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Research Paper

A Multidimensional Assessment of Spouted-bed Roasted Almonds for Mitigating Acrylamide Formation While Enhancing Sensory and Functional Attributes

Widya Puspantari[1], Heryoki Yohanes[1*], Eko Pratama Astin[1], Lusiana Kresnawati Hartanto[1], Mohamad Nafila Alfa[1], Kokom Komariyah[1], Gigih Atmaji[1], Edi Priyo Pramono[1], Wahju Eko Widodo[1], Wahyu Bahari Setianto[1*]

[1]*Research Center for Agroindustry, National Research and Innovation Agency (BRIN), KST Bacharuddin Jusuf Habibie, Tangerang Selatan, Banten, 15314, Indonesia*
***Corresponding author**: hery009@brin.go.id; wahy013@brin.go.id

Abstract
Almonds (*Prunus dulcis*) are widely valued for their nutritional composition and sensory properties, and roasting is commonly applied to enhance their flavor and extend their shelf life. However, thermal processing can degrade bioactive compounds and promote acrylamide formation. This study examined the effects of spouted-bed fluidization roasting at temperatures ranging from 150 to 180 °C for 5 to 7 min on acrylamide levels, antioxidant activity, physicochemical characteristics, and sensory profiles of almonds. The analytical methods included texture analysis, ultra-performance liquid chromatography (UPLC), colorimetry, Fourier-transform infrared spectroscopy (FTIR), and descriptive sensory evaluation. Acrylamide concentrations ranged from undetectable levels (<40 ppb) at 150 °C for 5 min to 1,672 ppb at 180 °C for 7 min. Total phenolic content increased at higher roasting temperatures (170–180 °C), reaching up to 0.90 mg GAE/g, while antioxidant activity decreased from 0.51 M BHA/g in raw almonds to 0.15–0.37 M BHA/g in roasted samples. Roasting also reduced the moisture content (from 5.38% to 1.09%) and fracturability (from 102.39 N to 71.81 N), increased the browning intensity (BI: 42.13 to 30.77), and altered the FTIR spectra, indicating the formation of esters and carboxylic acids via Maillard reactions. Sensory evaluation showed that higher temperatures enhanced crispiness and aroma, but also increased bitterness and burnt characteristics. Overall, spouted-bed roasting at 160–170 °C for 5–7 min minimized acrylamide formation while maintaining favorable sensory quality and preserving phenolic compounds. These results provide a basis for optimizing almond roasting parameters to improve safety and nutritional retention.

Keywords
Prunus dulcis, Spouted-Bed Roasting, Acrylamide, Antioxidant Activity, Maillard Reaction, Sensory Evaluation

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1. INTRODUCTION

Almonds (*Prunus dulcis*), nutrient-dense nuts that are widely recognized for their health benefits and sensory properties. Almonds are powerhouses of nutrients, containing a rich blend of proteins, unsaturated fatty acids, dietary fiber, vitamins, minerals, and phytochemicals with antioxidant properties. These compounds have been associated with substantially reduced risks of cardiovascular diseases, obesity, and type 2 diabetes (Barreca et al., 2020; Qureshi et al., 2016). Their global consumption has surged significantly owing to their nutritional advantages and growing consumer interest in health conscious eating.

Roasting is a key processing step that enhances the texture, flavor, and color of almonds through complex chemical reactions such as Maillard browning, lipid oxidation, and caramelization (Lukac et al., 2007; Suvari et al., 2017). However, these desirable changes may be accompanied by negative effects, including the degradation of nutritional compounds and the formation of harmful substances, such as acrylamide. This heat–induced compound is formed via the reaction of asparagine with reducing sugars and is classified as a potential carcinogen (Singh and Kushwah, 2018). Acrylamide concentrations in roasted almonds vary depending on the roasting method and temperature, ranging from 117 μg/kg at 129 °C to 221 μg/kg at 182 °C (Lukac et al., 2007; Suvari et al., 2017).

The impact of roasting on almond bioactivity remains debated. However, some studies have reported increased phenolic content and antioxidant activity due to cell wall disruption and Maillard reaction byproducts (Oliveira et al., 2018). Others have noted reductions attributed to the thermal degradation of flavonoids and unsaturated fatty acids (Lin et al., 2016). This inconsistency highlights the complex and multifaceted nature of the thermal effects on almond functionality. Roasting also modifies key physicochemical properties, such as texture, color

development, and moisture content. Prolonged roasting promotes browning via melanoidin formation, while higher temperatures tend to decrease fracturability, resulting in a firmer and crispier texture (Lipan et al., 2020; Varela et al., 2006).

Spouted-bed fluidization involves vertically introducing a fluid at a suitable velocity through the center of a granular material bed at the bottom. The fluid stream generates a central jet that carries the bed particles upward and then falls back into the peripheral annular region in the top medium layer. Gradually, the particles descended from the column (Góral et al., 2017). The spouted-bed introduced fluid vertically at an appropriate velocity through the middle of the bottom granular material bed. This fluid stream transported the bed particles upward into the central jet, and when they reached the top medium layer, they rained back into the peripheral annular zone. The fluidized coffee roaster employs compressed hot air to stir and roast coffee beans (Yohanes et al., 2022).

