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Process Optimization and Preliminary Quality Evaluation of Low-Fat Spicy Beef Jerky by Microwave-Assisted Pre-Drying and Oven Roasting

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ABSTRACT

This study developed and evaluated a microwave-assisted pre-drying and oven-roasting process for Low-Fat Spicy Beef Jerky using single-factor screening, a three-factor three-level orthogonal design, sensory evaluation, fuzzy comprehensive evaluation, and preliminary texture profile analysis. The formulation was based on 100 g fresh beef hind-leg muscle and contained beef powder, flavoring powder, cooking wine, light soy sauce, soybean oil, honey, sugar, cumin powder, oyster sauce, and chili powder. Beef powder concentration, microwave temperature, roasting temperature, and roasting time were investigated within the experimental ranges reported in the source study. Ten assessors evaluated color, flavor, texture, and taste on a 10-point scale, and the assigned normalized weights were 0.30, 0.20, 0.30, and 0.20, respectively. The orthogonal stage contained nine combinations, while six additional records were included in the combined K-value and analysis-of-variance assessment. The marginal optimum was 90 °C microwave pre-drying, 105 °C oven roasting, and 90 min roasting, and orthogonal sample 5 obtained the highest reported fuzzy comprehensive score of 8.26. The supplied statistical model was significant ($P < 0.001$), with $R2 = 0.739$ and adjusted $R2 = 0.712$. The original analytical framework also included volatile compounds, fatty acids, Fourier-transform infrared spectroscopy, and ion-mobility spectrometry. These methods and the original spectra are retained in the manuscript, while no chemical concentration or structural percentage is fabricated where numerical result tables are unavailable. The designation Low-Fat Spicy Beef Jerky is retained as the product identity; because finished-product proximate fat was not measured in the supplied record, no numerical nutrition claim is introduced.

KEYWORDS

Beef jerky; Microwave-assisted drying; Oven roasting; Sensory evaluation; Fuzzy comprehensive evaluation; Texture profile analysis; Low-Fat Spicy Beef Jerky

1. INTRODUCTION

Beef jerky is a low-moisture meat product whose final quality is strongly influenced by raw-material composition and the drying trajectory. Changes in moisture distribution, structural contraction, color development, flavor generation, and chewability can occur simultaneously during dehydration [1]. Comparative studies of traditional and modern beef-jerky processing have demonstrated that drying route can alter moisture content, shear-related behavior, color, free amino acids, fatty acids, and volatile flavor profiles [2]. Microwave-assisted hot-air drying has been investigated as a hybrid strategy because internal heating can accelerate moisture movement while conventional heating supports controlled surface development [3]. Hyperspectral studies further show that microwave-related drying routes can change moisture distribution and rehydration behavior in beef products [4].

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Reviews of jerky processing indicate that drying conditions, formulation, humectants, and emerging technologies collectively determine texture, stability, and sensory acceptance [5]. Multidimensional sensory evaluation is especially important for jerky because improved dryness may be accompanied by increased hardness, while stronger thermal treatment can intensify color and roasted notes at the expense of excessive darkening [6]. Fuzzy comprehensive evaluation offers a quantitative method for transforming multiple sensory judgments into a composite score through membership functions and weighted synthesis [7]. In beef jerky processing, confined drying has also been shown to influence water loss, muscle-fiber organization, texture, and processing efficiency, emphasizing the coupled nature of structure and dehydration [8]. Hot-air drying studies on beef jerky have demonstrated that drying temperature and time affect heat transfer, moisture migration, shrinkage, and final sensory quality [9].

Gradient drying has been explored to balance surface development and internal dehydration, supporting the view that an intermediate process window can be preferable to a uniformly severe treatment [10]. Process analytical technologies such as near-infrared hyperspectral imaging have been proposed for monitoring moisture changes during beef-jerky drying and for linking instrumental signals with process state [11]. The thermal history of meat also affects protein conformation, water-binding behavior, and texture because heating changes myofibrillar protein interactions and structural organization [12]. Microwave heating can introduce non-uniform temperature fields, making load geometry, dielectric properties, and equipment configuration important considerations when laboratory conditions are translated to larger systems [13].

Hybrid microwave techniques are therefore typically interpreted as part of an integrated thermal process rather than as an isolated replacement for conventional drying [14]. Fuzzy optimization has also been combined with statistical process optimization in other food systems, illustrating the value of integrating multidimensional quality assessment with factor-level analysis [15].

The objective of the present study was to preserve the original experimental framework while translating it into an English-language manuscript and organizing it according to the supplied Trans Tech Publications template. The work evaluates the formulation and process conditions of Low-Fat Spicy Beef Jerky, retains the original experimental subsections and analytical procedures, and adds a structured discussion of the relationships among formulation, microwave pre-drying, oven roasting, sensory quality, fuzzy evaluation, and texture. The selected condition is interpreted as a process-specific optimum within the tested design region rather than as a universal rule.

2. MATERIALS AND METHODS

2.1. Materials and Reagents

Fresh beef hind-leg muscle, including the locally described cucumber-strip cut, was purchased from the market and used as the principal raw material. Commercial beef powder, flavoring powder, cooking wine, sugar, chili powder, light soy sauce, soybean oil, cumin powder, oyster sauce, and honey were used as formulation ingredients. The original source records identify commercial suppliers for selected reagents, including chromatographic-grade n-heptane, analytical-grade n-hexane, methanol, 14% boron trifluoride-methanol solution, 2-octanol, saturated sodium chloride solution, 0.5 mol/L chloroform-methanol solution, 0.5 mol/L sodium hydroxide-methanol solution, and a mixed standard containing 37 fatty acid methyl esters. Exact catalog and lot numbers were not present in the supplied material.

2.2. Instruments and Equipment

The instruments used in the original experiment included an oven, microwave oven, heating magnetic stirrer, low-speed centrifuge, analytical balance, and gas chromatography-mass spectrometry system. The original equipment list and manufacturers are retained below.

