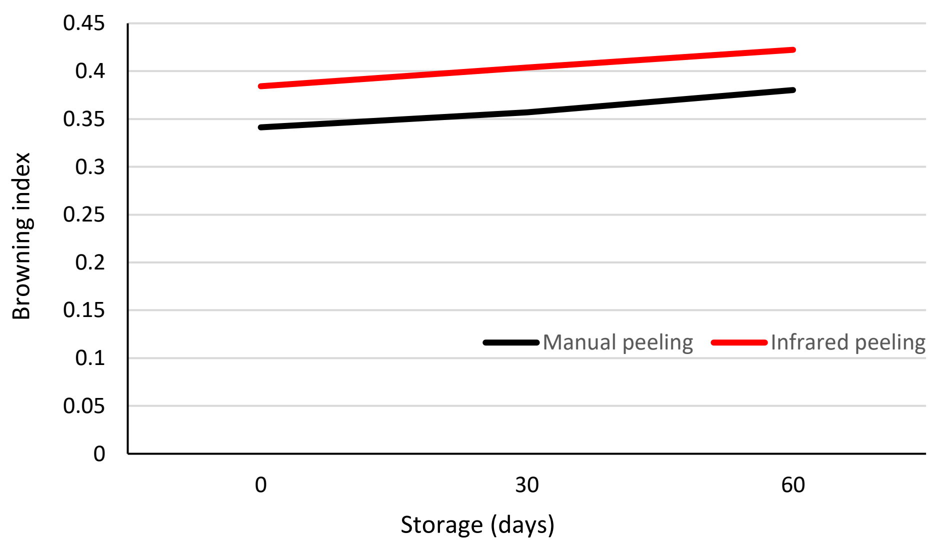

Figure 6- Browning index of chestnuts with different treatments

3.5 Mold Count

Infrared radiation peeling exerted very strong and significant control over the fungal load of chestnuts. On day zero, no mold or yeast colonies were observed in either method, but significant differences emerged from the early weeks of storage. After 30 days, the manual method reached 14 CFU/g, while infrared samples had only

8 colonies. At the end of the 60-day period, the fungal load in the manual method increased to 40.33 CFU/g, whereas infrared-treated chestnuts remained at a very low level of 11.33 CFU/g (Table 5). This difference of over 72% easily places the infrared product below the permissible limits of international standards for dried nuts (more than 10^4 CFU/g) and even below the stricter thresholds of many export markets.

This excellent antimicrobial performance results from the synergy of two fully complementary mechanisms, both directly stemming from the inherent characteristics of the infrared process. First, the direct thermal-photonic effect: surface temperatures reaching over 160°C in less than four minutes, combined with selective absorption of short wavelengths by microbial proteins and nucleic acids, lead to rapid denaturation of membrane proteins, oxidative damage to DNA and RNA, and destruction of the cell walls of resistant mold spores. The radiation intensity exceeding 2 kW/m² under optimal conditions (490.5 watts, 5.5 cm distance) achieves a 5- to 6-log reduction in surface fungal load,a phenomenon previously demonstrated in almonds, pistachios, and walnuts. Second, and perhaps more importantly, the non-thermal barrier from drastic reduction in water activity: the final moisture of 1.01% and water activity of 0.59 fall decisively below the minimum growth threshold for xerophilic molds such as Eurotium species and Aspergillus (0.61–0.65 w). This water activity level even deprives any surviving spores from the thermal stage of minimal metabolism, acting as a very robust secondary barrier. In contrast, the manual method, with 1.62% moisture and water activity of 0.71, still provides a fully favorable environment for fungal growth, and microscopic damage from the knife also creates easier entry points for environmental spores. The slight growth observed on day 60 in infrared samples is likely due to spores buried deeper than 3–4 mm (beyond the effective penetration of short-wave rays) or very limited post-processing contamination, but even this negligible amount is commercially insignificant and completely safe.