Spouted-bed roasting has been successfully applied to other food matrices, including coffee beans and cereal grains, due to its efficient heat and mass transfer characteristics. Spouted-bed roasting involves roasting at 210 °C for 22 min, enhancing volatile compound retention compared to conventional drum roasting, thus improving coffee quality and economic value (Nagaraju et al., 2016). Peanut samples were subjected to roasting in a vertical spouted-bed at 180 °C for durations of 5, 10, 15, and 20 min to examine the degradation of aflatoxins during the roasting process (Martins et al., 2017). Spouted–bed roasting of groundnuts utilizes a draft tube to enhance heat transfer and optimize processing conditions (Nagaraju and Sridhar, 2014). However, its application in nut roasting, particularly almonds, remains largely underexplored. Compared to conventional systems, spouted-bed roasters provide rapid and uniform heat distribution, better control over residence time, and energy efficiency, making them suitable for continuous industrial operations (Huang et al., 2023). Moreover, this technology has been recognized for its lower environmental impact, aligning with the growing demand for sustainable food processing solutions.

Despite these advantages, limited studies have systematically evaluated the effects of spouted–bed roasting on almond quality. Most previous work has focused on isolated parameters, such as acrylamide formation or antioxidant retention, often under conventional roasting conditions. As a result, there is insufficient understanding of how roasting temperature, time, and airflow dynamics in a spouted–bed system collectively influenced the chemical, physical, and sensory attributes of roasted almonds. A holistic assessment that integrates these dimensions is essential, as product acceptability depends on their interaction and combined effect. Furthermore, research linking sensory evaluation with instrumental measurements under spouted-bed conditions is still scarce, despite its importance for developing consumer preferred, high quality almond products.

This study was conducted to address these knowledge gaps by evaluating how variations in spouted-bed roasting conditions affect acrylamide content, antioxidant activity, physicochemical properties, and sensory characteristics of almonds. Advanced analytical tools, including High Performance Liquid Chromatography (HPLC) and Fourier Transform Infrared Spectroscopy (FT-IR), were employed to characterize chemical changes, while descriptive sensory analysis was used to assess organoleptic attributes. Through this integrated approach, the study aims to identify optimized roasting protocols that balance food safety, nutritional value, and sensory appeal. The findings are expected to support the development of controlled and scalable almond roasting strategies suited for industrial application.

2. EXPERIMENTAL SECTION

2.1 Materials

Blue Diamond almonds were sourced in May 2023 from Sacramento, California. All chemical reagents used were of analytical grade, and reagents for acrylamide analysis were of HPLC grade (Merck, Germany).

2.2 Instruments

The primary instrument used in this study was a spouted-bed roaster Giat Coffee Roastery (2024) for the roasting of almonds. A data logger (VSCLAB AR 09) and K-type thermocouple were employed to monitor and record the temperature profiles during roasting. For acrylamide extraction, a centrifuge (Multifuge X1 and X1R Pro Centrifuges, Thermo Fisher, USA) and solid-phase extraction (SPE) using reversed-phase C18 SPE cartridges (Hawach, China) were used. Acrylamide quantification was performed using high-performance liquid chromatography (HPLC) (Model L 201055, Shimadzu Corp., Japan) equipped with a UV detector set at 210 nm. The column used was an ultrapure silica-based C18 column (pore size: 120 Å, L: 150 mm, particle size: 5 μm, YMC–TRIART, Japan). To analyze functional group transformations, Fourier-transform infrared spectroscopy (FTIR) (Invenio FT–IR Spectrometer, Bruker, USA) was utilized. The total phenolic content and DPPH radical scavenging activity of the roasted almonds were measured in 96-well microplates using a microplate reader (Biotek Synergy HTX Multimode Reader, Agilent, USA). Color measurements were performed using a Chroma Meter CR–100 (Konica Minolta Inc., Japan). Calorific values were determined using a bomb calorimeter (IKA C 6000, China). Finally, the fracturability of raw and roasted almonds was assessed using a texture analyzer (Stable Micro Systems TA.XT Plus C, United Kingdom) equipped with a 2 mm diameter cylindrical probe.

2.3 Roasting Almonds

This study utilized a commercial spouted-bed roasting system developed by Giat Coffee Roastery (2024) to roast almonds. The roasting temperatures inside the spouted-bed chamber and the hot airflow were monitored using a data logger (VSCLAB AR 09) and a K-type thermocouple, as illustrated in Figure 1a. The spouted-bed roaster had dimensions of 100 mm (length) × 60 mm (width) × 150 mm (height). The roasting method was based on the spouted-bed principle, which employs heated

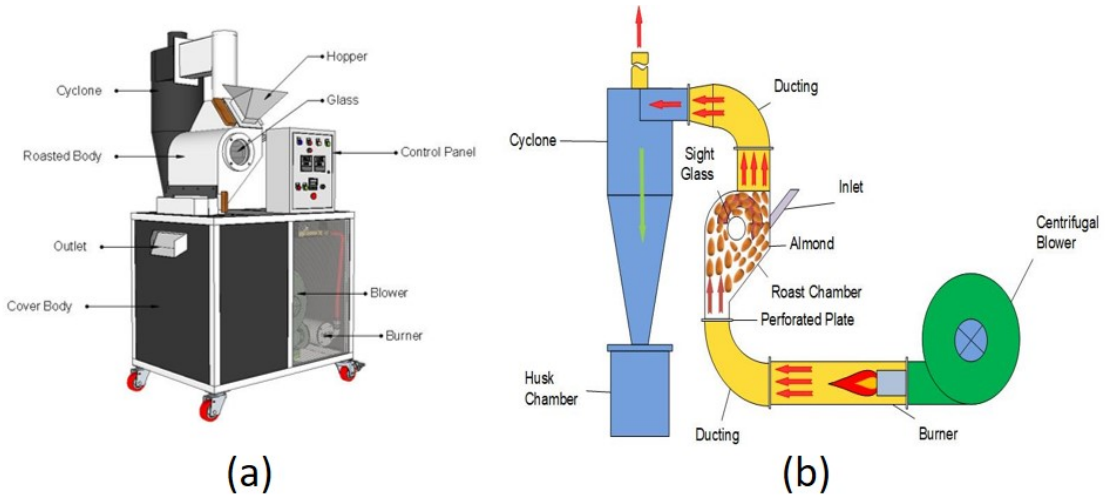

Figure 1. (a) Spouted-Bed Roaster Used in This Study; (b) Schematic Diagram of the Airflow and Almonds Movement in the Spouted-Bed Roasting System