Table 1. Main instruments

Instrument	Manufacturer
Oven	Guangzhou Weige Machinery Equipment Co., Ltd.
Microwave oven	Guangdong Midea Kitchen Appliance Manufacturing Co., Ltd.
Heating magnetic stirrer	Dingxin Instrument Equipment Co., Ltd.
Low-speed centrifuge	Shanghai Anting Scientific Instrument Factory
Analytical balance	Changzhou Surui Instrument Co., Ltd.
Gas chromatography-mass spectrometry system	Agilent Technologies

2.3. Experimental Methods

2.3.1. Determination of the Base Formulation

The base formulation of the spicy beef jerky was determined from preliminary flavor trials and sensory evaluation. Per 100 g fresh beef hind-leg muscle, the formulation consisted of 1.00 g beef powder, 0.64 g flavoring powder, 4.00 g cooking wine, 4.35 g light soy sauce, 3.00 g soybean oil, 6.00 g honey, 2.00 g sugar, 1.50 g cumin powder, 1.00 g oyster sauce, and 1.50 g chili powder.

Table 2. Base formulation of Low-Fat Spicy Beef Jerky

Ingredient	Amount per 100 g fresh beef
Beef powder	1.00 g
Flavoring powder	0.64 g
Cooking wine	4.00 g
Light soy sauce	4.35 g
Soybean oil	3.00 g
Honey	6.00 g
Sugar	2.00 g
Cumin powder	1.50 g
Oyster sauce	1.00 g
Chili powder	1.50 g

2.3.2. Processing Procedure

Fresh lean beef was trimmed to remove visible membrane and residual fat. Chilled beef was soaked in clean water for 30 min; frozen beef was thawed and then soaked for 2 h with one to two water changes. The meat was cut parallel to the muscle fibers into strips approximately 1-1.5 cm wide and 5-6 cm long. The strips were rinsed two to three times and drained.

Seasonings were added according to the base formulation and mixed by hand for 5-8 min to ensure uniform coating. Refrigerated marination was standardized at 12 h for the final translated protocol because the detailed operating subsection of the supplied record specifies 12 h. After marination, the strips were placed in a microwave-safe container and pre-dried at the designated microwave temperature for 10 min. The expressed liquid was discarded. The strips were then placed on a baking tray lined with oil-resistant paper, lightly brushed with honey, and roasted in a preheated oven. During roasting, the pieces were turned at approximately 30 and 60 min, with a light additional honey coating

when required. The finished product was cooled to room temperature under ventilation and vacuum packaged.

2.3.3. Operating Points

The original operating points were retained in translated form. Raw-material pretreatment consisted of trimming, soaking or thawing and soaking, fiber-direction cutting, repeated rinsing, and draining. Marination consisted of seasoning followed by refrigerated holding for 12 h. Microwave pre-drying was conducted for 10 min at the experimental temperature, followed by removal of expressed liquid. Oven roasting was carried out on oil-resistant paper in the middle rack of a preheated oven, with turning at 30 and 60 min and optional reapplication of a small amount of honey.

2.3.4. Single-Factor Experimental Design

Based on preliminary trials, four variables were considered influential to sensory quality while the other formulation and handling conditions were kept constant. Beef powder concentration was varied at 0%, 0.5%, 1%, 1.5%, and 2%. Microwave temperature was varied at 60, 70, 80, 90, and 100 °C. Roasting temperature was varied at 75, 90, 105, 120, and 135 °C. Roasting time was varied at 60, 70, 80, 90, and 100 min.

For the beef-powder experiment, 100 g fresh beef and the core seasoning system were fixed, while microwave temperature, roasting temperature, and roasting time were fixed at 80 °C, 105 °C, and 80 min, respectively. For the microwave experiment, beef powder was fixed at 1%, roasting temperature at 105 °C, and roasting time at 80 min. For the roasting-temperature experiment, beef powder was fixed at 1%, microwave temperature at 80 °C, and roasting time at 80 min. For the roasting-time experiment, beef powder was fixed at 1%, microwave temperature at 80 °C, and roasting temperature at 105 °C. Sensory evaluation was used to identify the practical working ranges for subsequent orthogonal optimization.

2.3.5. Sensory Evaluation Criteria

The sensory evaluation framework was developed with reference to GB/T 16291.1-2012. Ten student assessors observed and tasted the samples and scored color, flavor, texture, and taste on a 10-point scale. The overall weighted score was calculated as 0.30 × Color + 0.20 × Flavor + 0.30 × Texture + 0.20 × Taste [16].

Table 3. Sensory evaluation criteria for Low-Fat Spicy Beef Jerky

Attribute	Score range	Descriptor
Color	6-10	Uniform reddish-brown, bright and glossy
Color	3-6	Acceptable dark-red appearance with limited dullness
Color	0-3	Uneven dark-red or black appearance or obvious discoloration
Flavor	6-10	Strong meaty aroma with balanced salt, spice, and seasoning notes
Flavor	3-6	Recognizable meaty aroma with some seasoning imbalance
Flavor	0-3	Weak meaty aroma or pungent, burnt, or otherwise undesirable notes
Texture	6-10	Regular surface, moderate firmness, good elasticity, and chewability
Texture	3-6	Moderately acceptable firmness or elasticity
Texture	0-3	Very hard or soft, rough, sticky, or difficult to chew
Taste	6-10	Balanced saltiness with harmonious meaty and spicy taste
Taste	3-6	Acceptable saltiness but limited fullness
Taste	0-3	Markedly imbalanced taste or obvious off-flavor
Total score	10	0.30 × Color + 0.20 × Flavor + 0.30 × Texture + 0.20 × Taste

2.3.6. Fuzzy Mathematical Sensory Evaluation Model

(1) Orthogonal Experiment Optimization

Based on the single-factor experiments, microwave temperature, roasting temperature, and roasting time were selected for optimization using a three-factor, three-level orthogonal design.

Table 4. Orthogonal experimental factors and levels

Level	Microwave temperature (°C)	Roasting temperature (°C)	Roasting time (min)
1	70	90	70
2	80	105	80
3	90	120	90

(2) Factor Set

The factor set was defined as U = {A, B, C, D}, corresponding to color, flavor, texture, and taste, respectively. This structure was retained from the original experimental design so that the fuzzy evaluation remained consistent with the four sensory attributes.

(3) Weight Set

Three food-processing specialists assigned relative importance to the four sensory attributes, and the normalized weight vector was W = (0.30, 0.20, 0.30, 0.20). The weights sum to 1.00.

(4) Evaluation Grade Set

Five evaluation grades were established: very poor, poor, medium, good, and excellent. The midpoint scores assigned to these grades were 1.5, 3.5, 5.5, 7.5, and 9.5, respectively. These midpoint values were used to transform the fuzzy membership distribution into a composite score.