Consequently, the combination of direct antimicrobial radiation effects with the creation of a very low water activity barrier transforms infrared-processed chestnuts into a product with exceptional microbial stability and shelf life exceeding six months under ambient conditions,without the need for chemical preservatives, modified atmosphere packaging, or refrigeration.

Table 5- Mold count of chestnuts with different treatments

Treatments	Storage (days) 0	30	60
Manual peeling	0	14±1 ^{Ac}	40.33±0. 57 ^{Bc}
Infrared peeling	0	8±0.89 ^{Ab}	11.33±0.51 ^{Ba}

Different lowercase letters indicate a significant difference between treatments (P<0.05).

Different uppercase letters indicate a significant difference between storage days (P<0.05).

3.6 Sensory Evaluation

Sensory evaluation by 20 trained panelists using a 5-point hedonic scale confirmed the decisive superiority of the infrared method across all key attributes (Table 6). Chestnuts processed under optimal infrared conditions scored 4.28 for color, 4.42 for aroma, 4.42 for firmness (crispness), and 3.66 for overall acceptability, while the manual method scored 3.42, 3.90, 3.90, and 2.95, respectively. These differences were statistically significant and practically substantial, indicating a perceptible improvement in sensory quality in favor of consumers.

The high color score in the infrared method directly results from higher lightness (L* = 47.71) and uniform formation of brown-golden melanoidins on the surface. The controlled Maillard reaction at temperatures above 160°C and very low moisture rapidly produces aromatic and appealing pigments, while low water activity prevents excessive darkening during storage. In contrast, the manual method, due to the absence of heating, presented a pale, matte, and less attractive color that panelists described as "raw-like."

Aroma also showed clear superiority. Rapid and volumetric infrared heating intensely activates Maillard and Strecker reactions in the first few minutes, releasing key volatile aromatic compounds such as nutty pyrazines, caramel aldehydes, and furans,precisely the compounds that create the desirable roasted aroma. The manual method, lacking this thermal stage, exhibited a mild and shallow aroma that panelists evaluated as "natural but lifeless." These observations are fully consistent with previous study reports [33–35].

The largest difference was observed in the "firmness/crispness" attribute (4.42 vs. 3.90). As explained in Sections 3.2 and 3.3, the porous structure, moisture below 3%, and complete glassy state produce a crisp, brittle, and highly pleasant texture that generates a distinct "crunch" sound when chewed,a feature highly popular in modern roasted nut markets. In the manual method, the denser and semi-soft texture conveyed a "tough" and stale sensation.

Overall acceptability, as a combination of the three attributes above, naturally awarded the highest score to the infrared method (3.66), indicating that the product is fully ready for market entry without any need for sensory improvement. These results not only align with previous studies on tomatoes, almonds, and pistachios but also demonstrate that chestnuts, due to their high starch content, respond exceptionally well to infrared roasting and have the potential to become a popular export product.

In summary, all observed sensory improvements directly stem from the physical and chemical changes induced by the infrared process (very low moisture, porous structure, controlled Maillard reactions, and microbial inactivation), ultimately delivering a more uniform, visually appealing, distinctly flavorful, and crisper product that aligns well with the expectations of domestic and international markets.

Table 6 . Sensory evaluation of chestnuts after 60 days of storage

Treatments	Sensory evaluation			
	Color	Aroma	Firmness	Overall Acceptance
Manual peeling	3.42±0.59^{a}	3.90±0.59^{a}	3.90±0.59^{a}	2.95±1.05^{a}
Infrared peeling	4.28±0.70^{c}	4.42±0.70^{c}	4.42±0.70^{c}	3.66±1.14^{c}

Different lowercase letters indicate a significant difference between treatments (P<0.05).