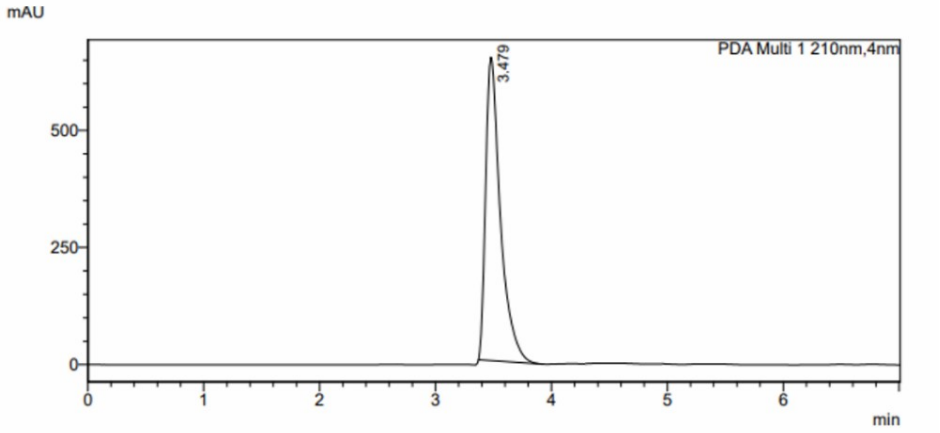

Figure 2. (Chromatogram of 100 ppm Acrylamide Standard Detected by HPLC at 210 nm, Showing a Retention Time of Approximately 3.479 Minutes

air generated by a gas burner and forced through the system by a blower, as depicted in Figure 1b. This technology facilitates uniform mixing, heating, and tempering through fluidization of the almond particles (Yohanes et al., 2022). Almonds were roasted at target temperatures of 150, 160, 170, and 180 °C for durations of 5 and 7 minutes. Upon completion of roasting, the blower continued to circulate air through the system to allow tempering of the almonds until their internal temperature decreased to approximately 50 °C.

2.4 Evaluation of Roasted Almonds

2.4.1 Acrylamide Content

The acrylamide content in roasted almonds was determined based on the method described by Endeshaw and Belay (2020), with minor modifications. A 2.5 g aliquot of ground roasted almonds sample was weighed into a 15 mL centrifuge tube, followed by the addition of 5 mL n–hexane and 10 mL distilled water. The mixture was vortexed thoroughly and then centrifuged at 5000 rpm for 10 minutes using a Multifuge X1/X1R Pro centrifuge (Thermo Fisher Scientific, USA). The upper hexane layer was discarded, and the aqueous phase was clarified by sequential addition of 1 mL Carrez I and 1 mL Carrez II solutions, followed by another centrifugation at the same speed and duration. The resulting supernatant was subjected to solid-phase extraction (SPE) using a reversed-phase C18 SPE cartridge (Hawach, China). Prior to sample loading, the SPE cartridge was conditioned with 1 mL methanol and 1 mL distilled water at a controlled flow rate of two drops per second. The first five drops of the eluent were discarded, and 4 mL of the filtrate was collected at a rate of one drop per second. The eluate was then concentrated under reduced pressure using a rotary evaporator. The concentrate was filtered through a

Table 1. Effect of Roasting Temperature and Time on Color Attributes (L*, a*, b*), Browning Index (BI), and Total Color Difference (ΔE) of Almond Samples

Roasting Conditions	L*	a*	b*	BI	ΔE
Unroasted	49.89±0.50a	9.87±0.26a	12.24±0.57a	42.13±1.28a	–
150 °C/5 min	46.50±0.49b	9.00±0.39b	10.88±0.53b	39.91±1.59b	2.26±0.28d
150 °C/7 min	46.86±0.30b	9.52±0.35a	10.56±0.37b	39.90±1.22b	2.24±0.21d
160 °C/5 min	46.93±0.40b	9.06±0.25b	10.62±0.36b	39.29±1.04b	2.31±0.21d
160 °C/7 min	46.07±0.40c	8.93±0.25b	9.57±0.43c	37.04±1.23c	2.71±0.19c
170 °C/5 min	45.75±0.47cd	8.25±0.40c	8.94±0.47d	34.48±1.51d	3.00±0.21b
170 °C/7 min	45.35±0.36d	8.50±0.26c	8.75±0.35d	34.68±1.10d	3.06±0.15b
180 °C/5 min	45.41±0.40d	8.38±0.33c	8.74±0.48d	34.49±1.49d	3.07±0.18b
180 °C/7 min	44.15±0.36e	7.67±0.27d	7.47±0.38e	30.77±1.15e	3.56±0.13a

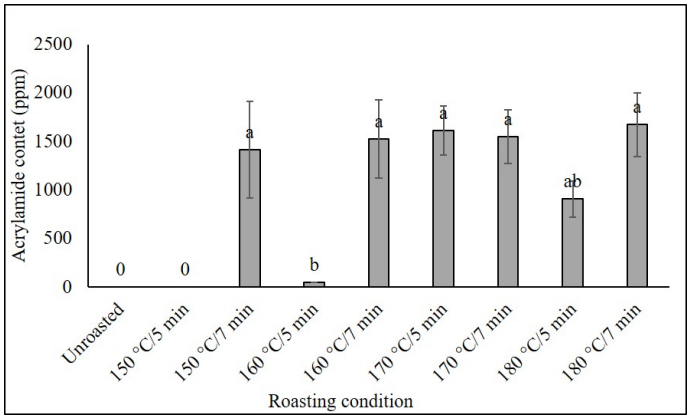

Figure 3. Effect of Roasting Conditions on Acrylamide Content in Roasted Almonds. Values Are Mean ± SD. Different Letters Indicate Significant Differences ($p < 0.05$)

0.2 μm regenerated cellulose membrane filter and transferred into autosampler vials for subsequent HPLC analysis.