3. MEASUREMENT OF EXPERIMENTAL INDICES

3.1. Extraction of Volatile Flavor Compounds

Volatile flavor compounds were extracted using purge-and-trap. A 2.0 g sample was placed in a 20 mL brown vial, 0.2 mL 2-octanol was added as internal standard, and the vial was sealed for purge-and-trap extraction followed by GC-MS analysis.

3.1.1. Purge-and-Trap and GC-MS Conditions

The purge-and-trap method was operated in soil mode. Standby conditions were a valve-box temperature of 140 °C, transfer-line temperature of 140 °C, sample-base temperature of 90 °C, sample-cup temperature of 60 °C, and standby flow of 10 mL/min. The purge stage included 10 min sample preheating, 0.25 min pre-purge, 20 min purging at 60 mL/min and 60 °C, followed by a 2 min dry purge at 100 mL/min and 20 °C. Desorption was initiated after preheating to 215 °C, with a desorption time of 3 min at 220 °C. The bake stage lasted 2 min at 200 mL/min and 280 °C, with the MCS at 180 °C.

The GC column was HP-5 MS (30 m × 0.25 mm × 0.25 μm), the injector temperature was 240 °C, and the carrier gas was helium at $1.^{0}$ mL/min. The oven program started at 40 °C for 1 min, increased at 3 °C/min to 100 °C and held for 3 min, then increased at 6 °C/min to 160 °C and held for 2 min, and finally increased at 19 °C/min to 240 °C and held for 4 min. The injection volume was $5.^{0}$ μL and the split ratio was 20:1. MS conditions included electron-impact ionization at 70 eV, an ion-source temperature of 230 °C, quadrupole temperature of 150 °C, full-scan acquisition from m/z 30-350, and a solvent delay of 6 min.

3.1.2. Qualitative and Semi-Quantitative Analysis

Compounds with library matching above 70% were retained for identification by comparison with the NIST 11.0 database. Relative content was calculated by peak-area normalization. Semi-quantification used 2-octanol as internal standard, with concentration calculated from the internal-standard response according to Eq. (1): $C_i = C_t \times A_i / A_t$ *(1)* where C_i is the mass concentration of the compound (mg/g), C_t is the mass concentration of the internal standard (mg/g), A_i is the chromatographic peak area of the compound, and A_t is the peak area of the internal standard.

3.2. Fatty Acid Determination

3.2.1. Fatty Acid Extraction

Fatty acids were determined according to GB 5009.168-2016 with the extraction procedure described in the original study. A 2.0 g sample and 200 μL internal-standard solution were placed in a mortar and ground with 30 mL of 0.5 mol/L chloroform-methanol solution. The mixture was extracted at room temperature for 24 h and filtered into a conical flask. Three milliliters of 0.5 mol/L sodium hydroxide-methanol solution were then added, and the mixture was sealed and shaken [17].

The mixed solution was transferred into a centrifuge tube and heated in a 100 °C water bath for 30 min for preliminary decomposition. After cooling to room temperature, 4 mL of 14% boron trifluoride-methanol solution were added. The mixture was heated again at 100 °C for 5 min and cooled. Two milliliters of chromatographic-grade n-hexane and internal standard were added and mixed thoroughly, followed by 5 mL saturated sodium chloride solution. After standing, the mixture was centrifuged at 1000 rpm for 10 min. The upper layer was collected with a syringe, passed through a 0.22 μm filter, transferred into a brown vial, and stored for GC analysis.

3.2.2. GC Conditions

The reported GC conditions were an HP-5 capillary column (30 m × 0.25 μm × 0.25 mm), injector temperature 250 °C, pressure 91.01 kPa, total flow 7 mL/min, constant-pressure splitless injection, injection volume 1 μL, hydrogen carrier gas at 99.99% purity, and a temperature program of 50 °C for 2 min followed by 7 °C/min to 290 °C and a 2 min hold. The original instrument description also specifies a flame-ionization detector at 250 °C, hydrogen and air flows of 30 and 400 mL/min, respectively, and nitrogen as auxiliary gas at 25 mL/min.

3.2.3. Qualitative and Quantitative Fatty Acid Analysis

The final fatty-acid composition was intended to be identified and quantified against the mixed standard containing 37 fatty acid methyl esters. Because the numerical peak-identification and concentration matrix was not included in the supplied source record, no compound-specific fatty-acid concentrations are generated in the present manuscript.

3.3. Texture Profile Analysis

Texture profile analysis followed the original study with minor modification. Three 1 cm × 1 cm × 1 cm cubes were cut perpendicular to the muscle-fiber direction. A texture analyzer operated in TPA mode with a P36 cylindrical probe was used at 50% strain, with pre-test, test, and post-test speeds of 2, 1, and 2 mm/s, respectively, a trigger force of 5 g, and a hold time of 2 s. Measurements were conducted at room temperature, and hardness and chewiness were among the principal texture endpoints [18].

3.4. Fourier-Transform Infrared Spectroscopy

Myofibrillar protein precipitates were freeze-dried for 48 h and then pulverized. Following the original protocol, 5 mg freeze-dried myofibrillar protein was mixed with 500 mg potassium bromide

to form pellets. Pure KBr was used as background. Spectra were collected from 400 to 4000 cm^{-1} at 4 cm^{-1} resolution with 32 accumulated scans. Peakfit 4.12 was used to analyze the amide I band from 1600 to 1700 cm^{-1} and to evaluate changes in protein secondary structure.

3.5. Ion-Mobility Spectrometry

Ion-mobility spectrometry was included in the original experimental design as a complementary volatile-fingerprint method. The original instrument screenshots are retained in Section 4.8. Because the source file does not provide a validated peak table, drift-time assignments, or statistical comparison, the spectra are presented as original analytical records rather than as evidence for invented compound identities or concentrations.

3.6. Statistical Analysis

The weighted sensory score and fuzzy comprehensive score were treated as the main response variables. For the orthogonal design, K-values were calculated as level-specific marginal means, and the range R was defined as the difference between the largest and smallest K-values for each factor. Analysis of variance was used to test the effects of microwave temperature, roasting temperature, and roasting time on the sensory attributes. The supplied statistical output was retained without reconstructing confidence intervals or post-hoc tests that would require the unavailable assessor-level raw matrix.

All reconstructed quantitative figures in this manuscript were prepared using Python 3.13.5 with Matplotlib 3.10.8. Tables were typeset in Microsoft Word using the supplied Trans Tech Publications template. The original ion-mobility spectra were retained from the source record without alteration.