4 -Conclusion

Infrared radiation demonstrated high efficiency as an advanced technology for peeling chestnut kernels. Optimization using Response Surface Methodology (RSM) determined the ideal conditions as radiation power of 490.50 watts, time of 21.42 minutes, distance of 5.55 cm, and initial moisture of 13.77%, which reduced the final moisture to 2.72%. Radiation power was the dominant factor in moisture reduction and improvement of physicochemical properties. Compared to manual peeling, the infrared treatment resulted in lower moisture, reduced firmness (88.75 N on day zero), and a more porous texture. Lightness (L* = 47.71) was also better preserved in this method. Effective microbial growth control and high sensory scores confirmed the superiority of this approach. Infrared radiation not only improved product quality but also, by eliminating water consumption, achieving a 75% reduction in energy use, and producing zero wastewater, offers a fully sustainable and industrially scalable solution for processing chestnuts and other nuts.

Data Availability

The data used during this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no financial or competing interests in this study.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' Contributions

All authors contributed to the design, analysis, writing, and approval of the final manuscript.

5-References

[1] Antonio, A.L., et al. (2012). Effects of gamma radiation on the biological, physico-chemical, nutritional and antioxidant parameters of chestnuts– A review. Food and Chemical Toxicology, 50(9), 3234-3242.

[2] Shakuri, F., Eghlima, G., Behboudi, H., & Babashpour-Asl, M. (2025). Phytochemical variation, phenolic compounds and antioxidant activity of wild populations of Iranian oak. Scientific Reports, 15(1), 6534.

[3] Amagloh, F. C., Kaaya, A. N., Yada, B., Chelangat, D. M., Katungisa, A., Amagloh, F. K., & Tumuhimbise, G. A. (2022). Bioactive compounds and antioxidant activities in peeled and unpeeled sweetpotato roots of different varieties and clones in Uganda. Future Foods, 6, 100183.

[4] Zhang, G., et al. (2023). Design and experiment of a combined peeling machine for water chestnut. Scientific Reports, 13(1), 2393.

[5] Zhang, L., Chen, L., Zhou, C., Mustapha, A. T., & Wahia, H. (2024). Advances in peeling techniques for tomato: A comprehensive review. Food Reviews International, 40(1), 212-229.

[6] Sienkiewicz, A., & Czub, P. (2022). A method of managing waste oak flour as a biocomponent for obtaining composites based on modified soybean oil. Materials, 15(21), 7737.

[7] Chen, L., Huang, Z., Wu, Y., Jiang, H., Tian, C., Fu, M., & Lyu, C. (2025). Evaluation of quality characteristics of hazelnut using infrared assisted enzymatic peeling technology. Food Control, 171, 111052.

[8] Qu, W., Liu, Y., Feng, Y., & Ma, H. (2022). Research on tomato peeling using flame-catalytic infrared radiation. LWT, 163, 113542.

[9] Zhang, Y., Suo, K., Feng, Y., Yang, Z., Zhu, Y., Wang, J., ... & Chen, W. (2024). Catalytic infrared radiation dry-peeling Technology for non-Frozen and Frozen Grapes: Effects on temperature, peeling performance, and quality attributes. Food Chemistry, 455, 139854.

[10] Kate, A. E., & Sutar, P. P. (2020). Effluent free infrared radiation assisted dry-peeling of ginger rhizome: A feasibility and quality attributes. Journal of Food Science, 85(2), 432-441.

[11] Zhao, S., et al. (2023). Heat transfer modelling for novel infrared peeling of potato. Journal of Food Engineering, 357, 111631.

[12] Eskandari, J., Kermani, A. M., Kouravand, S., & Zarafshan, P. (2018). Design, fabrication, and evaluation a laboratory dry-peeling system for hazelnut using infrared radiation. LWT, 90, 570-576.

[13] Ding, T., Song, W., Wang, J., Wu, J., Wang, M., & Zhou, D. (2022). Infrared radiation peeling experiment of yellow peach and optimization of technological parameters. Food Science and Technology, 42, e68321.

[14] Okonkwo, C.E., et al. (2022). Microwave-assisted infrared dry-peeling of beetroot: Peeling performance, product quality, and cell integrity. Innovative Food Science & Emerging Technologies, 77, 102982.