Acrylamide levels in roasted almonds were quantified using high-performance liquid chromatography (HPLC) (Model L 201055, Shimadzu Corp., Japan) equipped with a UV detector set at 210 nm. Chromatographic separation was performed using a reversed-phase C18 column (YMC–TRIART C18, 150 mm × 4.6 mm, 5 μm, 120 Å, Japan). The mobile phase consisted of methanol and 6 mM potassium dihydrogen phosphate buffer (pH 3.5) mixed in a 96:4 (v/v) ratio and was delivered at a flow rate of 0.50 mL/min. For quantification, n–butylacrylamide (NBA) at a concentration of 100 ppm was used as an external standard.

2.4.2 Determination of Phenolic Compounds and Antioxidant Activity

Total phenolic content was quantified using the Folin–Ciocalteu method as described by Lukman et al. (2024) with slight modifications. A 20 μL aliquot of the sample was mixed with 100 μL of 10% (v/v) Folin–Ciocalteu reagent, and the mixture was incubated for 3 minutes. Subsequently, 80 μL of 1 M Na_2CO_3 was added, followed by incubation for 20 minutes. The absorbance was measured at 760 nm. Gallic acid was used as the calibration standard, and the results were expressed as milligrams of gallic acid equivalent per gram of sample (mg GAE/g).

The DPPH radical scavenging activity was assessed following the method of Oktiansyah et al. (2024) with modifications. A 25 μL aliquot was mixed with 200 μL of DPPH solution in ethanol (final concentration: 150 μM). The mixture was incubated at room temperature in the dark for 20 minutes, and the absorbance was recorded at 517 nm using a 96-well microplate reader (Biotek Synergy HTX Multimode Reader, Agilent, USA). The percentage of radical inhibition was calculated using Equation 1:

$$\%\ (\mathrm{IC}) = \frac{A_{\mathrm{blanko}} - A_{\mathrm{sample/standard}}}{A_{\mathrm{blanko}}} \times 100\% \qquad (1)$$

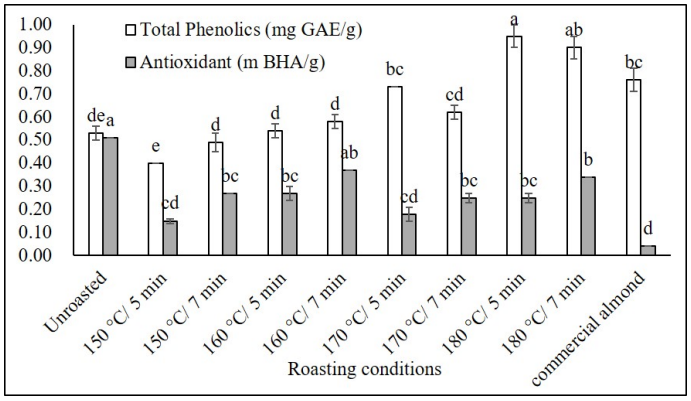

Figure 4. Total Phenolic Content (mg GAE/g) and Antioxidant Activity (M BHA/g) of Almonds at Various Roasting Temperatures

2.4.3 Color Profiles

The color characteristics of raw and roasted almonds were measured using a Minolta Chroma Meter CR–100 (Konica