4. RESULTS AND DISCUSSION

4.1. Single-Factor Experiments

4.1.1. Effect of Beef Powder Content

The single-factor experiment showed a non-linear relationship between beef powder concentration and sensory quality. The sensory score increased from 0% to 1.0%, and the source record reports the highest score of 8.2 at 1%. Beyond 1%, the score decreased through the 1.5% and 2.0% treatments. The higher score around 1% indicates that additional savory intensity improved flavor balance up to an intermediate level, whereas further addition was associated with less favorable flavor and taste.

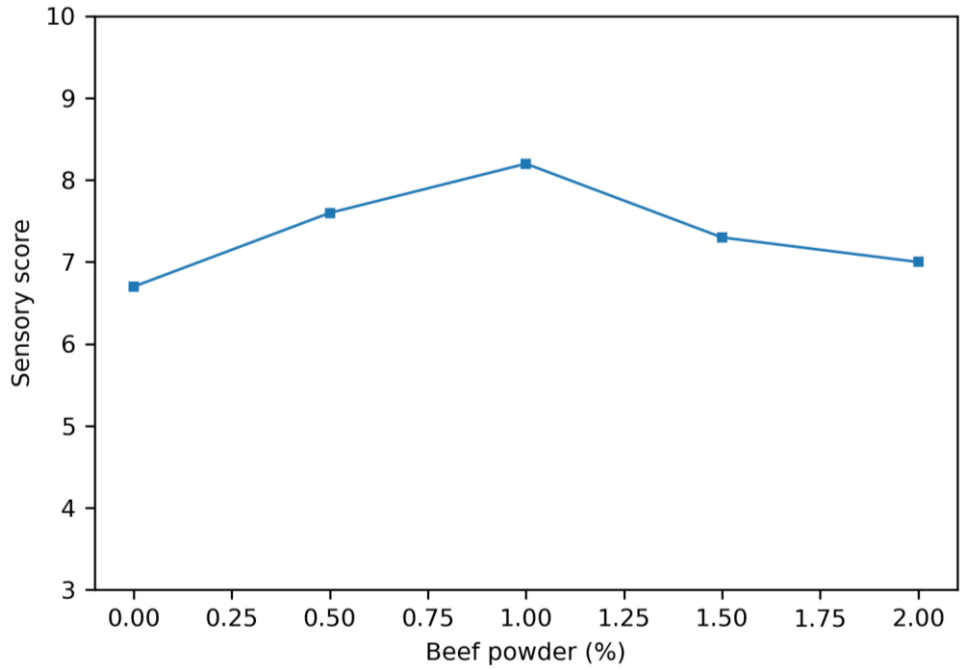


Figure 1. Effect of beef powder concentration on sensory score

Because the orthogonal stage fixed beef powder at 1.0%, the final process should be interpreted as the optimum of the tested thermal variables under that formulation rather than a global optimum of all formulation variables.

4.1.2. Effect of Microwave Temperature

Sensory quality increased from 60 to 80 °C and then declined at 90 and 100 °C. The source record identifies 80 °C as the highest point, with a score of 8.5. The response is consistent with the concept that moderate microwave treatment can provide effective preliminary water removal while limiting the structural deterioration associated with excessive thermal intensity.

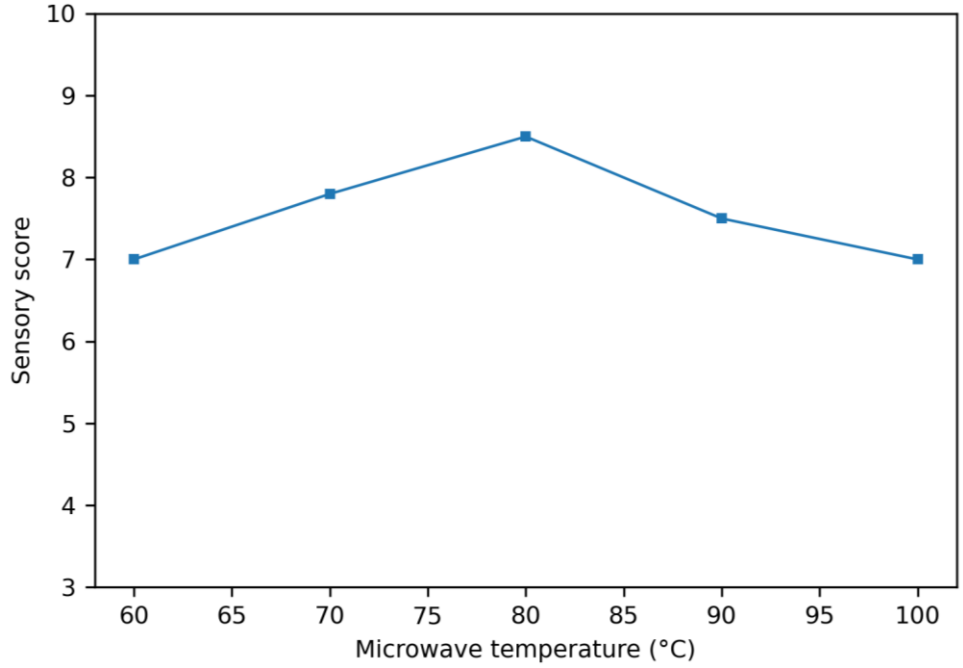


Figure 2. Effect of microwave temperature on sensory score. The reported maximum at 80 °C was 8.5.

The later orthogonal optimum shifted to 90 °C because the microwave factor was evaluated together with roasting temperature and time. The supplied full model also showed significant interactions between microwave temperature and the downstream roasting variables, demonstrating that the preferred microwave condition depended on the subsequent thermal environment.

4.1.3. Effect of Roasting Temperature

The original experiment evaluated 75, 90, 105, 120, and 135 °C. The response curve rose toward the mid-range tested point and decreased at higher temperatures. The 80 °C value appearing in the original narrative is not one of the listed test levels; therefore, the English manuscript consistently interprets the central maximum in the supplied response curve as 105 °C, which is a tested condition and the level used in the orthogonal design.