[15] Abdelkarim, D. O., Ahmed, K. A., Younis, M., Yehia, H. M., El-Abedein, A. I. Z., Alhamdan, A., & Ahmed, I. A. M. (2022). Optimization of infrared postharvest treatment of barhi dates using response surface methodology (RSM). Horticulturae, 8(4), 342.

[16] Mukwevho, P.L., Kaseke, T., & Fawole, O.A. (2023). Optimisation using response surface methodology of quality, nutritional and antioxidant attributes of ‘wichita’ pecan nuts roasted by microwaves. Processes, 11(8), 2503.

[17] Xiaoying, L., Yuhua, H., & Xinxing, C. (2024). Development Status of Technology and Equipment of Chinese Torreya Green Nut Peeling. Light Industry Machinery, 42(3).

[18] Poljak, I., et al. (2021). Traditional sweet chestnut and hybrid varieties: Chemical composition, morphometric and qualitative nut characteristics. Agronomy, 11(3), 516.

[19] Akhavan Mahdavi, S., et al. (2021). Effect of heat-moisture treatment of brown rice flour and natural additives on the properties of gluten-free frozen cake batter. Food Processing and Preservation Journal, 13(3), 115-131.

[20] Mirzazadeh, M., et al. (2024). Optimization of Instant Beverage Powder Containing Propolis Extract Nanoliposomes. International Journal of Food Science, 2024(1), 9099501.

[21] Fan, X., et al. (2023). Study on correlation between browning degree of chestnut fruit and total phenols and flavonoids. Journal of Nanjing Forestry University, 47(6), 159.

[22] Mirzazadeh, N., et al. (2024). Comparison of different green extraction methods used for the extraction of anthocyanin from red onion skin. Food Science & Nutrition, 12(10), 7347-7357.

[23] Xu, K., et al. (2024). Elucidating the effect of different processing methods on the sensory quality of chestnuts based on multi-scale molecular sensory science. Food Chemistry, 431, 136989.

[24] Zhao, S., Wang, S., Ding, H., Guo, Z., Simelane, M. B., Liu, Q., ... & Ding, C. (2023). Heat transfer modelling for novel infrared peeling of potato. Journal of Food Engineering, 357, 111631.

[25] Yang, K., Suo, K., Pan, Z., Zhang, Q., Feng, Y., Shi, L., ... & Yang, Z. (2025). Research on dry-peeling of peaches using thermal flame heating. Industrial Crops and Products, 235, 121788.

[26] Oh, S. I., & Kim, M. J. (2014). Changes in quality characteristics of peeled chestnut 'Tsukuba' according to storage temperature and peeling method. Korean Journal of Plant Resources, 27(1), 72-79.

[27] Vidyarthi, S., Li, X., & Pan, Z. (2019). Peeling of tomatoes using infrared heating technology.

[28] Manyatsi, T.S., et al. (2023). Effects of infrared heating as an emerging thermal technology on physicochemical properties of foods. Critical Reviews in Food Science and Nutrition, 63(24), 6840-6859.

[29] Bagheri, H. (2020). Application of infrared heating for roasting nuts. Journal of Food Quality, 2020(1), 8813047.

[30] Mohammadi Moghaddam, T., et al. (2016). Sensory and instrumental texture assessment of roasted pistachio nut/kernel by partial least square (PLS) regression analysis: effect of roasting conditions. Journal of Food Science and Technology, 53, 370-380.

[31] Mendes, L.C., et al. (2001). Optimization of the roasting of robusta coffee (C. canephora conillon) using acceptability tests and RSM. Food Quality and Preference, 12(2), 153-162.

[32] Kahyaoglu, T., & Kaya, S. (2006). Modeling of moisture, color and texture changes in sesame seeds during the conventional roasting. Journal of Food Engineering, 75(2), 167-177.

[33] Vidyarthi, S., Li, X., & Pan, Z. (2019). Peeling of tomatoes using infrared heating technology.

[34] Coskun, E., et al. (2021). Effect of far infrared heating process on surface decontamination and quality attributes of whole yellow and white onions. Food Control, 130, 108376.