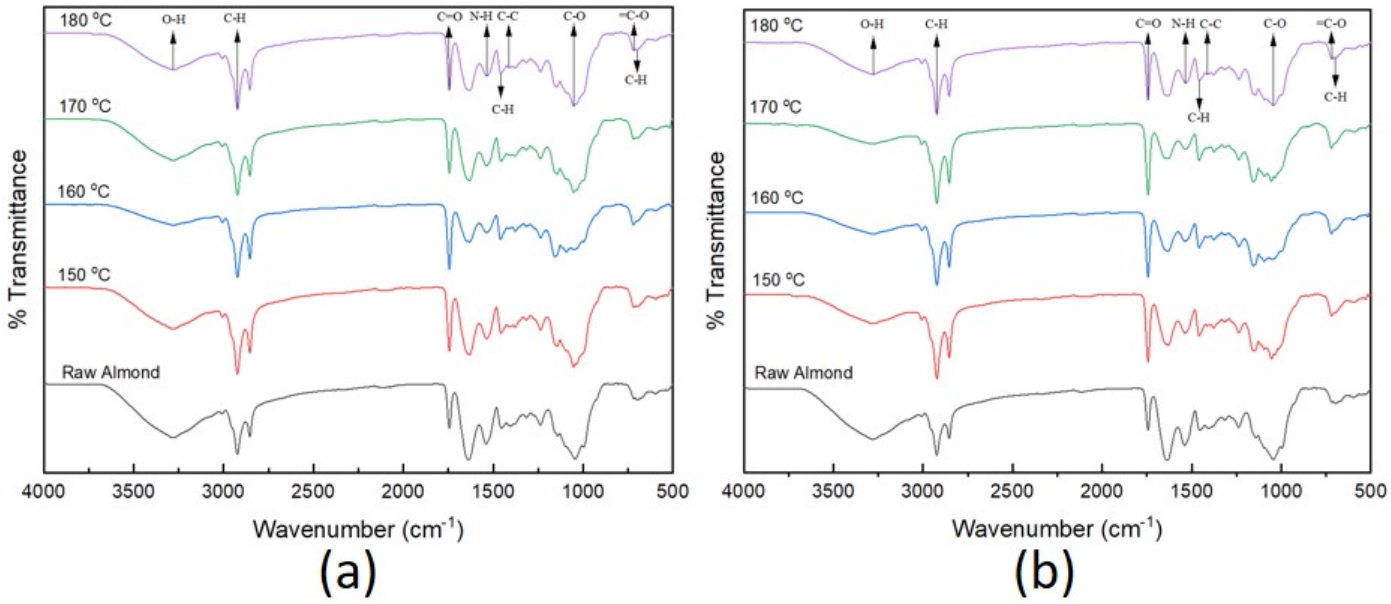

Figure 5. FTIR Spectra of Raw and Roasted Almonds at Different Temperatures: (a) Roasting Duration of 5 Minutes and (b) Roasting Duration of 7 Minutes

Table 2. Effect of Roasting Temperature and Time on the Fracturability of Almonds, Expressed as Fracture Force (N). Values Represent Mean Fracture Force Measured Using a Texture Analyzer

Roasting conditions	Fracturability (N)
Unroasted	102.39±10.98[a]
150 °C/5 min	99.31±11.24[ab]
150 °C/7 min	91.31±18.44[ab]
160 °C/5 min	91.38±12.67[abc]
160 °C/7 min	85.36±6.44[bcd]
170 °C/5 min	84.79±12.41[bcd]
170 °C/7 min	81.81±8.64[d]
180 °C/5 min	83.39±12.5[bcd]
180 °C/7 min	75.24±8.23[cd]

* Average and standard deviation (n = 10). Different lowercase letters indicate significant differences ($p < 0.05$). ANOVA, Tukey's test.

Minolta Inc., Japan). The analysis followed the Commission Internationale de lÉclairage (CIE) system, utilizing the L*, a*, and b* color coordinates. In this system, L* represents lightness (0 = black, 100 = white), a* indicates the red–green axis (positive values = red, negative = green), and b* indicates the yellow–blue axis (positive = yellow, negative = blue). The obtained L*, a*, and b* values were used to calculate the browning index (BI) according to Equation 2 (Lukac et al., 2007).

$$Z = \frac{a^* + 1.75\,L^*}{5.645\,L^* + a^*}$$

$$BI = \frac{Z - 0.31}{0.17 \times 100} \quad (2)$$

2.4.4 Fracturability

The fracturability of raw and roasted almonds was evaluated using a texture analyzer (Stable Micro Systems TA.XT Plus C, United Kingdom). Penetration tests were conducted to assess the mechanical textural properties of the almonds, following the method described by the Almond Board of California (Huang, 2014). A 2 mm diameter cylindrical probe was mounted on the texture analyzer and used to penetrate the almonds along their longitudinal axis. The test was performed at a crosshead speed of 1.0 mm/s, with a penetration depth of approximately 4 mm. The resulting force distance curve from a representative penetration test is shown in the figure below. A total of ten almond samples were analyzed for each roasting condition.

2.4.5 Proximate and Calorie Analysis

Proximate analysis was conducted following AOAC Method 945.16 (AOAC, 2005), while the calorific value was determined using a bomb calorimeter (IKA C 6000, China) as described by Cleveland and Morris (2015).

2.4.6 FTIR Profiles

Fourier Transform Infrared Spectroscopy (FTIR) (Invenio FT–IR Spectrometer, Bruker, USA) was employed to analyze

Table 3. Proximate Composition of Almonds Roasted at Different Temperatures and Durations

Roasting conditions	Water content (%)	Fat (%)	Protein (%)	Ash (%)	Carbohydrate (%)
Unroasted	5.38±0.05^{e}	52.20±0.00^{d}	16.51±0.00^{c}	2.99±0.00^{a}	22.93±0.01^{a}
150 °C/5 min	2.61±0.00^{d}	63.04±0.03^{a}	24.71±0.01^{ab}	2.81±0.09^{c}	6.84±0.08^{e}
150 °C/7 min	2.40±0.00^{d}	57.13±0.04^{b}	25.07±0.01^{a}	3.19±0.06^{b}	12.22±0.05^{d}
160 °C/5 min	1.99±0.00^{abc}	62.90±0.04^{a}	24.61±0.01^{ab}	2.96±0.16^{c}	7.55±0.17^{e}
160 °C/7 min	1.97±0.00^{abc}	57.13±0.01^{b}	17.39±0.57^{c}	3.09±0.02^{bc}	20.42±0.58^{b}
170 °C/5 min	1.70±0.00^{cd}	64.05±0.01^{a}	22.82±0.01^{d}	3.10±0.02^{bc}	8.12±0.34^{f}
170 °C/7 min	1.50±0.00^{d}	56.30±0.04^{b}	23.83±0.01^{b}	3.04±0.11^{bc}	15.33±0.11^{c}
180 °C/5 min	1.14±0.00^{d}	62.86±0.03^{a}	22.57±0.57^{d}	2.87±0.17^{c}	10.56±0.40^{d}
180 °C/7 min	1.09±0.00^{e}	55.18±0.00^{e}	24.38±0.01^{ab}	3.26±0.03^{b}	16.10±0.02^{c}

* Average and standard deviation (n=3). Nd: Not detected. Different letters indicate significant differences ($p < 0.05$, ANOVA, Tukey's test).

functional group transformations in almonds during the roasting process, as described by Sharma and raj (2018).