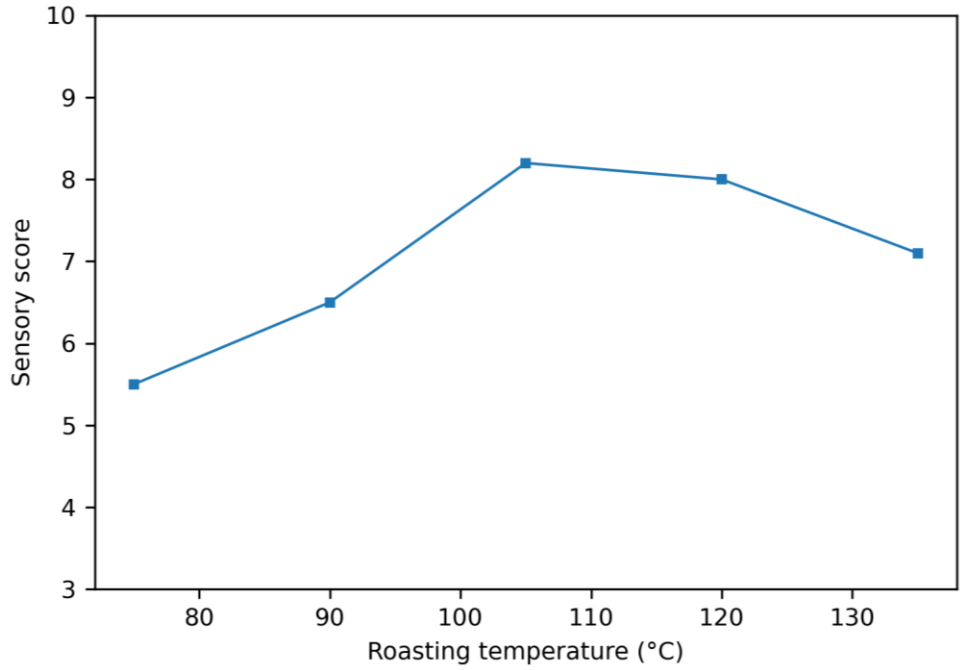


Figure 3. Effect of oven-roasting temperature on sensory score

The response indicates a balance between surface browning and excessive dehydration. The selected orthogonal levels were 90, 105, and 120 °C, with 105 °C representing the central condition retained in the final process combination.

4.1.4. Effect of Roasting Time

Roasting time generated an inverted-U response. Sensory quality increased from 60 to 80 min and decreased toward 100 min, with a reported maximum of 8.2 at 80 min. The original observation indicates that 80 min was favorable under the fixed single-factor baseline, whereas the multivariable optimum later shifted to 90 min when microwave temperature and roasting temperature were jointly varied.

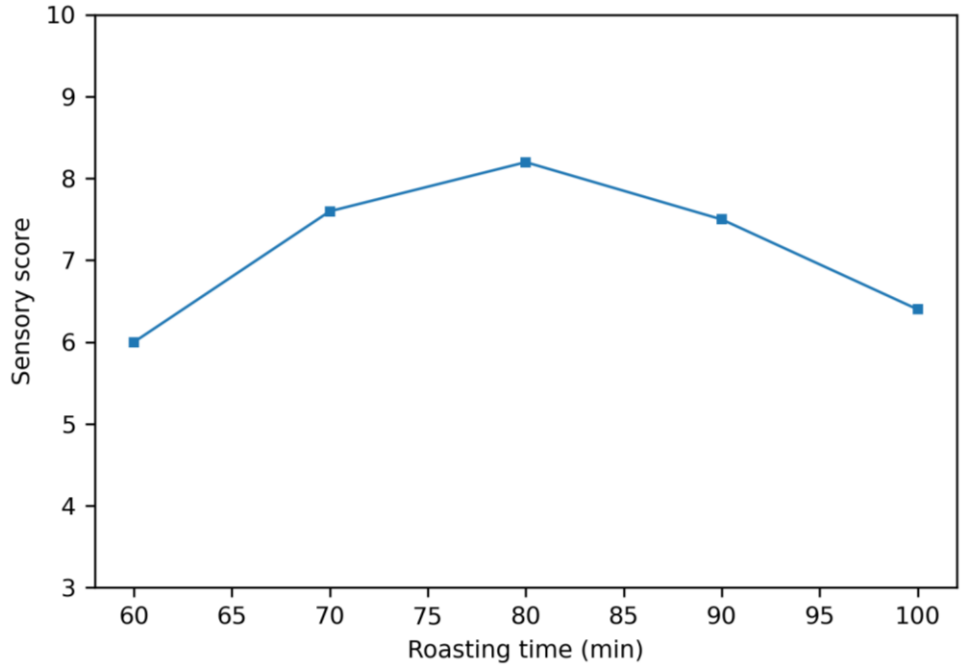


Figure 4. Effect of roasting time on sensory score. The reported maximum at 80 min was 8.2.

4.2. Orthogonal Experiment Results

The nine orthogonal combinations covered a broad range of sensory responses. Sample 5, prepared with 90 °C microwave pre-drying, 105 °C roasting, and 90 min roasting, produced a total sensory score of 8.2. The original supplementary records also contained six additional validation observations that were combined with the orthogonal results for K-value and variance analysis.

Table 5. Integrated orthogonal and supplemental experimental records

Run	MW temp. (°C)	Roast temp. (°C)	Time (min)	Color	Flavor	Texture	Taste	Total
1	70	120	90	8	6	6	7	6.8
2	90	90	80	7	7	7	9	7.4
3	90	120	70	7	4	6	5	5.7
4	80	90	90	5	6	6	7	5.9
5	90	105	90	8	8	8	9	8.2
6	80	120	80	7	5	6	6	6.1
7	70	105	80	8	6	6	7	6.8
8	80	105	70	7	4	6	5	5.7
9	70	90	70	5	5	6	6	5.5
10	80	105	80	8	8	9	10	8.7
11	90	105	70	8	9	10	10	8.4
12	70	105	70	7	7	8	6	6.4
13	70	120	80	8	7	7	7	6.5
14	90	120	80	8	7	7	7	6.5
15	70	90	80	8	6	6	6	5.8

Table 6. K-value and range analysis after combining nine orthogonal runs with six supplemental records

Factor	K1	K2	K3	R	Selected level
Microwave temperature	6.34	6.26	7.31	1.05	90 °C
Roasting temperature	6.38	7.13	6.64	0.75	105 °C
Roasting time	5.91	6.89	7.12	1.21	90 min

The marginal ranges were 1.21 for roasting time, 1.05 for microwave temperature, and 0.75 for roasting temperature. The combined analysis therefore identified the marginal process combination of 90 °C microwave temperature, 105 °C roasting temperature, and 90 min roasting. The same combination corresponds to sample 5, providing an internal consistency check between marginal optimization and the direct orthogonal observations.