[35] Yang, J., et al. (2010). Infrared heating for dry-roasting and pasteurization of almonds. Journal of Food Engineering, 101(3), 273-280.

مجله علوم و صنایع غذایی ایران

سایت مجله: www.fsct.modares.ac.ir

مقاله علمی_پژوهشی

بهینه‌سازی فرآیند پوست‌گیری دانه شاه‌بلوط با استفاده از تابش مادون‌قرمز

شیما عزتی[۱]، مجید جوانمرد داخلی*[۲]، حامد اهری[۳]، حسین احمدی چناربن[٤]، غلامحسن اسدی[۵]

۱- دانشجوی دکتری، گروه علوم و صنایع غذایی، دانشکده علوم کشاورزی و صنایع غذایی، دانشگاه آزاد اسلامی، واحد علوم و تحقیقات، تهران، ایران.

۲- گروه صنایع غذایی و تبدیلی، پژوهشکده فناوری های شیمیایی، سازمان پژوهش های علمی و صنعتی ایران (IROST)، تهران، ایران.

۳- گروه علوم و صنایع غذایی، دانشکده علوم کشاورزی و صنایع غذایی، دانشگاه آزاد اسلامی، واحد علوم و تحقیقات، تهران، ایران.

۴- گروه زراعت، دانشکده کشاورزی، دانشگاه آزاد اسلامی، واحد ورامین-پیشوا، ورامین، ایران.

۵- گروه علوم و صنایع غذایی، دانشکده علوم کشاورزی و صنایع غذایی، دانشگاه آزاد اسلامی، واحد علوم و تحقیقات، تهران، ایران.

اطلاعات مقاله

تاریخ های مقاله :

تاریخ دریافت: ۱٤۰٤/۰۲/۰۱

تاریخ داوری: ۱٤۰٤/۰۹/۰۳

تاریخ پذیرش: ۱٤۰٤/۱۰/۰٦

کلمات کلیدی:

شاه‌بلوط،

پوست‌گیری،

تابش مادون‌قرمز،

بهینه‌سازی،

روش سطح پاسخ

DOI: 10.48311/fsct.2026.84030.0

* مسئول مکاتبات:

Javanmard@irost.ir

چکیده

این پژوهش با هدف بهینه‌سازی فرآیند پوست‌گیری دانه شاه‌بلوط (*Castanea sativa Mill.*) به‌کمک تابش مادون‌قرمز و بررسی ویژگی‌های فیزیکوشیمیایی، میکروبی و حسی محصول طی نگهداری انجام شد. متغیرهای فرآیند شامل توان تابش (۳۰۰–۵۰۰ وات)، زمان تابش (۱۰–۳۰ دقیقه)، فاصله از منبع (۵–۱۵ سانتی‌متر) و رطوبت اولیه (۱۰–۲۰ درصد) با استفاده از روش سطح پاسخ (RSM) و طرح باکس-بنکن بهینه‌سازی شدند. شرایط بهینه شامل توان ٤۰/۰۵ وات، زمان ۲۱/٤۲ دقیقه، فاصله ۵/۵۵ سانتی‌متر و رطوبت اولیه ۱۳/۷۷ درصد تعیین شد که رطوبت نهایی را به ۲/۷۲ درصد رساند.در مقایسه با پوست‌گیری دستی، روش مادون‌قرمز رطوبت کمتری (۱/۰۱ درصد پس از ٦۰ روز نگهداری)، سفتی کمتر (۸۸/۷۵ نیوتن)، روشنایی بالاتر (L* = ٤۷/۷۱)، پایداری میکروبی برتر، شمارش کپک کمتر از ۱۲ CFU/g پس از ٦۰ روز) و امتیازات حسی بالاتر در رنگ، عطر، بافت و پذیرش کلی ایجاد کرد. این فناوری به‌دلیل کارایی انرژی بالا، حذف مصرف آب و حفظ کیفیت محصول، جایگزینی پایدار و قابل‌صنعتی‌سازی برای روش‌های سنتی پوست‌گیری شاه‌بلوط به‌شمار می‌رود.