2.4.7 Descriptive and Hedonic Analysis

The samples were coded using randomly assigned three-digit numbers. A total of 30 semi-trained panelists (aged 20–40 years, both male and female) were recruited to evaluate the roasted almonds. These panelists had received prior training on sweet and bitter taste attributes based on the Almond Sensory Attribute Training guidelines King and Heymann (2014). The sensory evaluation included both descriptive analysis and hedonic testing. In the descriptive analysis, panelists rated seven sensory attributes: bitterness, sweetness, toasty flavor, cracked appearance, crunchiness, aroma, and hardness, using a 0-10 points scale. The hedonic evaluation was performed concurrently, assessing color, aroma, texture, and overall acceptability using a 9-point hedonic scale (1 = extremely dislike; 9 = extremely like).

Table 4. Caloric Content (Cal/g) of Roasted Almonds Subjected to Different Roasting Temperatures for 7 Minutes

Roasting conditions	Calories (Cal/g)
Unroasted	6912
150 °C	7027
160 °C	7088
170 °C	7099
180 °C	7132

2.5 Statistical Analysis

One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test ($\alpha = 0.05$) was conducted to evaluate the effects of independent variables (i.e., roasting temperature and time) on the measured parameters (acrylamide content, total phenolic, antioxidant activity, color profiles, fracturability, proximate and calories). Principal component analysis (PCA) was employed to explore correlations among the sensory and instrumental attribute parameters. All statistical analyses were performed using Minitab 19 software (Minitab Inc., USA).

3. RESULTS AND DISCUSSION

3.1 Acrylamide Content

Acrylamide, a compound classified as a probable human carcinogen, has raised concerns due to its presence in commonly consumed foods, including roasted almonds (King and Heymann, 2014). In this study, the elution time of the acrylamide standard was recorded at 3.479 minutes (Figure 2), and this retention time was used to identify acrylamide in almond samples after roasting.

Figure 3 illustrates the formation of acrylamide in roasted almonds under various temperature and time conditions. The acrylamide content ranged from 49 to 1,672 ppb, depending on the roasting parameters. Notably, acrylamide was not detected in almonds roasted at 150 °C for 5 minutes, with a limit of detection (LOD) of 40 ppb. No statistically significant differences ($p > 0.05$) were observed in acrylamide levels across the different roasting temperatures and durations. In contrast to previous studies, acrylamide formation in this study was only detected at temperatures above 150 °C. Earlier research reported acrylamide formation at 129 °C and 145 °C using fluidized-bed hot air roasting, and at 170 °C in conventional oven roasting (Lukac et al., 2007; Suvari et al., 2017; Zhang et al., 2011). As expected, dark-roasted almonds exhibited the highest acrylamide concentrations. In some cases, levels as high as 1,672 ppb have been reported Mesías et al. (2024).

3.2 The Total Phenolic Content and Antioxidant Activity

Figure 4 illustrates that unroasted almonds exhibit a total phenolic content of 0.53 mg GAE/g, while roasted almonds show a variable range between 0.40 and 0.90 mg GAE/g, depending on roasting conditions. A significant increase in phenolic content was observed at 170–180 °C ($p < 0.05$). This enhancement is likely due to the thermal disruption of cellular structures, which facilitates the release of bound phenolic compounds during heating, as well as the formation of Maillard reaction products that interact with the Folin–Ciocalteu reagent.

Table 5. The FTIR Profiles of Raw and Roasted Almonds at Different Roasting Conditions

Wavenumber Range (cm^{-1})	Peak Position (cm^{-1})									Bend Assignment
		150 °C		160 °C		170 °C		180 °C		
	Raw Almond	5 min	7 min	5 min	7 min	5 min	7 min	5 min	7 min	
3300–2500	3276.865	3276.049	3275.582	3275.418	3275.948	3276.114	3276.930	3276.872	3276.850	O–H stretch
3000–2850	3008.084	3006.715	3006.517	3006.584	3006.592	3006.590	3006.994	3006.994	3006.994	C–H stretch
3000–2850	2923.310	2922.978	2922.374	2922.963	2922.622	2922.931	2922.963	2923.002	2922.963	C–H stretch
3000–2850	2853.647	2853.387	2853.260	2853.266	2853.438	2853.387	2853.437	2853.447	2853.393	C–H stretch
1750–1735	1744.118	1744.022	1743.903	1743.969	1743.966	1743.918	1743.810	1744.015	1744.114	C=O stretch
1650–1580	1635.548	1630.917	1630.934	1631.334	1631.005	1647.968	1630.386	1630.886	1628.472	N–H bend
1550–1450	1539.181	1537.954	1537.934	1535.199	1533.951	1533.960	1535.960	1535.909	1534.546	N–H bend
1470–1450	1453.666	1450.679	1450.345	1457.359	1457.159	1457.150	1457.619	1457.515	1457.619	C–H bend
1500–1400	1403.384	1410.895	1414.030	1413.406	1412.406	1411.706	1415.349	1412.666	1413.398	C–C stretch
1320–1000	1315.040	1377.992	1376.187	1314.310	1314.402	1377.991	1315.349	1377.927	1377.227	C=O stretch
1320–1000	1237.541	1315.445	1315.426	1315.274	1315.464	1315.157	1315.421	1315.191	1315.121	C=O stretch
1320–1000	1140.845	1236.710	1236.703	1157.424	1236.899	1157.434	1236.907	1236.907	1236.397	C=O stretch
1320–1000	1043.851	1143.311	1156.037	1095.308	1103.136	1095.058	1144.933	1095.081	1144.799	C=O stretch
1000–650	996.066	1052.211	1051.921	1051.566	1054.701	1051.566	1054.701	1051.771	1044.076	C=O bend
725–720	–	718.219	717.911	720.003	720.000	718.760	720.146	718.595	718.594	C–H rock

Comparable findings were reported by Oliveira et al. (2020), who observed increased phenolic content and antioxidant activity in *Prunus dulcis* after roasting at 138 °C for 33 minutes. In contrast, the highest antioxidant activity was recorded in raw almond samples (0.51 M BHA/g), whereas roasted almonds exhibited significantly reduced activity, ranging from 0.15 to 0.37 M BHA/g ($p < 0.05$). Interestingly, no direct correlation was established between the total phenolic content and antioxidant activity in this almond variety. Although thermal processing may degrade some bioactive compounds, it also produces Maillard-derived antioxidants, which may contribute to the overall activity observed.