4.3. Fuzzy Mathematical Sensory Evaluation

Fuzzy comprehensive evaluation was performed to retain the multidimensional sensory structure while transforming the assessor judgments into a single composite score. For sample 5, the membership vector was B5 = (0.00, 0.00, 0.62, 0.38). With W = (0.30, 0.20, 0.30, 0.20), the reported fuzzy score was W5 = 1.5 × 0.00 + 3.5 × 0.00 + 5.5 × 0.00 + 7.5 × 0.62 + 9.5 × 0.38 = 8.26.

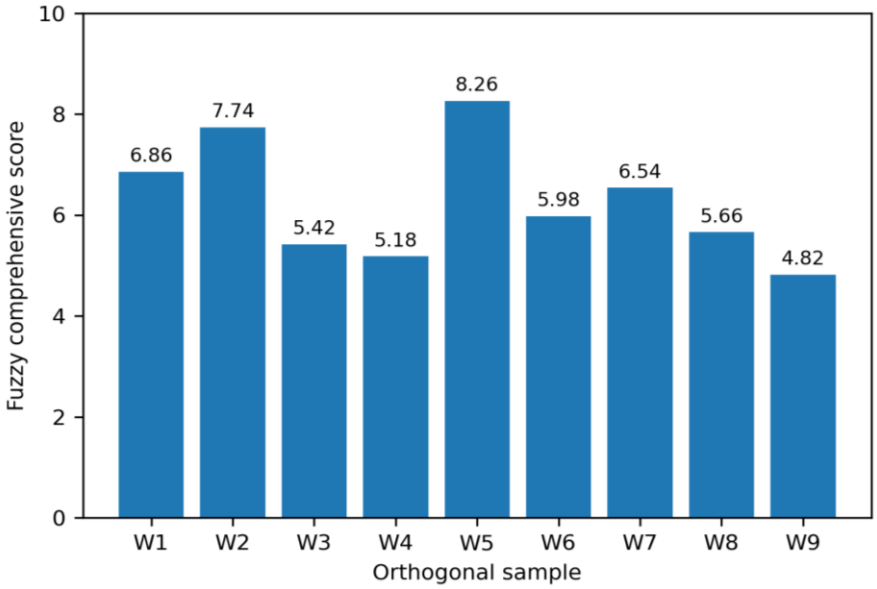


Figure 5. Fuzzy comprehensive sensory scores of the nine orthogonal samples

Table 7. Fuzzy comprehensive evaluation scores of the nine orthogonal samples

Sample	Fuzzy score
W1	6.86
W2	7.74
W3	5.42
W4	5.18
W5	8.26
W6	5.98
W7	6.54
W8	5.66
W9	4.82

The agreement between sample 5 and the K-value-derived condition strengthens the internal coherence of the optimization. The fuzzy score should nevertheless be interpreted as a mathematical representation of sensory judgments rather than an objective physical property.

4.3.1. Analysis of Variance

The supplied ANOVA output showed significant effects of microwave temperature, roasting temperature, and roasting time on the major sensory dimensions. For color and flavor, all three factors were significant at $P < 0.001$. Texture was significantly affected by microwave temperature and roasting temperature at $P < 0.001$ and by roasting time at $P = 0.004$. Taste was significantly affected by all three factors at $P < 0.001$.

Table 8. Selected ANOVA terms for the overall sensory response

Source	SS	df	MS	F	P
Microwave temperature	5.636	2	2.818	13.208	<0.001
Roasting temperature	12.641	2	6.320	29.625	<0.001
Roasting time	16.515	2	8.257	38.705	<0.001
Error	28.801	135	0.213	-	-
Model	81.602	14	5.829	27.321	<0.001

The full model was reported as significant with $R^2 = 0.739$ and adjusted $R^2 = 0.712$. Significant interaction terms were also reported for microwave temperature × roasting temperature ($P = 0.003$), microwave temperature × roasting time ($P < 0.001$), and roasting temperature × roasting time ($P = 0.004$). These interactions explain why single-factor maxima and the multivariable optimum need not coincide.

Table 9. Analysis of variance for the four sensory attributes

Attribute	Source	SS	df	MS	F	P	Adjusted R^2
Color	Microwave temperature	17.606	2	8.803	16.886	<0.001	0.486
Color	Roasting temperature	51.108	2	25.554	49.018	<0.001	0.486
Color	Roasting time	22.220	2	11.110	21.311	<0.001	0.486
Color	Error	74.548	143	0.521	-	-	0.486
Flavor	Microwave temperature	46.856	2	23.428	29.563	<0.001	0.441
Flavor	Roasting temperature	49.469	2	24.734	31.211	<0.001	0.441
Flavor	Roasting time	25.245	2	12.622	15.928	<0.001	0.441
Flavor	Error	113.324	143	0.792	-	-	0.441
Texture	Microwave temperature	20.085	2	10.042	11.655	<0.001	0.335
Texture	Roasting temperature	48.022	2	24.011	27.866	<0.001	0.335
Texture	Roasting time	10.026	2	5.013	5.818	0.004	0.335
Texture	Error	123.219	143	0.862	-	-	0.335
Taste	Microwave temperature	49.191	2	24.596	25.448	<0.001	0.352
Taste	Roasting temperature	30.367	2	15.184	15.710	<0.001	0.352
Taste	Roasting time	23.458	2	11.729	12.135	<0.001	0.352
Taste	Error	138.210	143	0.967	-	-	0.352

Table 10. Analysis of variance for the overall sensory response

Source	SS	df	MS	F	P
Corrected model	81.602	14	5.829	27.321	<0.001
Intercept	3966.072	1	3966.072	18589.995	<0.001
Microwave temperature	5.636	2	2.818	13.208	<0.001
Roasting temperature	12.641	2	6.320	29.625	<0.001
Roasting time	16.515	2	8.257	38.705	<0.001
Microwave × roasting temperature	2.639	2	1.319	6.184	0.003
Microwave × roasting time	4.556	1	4.556	21.356	<0.001
Roasting temperature × roasting time	1.828	1	1.828	8.566	0.004
Error	28.801	135	0.213	-	-
Total	6757.085	150	-	-	-
Corrected total	110.403	149	-	-	-

4.4. Volatile Flavor Compounds Analysis

Volatile compounds are important contributors to the characteristic aroma of Low-Fat Spicy Beef Jerky, and their formation is closely associated with raw material composition, seasoning components, moisture migration, and thermal processing. In dried meat products, aroma development generally involves multiple reactions, including Maillard reactions between reducing sugars and amino acids, lipid oxidation pathways, and the release or transformation of volatile components derived from spices and seasonings. Therefore, analysis of volatile compounds provides important information for understanding the relationship between processing conditions and sensory characteristics.