3.3 The Color Profiles

High roasting temperatures and extended roasting times significantly affected the moisture content, as well as the browning index (BI) and color parameters (L^*, a^*, and b^*) ($p < 0.05$). As temperature and time increased, the values of L^*, a^*, b^*, and BI in the roasted almonds decreased. At the highest roasting temperature, L^* decreased from 48.89 to a range of 44.15–46.95, a^* decreased from 9.87 to 7.67–9.52, b^* decreased from 12.24 to 7.47–10.88, and BI decreased from 42.13 to 30.77–39.29. In contrast, ΔE (total color difference) increased to 3.56 at the highest temperature (Table 1). The decrease in L^*, a^*, and b^* values is attributed to the formation of melanoidin pigments, which result from the reaction between amino acids and reduc-

ing sugars during the Maillard reaction (Murata, 2021). Similar trends were observed by (Lipan et al., 2020), who reported L* values ranging from 46.0 to 41.0, a* from 18.1 to 12.6, and b* from 31.7 to 15.3 when almonds were roasted at temperatures between 150–190 °C. According to Alamri et al. (2022), the browning index tends to increase with longer roasting times but may decrease after prolonged exposure.

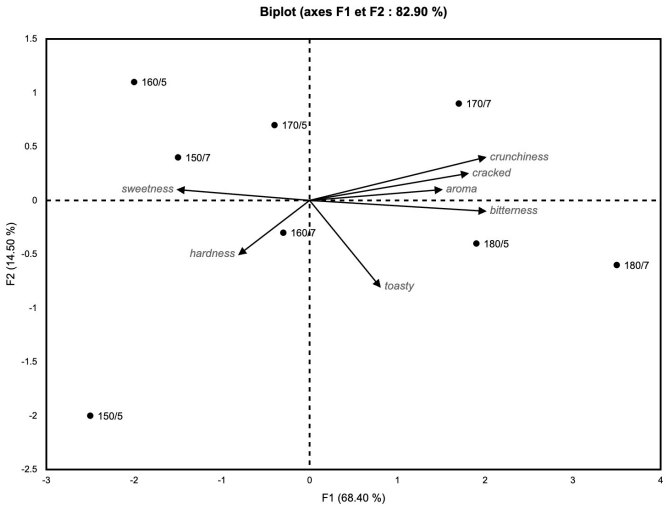

Figure 6. PCA Biplot Shows the Associations Between Roasting Conditions and Sensory Attributes of Almond Samples. PC1 and PC2 Accounted for 82.90% of the Total Variation

3.4 The Fracturability

The fracturability of almonds showed a significant decrease from 102.39 N in raw samples to a range of 99.31–71.81 N after roasting at 170 °C and 180 °C ($p < 0.05$) (Table 2). This reduction in fracture force is attributed to the thermal softening effect, which lowers the rigidity and mechanical resistance of the almond structure. This trend is consistent with previous findings by Varela et al. (2006) and Ng et al. (2014), who also reported decreased textural strength following thermal processing. As both roasting temperature and duration increased, the fracturability values tended to decline, indicating a softer texture. Additionally, the nonuniformity in fracture force measurements observed after roasting may be due to variations in almond size, which ranged from 23 to 30 mm. These results suggest that higher roasting temperatures reduce the force required to fracture almonds, thereby confirming the mechanical impact of roasting on almond texture (Apaydın et al., 2024).

3.5 Proximate and Calorie Content

Table 3 presents a comparative analysis of the proximate composition of almond samples subjected to various roasting conditions. Moisture content decreased significantly with increasing temperature and roasting time ($p < 0.05$), primarily due to evaporation. According to the Almond Board of California, maintaining a moisture content below 3% in roasted almonds is critical for preserving product quality and shelf life (Huang, 2014). Fat content varied across treatments, with the highest level observed at 170 °C for 5 minutes, while protein content remained relatively stable. The carbohydrate content tended to increase at higher temperatures, likely due to the Maillard reaction and caramelization. Statistically, roasting conditions had a significant effect on overall nutritional composition ($p < 0.05$). Contrary to some previous studies, the carbohydrate and fat contents remained relatively stable post-roasting, although minor variations may occur depending on the roasting method used Kodad et al. (2016). Heating can damage the almond skin, thereby exposing lipids to air and increasing the risk of oxidative rancidity. However, storing roasted almonds in vacuum packaging at low temperatures can help maintain quality during storage. Table 4 shows that the caloric content of almonds increased slightly after roasting, ranging from 7027 to 7132 Cal/g. The softening of texture due to roasting may facilitate lipid release and enhance caloric bioavailability, as also reported by Gebauer et al. (2016).

3.6 The FTIR Spectra Profiles

Fourier Transform Infrared (FTIR) spectroscopy analysis of roasted and unroasted almonds revealed distinct differences in functional group profiles, indicating that the roasting process significantly alters almond composition. The observed variations in % transmittance (%T) across multiple spectral regions reflect changes in molecular structures and interactions caused by thermal exposure. As shown in Table 5, roasted almonds exhibited a decrease in %T for alkanes (3000–2850 cm^{-1}), primary amines (1750–1735 cm^{-1}), and secondary amines (1550–1450 cm^{-1}), while increases in %T were observed for carboxylic acids (3300–2500 cm^{-1}), esters (1750–1735 and 1320–1000 cm^{-1}), aromatics (1500–1400 cm^{-1}), and alkenes (1000-650 cm^{-1}). Notably, a new peak emerged at 725-720 cm^{-1} (C–H rock) in the roasted samples, suggesting the formation of novel compounds during roasting (Figure 5). These spectral changes are closely associated with the Maillard reaction, which contributes to the development of aroma and color during roasting. The reduction in alkanes and amines, alongside the increase in carboxylic acids, aromatics, alkenes, and esters, indicates complex molecular transformations triggered by heat. This observation aligns with findings by Mottram et al. (2002), who reported elevated %T of esters in roasted coffee due to the emergence of volatile compounds and Maillard-derived pigments. Similarly, Ng et al. (2014) observed an increase in carboxylic acid and ester levels in almonds roasted at high temperatures. Conversely, while roasting promotes the formation of desirable functional groups, it may also lead to the degradation of heat-sensitive compounds, potentially reducing certain flavor notes. This duality underscores the chemical complexity of thermal processing (Enders et al., 2021).

3.7 The Descriptive and Hedonic Analysis

Principal component analysis (PCA) was conducted to evaluate the sensory profiles of roasted almonds under varying

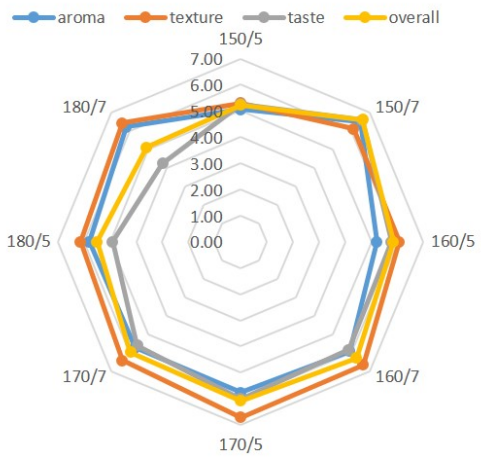

Figure 7. Spider Plot of Sensory Evaluation Scores of Almonds Roasted at Different Temperatures and Durations, Assessed by 30 Semi-Trained Panelists Based on Color, Aroma, Texture (Crispiness), Taste, and Overall Acceptability of the Samples

roasting conditions. As illustrated in Figure 6, the first two principal components (PC1 and PC2) explained 82.90% of the total variance, indicating a strong discriminatory capacity of the model. The samples are clustered into four distinct groups based on roasting temperature. Almonds roasted at 150 °C and 160 °C were associated with sensory attributes such as sweetness and hardness, whereas those roasted at 170 °C and 180 °C were characterized by crack formation, crunchiness, intense aroma, toasty notes, and bitterness. Notably, roasting at 180 °C resulted in almonds exhibiting a burnt aroma, surface cracking, and pronounced bitterness, suggesting more extensive thermal-induced reactions. Prolonged roasting further intensified aroma differences ($p < 0.05$), likely due to the enhanced formation of volatile organic compounds (VOCs) such as pyrazines and furans, which are key contributors to roasted and burnt sensory notes. These findings are consistent with data from The Good Scents Company (2018), which reported that almonds roasted at 170–190 °C developed strong "burn" aromas, while such characteristics were absent at lower temperatures (150–160 °C). The increased bitterness observed at higher temperatures was attributed to elevated levels of benzaldehyde, a compound released from the breakdown of amygdalin glycosides. Benzaldehyde is the principal aromatic compound in almonds, contributing to their distinctive flavor and aroma, and its concentration rises with roasting intensity. Similar observations were reported by Oliveira et al. (2020), who noted increased benzaldehyde levels and bitterness in six almond cultivars following thermal treatment.

Figure 7 presents the results of the sensory evaluation conducted with 30 semi-trained panelists who assessed almonds roasted at various temperatures and durations based on five sensory attributes: color, aroma, texture (crispiness), taste, and overall acceptability. Both crispiness and aroma improved with increasing roasting temperature. Almonds roasted at 150 °C for 5 min received the lowest scores across all sensory parameters, whereas samples roasted at 150 °C for 7 min and 160 °C were rated more favorably. At 170 °C, the taste scores began to decline, and a significant reduction ($p < 0.05$) was observed at 180 °C, where a bitter taste developed due to the elevated formation of benzaldehyde during high-temperature heating. This observation is supported by previous studies by Lipan et al. (2020) and Franklin et al. (2018), who reported increased benzaldehyde concentrations with rising roasting temperatures. In addition, significant differences in almond texture ($p < 0.05$) were observed at roasting temperatures of 150 °C and higher, suggesting that the thermal treatment had a pronounced effect on crispiness and structural integrity.

4. CONCLUSIONS

This study demonstrates that spouted-bed roasting at 160–170 °C for 5-7 min effectively reduces acrylamide content while preserving phenolic compounds and enhancing the sensory quality of almonds. Compared to conventional oven and fluidized bed roasting methods, the spouted-bed approach offers a superior balance between food safety, nutritional retention, and sensory performance. The system enables uniform heat distribution and precise residence time control, which contributes to the preservation of crisp texture and enhancement of desirable aroma without inducing excessive bitterness. These findings support the potential of spouted-bed roasting as a scalable and sustainable alternative for producing safer and more consumer-preferred roasted almonds. Future research should focus on process kinetics, storage stability, as well as wider consumer acceptance to facilitate broader industrial adoption.

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