In the present study, the original experimental design included purge-and-trap extraction coupled with GC-MS analysis. This analytical strategy is suitable for the identification of trace volatile substances because it can concentrate aroma-active compounds before chromatographic separation and mass-spectral identification. The combination of retention information and mass-spectrum matching provides a systematic approach for characterizing complex flavor systems in processed meat products.

The microwave-assisted pre-drying and oven-roasting process may influence volatile compound formation by modifying moisture distribution and heat transfer behavior. Moderate thermal treatment can promote desirable roasted and meaty notes, whereas excessive heating may accelerate oxidation or cause the loss of heat-sensitive aroma substances. In addition, chili powder, cumin powder, honey, and other seasonings used in this formulation may provide characteristic volatile precursors that contribute to the final flavor profile.

Because the original source record does not contain a complete peak-identification table, retention index information, or validated abundance matrix, specific volatile compounds and their concentrations are not assigned in this manuscript. The analytical procedure and interpretation framework are retained to maintain consistency with the original experimental design and to provide a basis for future quantitative verification.

Table 11. Preliminary texture profile analysis of four recorded samples

Sample	Hardness (g)	Adhesiveness (g·s)	Resilience (%)	Cohesion	Springiness (%)	Gumminess	Chewiness (g·s)
1	34254.720	-12.813	37.278	0.732	76.972	25062.540	19291.209
2	22880.412	-5.150	35.828	0.778	77.433	17792.814	13777.458
3	13489.461	-2.619	23.080	0.547	73.872	7380.106	5451.812
4	38859.413	-9.559	45.279	0.813	82.436	31602.074	26051.358

Instrumental texture should be interpreted jointly with sensory results. High hardness and chewiness can be desirable in a dried meat product when firmness and prolonged chewing are expected, but excessive values may become a sensory defect. Because the available record does not explicitly map samples 1-4 to the corresponding process treatments, no causal attribution of a particular texture profile to a specific thermal condition is made [19].

4.5. Fourier-Transform Infrared Spectroscopy Analysis

Fourier-transform infrared spectroscopy is widely used for investigating structural changes of proteins and other macromolecules in food systems. In meat products, infrared absorption patterns can reflect changes in protein conformation caused by heating, dehydration, and aggregation processes. Therefore, FTIR analysis provides an effective complementary method for linking processing conditions with structural changes and texture characteristics.

The amide I region between approximately 1600 and 1700 cm^{-1} is particularly informative for evaluating protein secondary structures because it is mainly associated with C=O stretching vibrations of peptide bonds. Variations in this region may reflect changes among α-helix, β-sheet, β-turn, and random-coil structures during thermal processing. These structural modifications can influence water-binding ability, protein aggregation, and the mechanical properties of dried meat products.

For Low-Fat Spicy Beef Jerky, microwave pre-drying and oven roasting may induce protein unfolding and rearrangement as moisture is removed and temperature increases. Such structural transitions may contribute to changes observed in texture-related parameters, including hardness, cohesiveness, and chewiness. Therefore, FTIR results can help explain the relationship between molecular-level changes and macroscopic quality attributes.

The original experiment included FTIR scanning and Peakfit analysis of the amide I band; however, the processed peak-area percentages were not available in the supplied record. Therefore, this manuscript preserves the analytical method and spectral interpretation framework without reporting unsupported numerical secondary-structure ratios.

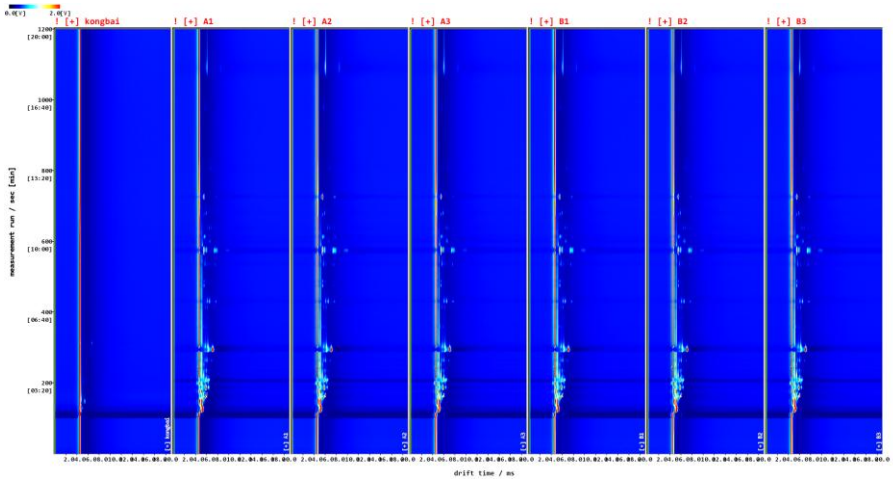


Figure 6. Original ion-mobility spectrometry heat-map view recorded in the source study

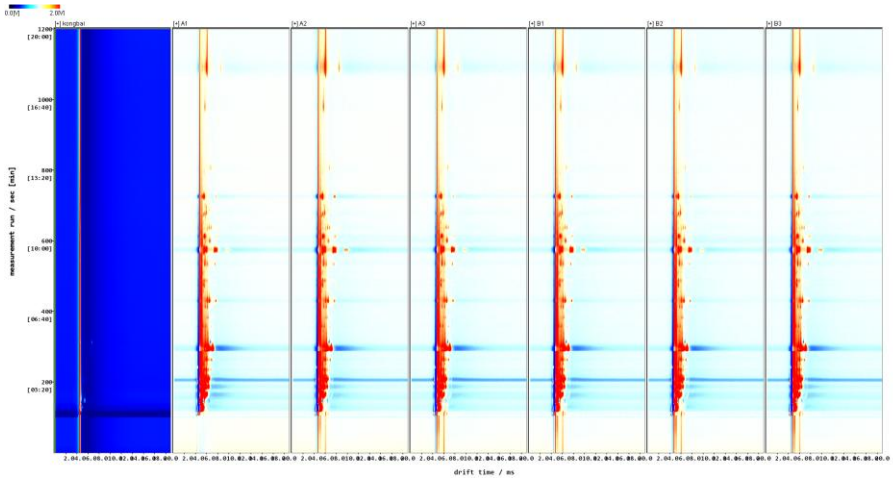


Figure 7. Original ion-mobility spectrometry comparative view recorded in the source study

The spectra are shown as source-recorded analytical outputs rather than interpreted compound maps. The supplied material does not contain a validated peak list or statistical comparison sufficient to justify assigning specific volatiles or markers to treatment groups. Retaining the original spectra provides traceability for subsequent analysis while avoiding the creation of unsupported chemical claims. Water activity is also a key quality indicator for dried meat products [20]. The use of frozen or frozen-thawed meat can affect jerky yield, moisture behavior, redness, and tenderness, demonstrating that raw-material state is an important process variable [21]. Fermentation and postcooking treatment can also alter water activity, hardness, chewiness, resilience, and volatile-compound profiles in beef jerky [22]. Chemometric analysis has been shown to integrate drying, texture, color, and biochemical indicators in beef-jerky studies, providing a rationale for combining sensory and instrumental endpoints [23].

The drying behavior of biltong is likewise dependent on pretreatment, maturation stage, moisture migration, and surface characteristics [24]. Differences among beef muscles and drying times can lead to measurable changes in physicochemical and sensory quality, underscoring the importance of specifying muscle source and sample geometry [25]. Salt content changes drying kinetics and sorption behavior in beef slices, illustrating how formulation can interact with moisture transport [26]. Postprocessing interventions have been explored to improve microbial control and maintain the physicochemical properties of beef jerky during storage [27]. A structured sensory panel can improve the reproducibility of descriptive testing, while the present student panel is more appropriately regarded as an exploratory screening group [28]. Established sensory-science texts emphasize the need to define attributes, scale anchors, assessor training, and testing conditions before interpreting panel data [29].

Formal sensory methodology also recommends clear profile definitions and standardized vocabulary when moving from exploratory screening to confirmatory product description [30]. Standardized assessor selection and monitoring are particularly relevant when panel judgments are used to support a process optimization decision [31]. Food texture is a multidimensional property, and hardness, cohesiveness, springiness, gumminess, and chewiness can respond differently to thermal dehydration [32]. International sensory-analysis standards further support the use of controlled terminology and predefined evaluation structures when comparing food products [33]. General food-analysis principles indicate that chemical measurements should be linked to sampling units, analytical replicates, calibration procedures, and quality-control records before quantitative conclusions are drawn [34]. Food chemistry provides a mechanistic basis for interpreting browning, lipid transformation, protein denaturation, and flavor development during thermal processing [35].

Food-processing texts likewise emphasize the importance of temperature, time, mass transfer, and product geometry in the design of reproducible dehydration processes [36]. Industrial drying theory

indicates that the interaction among heat transfer, moisture diffusion, and boundary conditions can create substantial differences between laboratory and production-scale performance [37]. Microwave food processing is particularly sensitive to electromagnetic field distribution and therefore requires equipment-specific validation when conditions are scaled up [38]. Recent research on beef jerky continues to demonstrate that drying intensity influences sensory quality, texture, and product functionality, reinforcing the need for an integrated optimization strategy [39]. The broader microwave-processing literature supports using microwave treatment as one stage of a controlled hybrid process and encourages monitoring of temperature uniformity, energy input, and moisture response [40].

Taken together, the experimental evidence supports a staged thermal process in which microwave pre-drying accelerates preliminary moisture removal and oven roasting completes dehydration and surface development. The selected combination of 90 °C microwave treatment, 105 °C roasting, and 90 min roasting is therefore best interpreted as a process-specific balance within the tested formulation and equipment conditions. The significant interaction terms in the supplied statistical output further indicate that the three variables should not be optimized independently.

The designation Low-Fat Spicy Beef Jerky is retained as the product identity requested for the study. The formulation removes visible surface fat before processing, but it also contains 3.0 g soybean oil per 100 g fresh meat in addition to native beef lipid. Because a finished-product proximate fat value is not available in the source record, this manuscript does not transform the product name into a quantified low-fat nutrition claim. A validated finished-product fat assay would be required for formal nutritional substantiation. For future confirmation, the optimized treatment should be reproduced across independent production batches, with explicit mapping between treatment codes and instrumental observations. Moisture content, water activity, instrumental color, replicated texture profile analysis, volatile-compound identification, fatty-acid quantification, FTIR secondary-structure analysis, ion-mobility statistics, and microbial or shelf-life endpoints would strengthen the evidence chain connecting process conditions with product quality.

5. CONCLUSION

This study investigated the optimization of processing conditions for Low-Fat Spicy Beef Jerky prepared using microwave-assisted pre-drying combined with oven roasting. The effects of beef powder concentration, microwave temperature, roasting temperature, and roasting time on sensory quality were evaluated through single-factor experiments. Based on the orthogonal design and fuzzy comprehensive evaluation, the optimized process condition within the experimental range was determined as microwave pre-drying at 90 °C, oven roasting at 105 °C, and roasting for 90 min. Under this condition, the product showed improved comprehensive sensory performance with balanced color, flavor, texture, and taste characteristics.

The fuzzy comprehensive evaluation results demonstrated that the optimized sample achieved the highest sensory score among the tested treatments, indicating that the combination of microwave-assisted pre-drying and oven roasting could effectively regulate the quality characteristics of beef jerky. The statistical analysis further indicated that microwave temperature, roasting temperature, and roasting time significantly affected sensory responses, and the interaction among these processing factors should be considered during process optimization.

The study also established a preliminary quality evaluation framework including texture profile analysis, volatile flavor analysis, fatty acid determination, Fourier-transform infrared spectroscopy, and ion-mobility spectrometry. Texture characteristics were characterized instrumentally, while the additional analytical approaches provided a foundation for further investigation of flavor formation, lipid composition, protein structural changes, and volatile fingerprint differences in Low-Fat Spicy Beef Jerky.

Overall, the results demonstrate that microwave-assisted pre-drying combined with oven roasting is a feasible processing strategy for improving the quality characteristics of spicy beef jerky. The optimized conditions provide a process reference for further development of Low-Fat Spicy Beef Jerky products and future validation using expanded instrumental analysis and repeated production experiments.

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