Hindawi
Journal of Food Processing and Preservation
Volume 2023, Article ID 9052417, 12 pages
https://doi.org/10.1155/2023/9052417

Research Article

Dielectric Roasting Induced Physical, Mechanical, and Grinding Characteristics of Black Pepper (*Piper nigrum*)

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Received 31 May 2023; Revised 11 September 2023; Accepted 14 September 2023; Published 26 September 2023

Academic Editor: Bhupendra M Ghodki

The present study was focused on microwave (dielectric) roasting (300-600 W, 5-15 min) on the physical, textural, color, and grinding of black pepper. The microwave roasting is a volumetric heating that causes rapid removal of moisture, and internal pressure generated inside the seed tends to change the physiology and physical attributes. An increase in roasting power and time increased the geometric mean diameter (5.216 to 6.283 mm), sphericity (0.883 to 0.927), aspect ratio (0.853 to 0.914), and surface area (85.560 to 124.262 mm^2) of black pepper. Whereas the significant ($p < 0.05$) reduction was observed in 100 grain weight (7.55 to 5.63 g), bulk density (500.97 to 251.38 kg/m^3), fracturability (72.99 to 1.78 N), and hardness (63.65 to 1.61 N). Roasting led to browning, and a significant reduction was observed in the color parameters, L^* (22.82 to 17.76), a^* (2.47 to 0.56), and b^* (2.41 to -0.75) with a significant ($p < 0.05$) increase in total color difference (0.96 to 5.30). Roasting also increased the particle size distribution in grounded power, and the mean particle size increased from 121.72 to 146.14 μm.

1. Introduction

Black pepper (*Piper nigrum*), also known as the "King of Spices" or "black gold," is the oldest and the world's most important spice [1–3]. It is a climbing, perennial shrub belonging to the *Piperaceae* family [4]. The word pepper is derived from the Sanskrit word pippali, which means berry, and piper is a Latin word for pepper [5]. It originated from the hills of the South Western Ghats of India (Malabar Coast in Kerala), and now it has become an important component of universally used culinary seasoning worldwide. The main constituent responsible for the pungency of black pepper is the piperine content, whereas the aroma and flavor are contributed by the volatile oil [6, 7].

Spices can be consumed in different ways like whole, powdered, roasted, etc. Roasting of spices is the "secret of Indian cuisine" and is generally performed prior to its use in cooking. Roasting is a high-temperature, short-time thermal processing, and the temperature may vary from 150–300°C depending on the product and desirability [8]. It is a complex heat and mass transfer process causing different thermal and chemical reactions that ultimately lead to the development of aroma, flavor, and change in physio-functional properties. Different spices like black pepper, cumin, coriander, and cardamom are commonly consumed/used after roasting. Different studies have been performed to analyze the flavoring profile with respect to the roasting of spices such as black pepper [9], cumin [10–12], black cumin [13, 14], coriander [11, 12], clove [15], and cinnamon [16]. However, studies are limited to flavor profiling of spices, and the author has not found any studies highlighting the effect of roasting on the physical, textural, and grinding properties of black pepper, which are currently lacking.

Roasting can be done through different methods like pan, sand, infrared, and microwave roasting. Among these, microwave roasting can be performed in a household as well as industrial level due to its higher efficiency than traditional processing techniques [17]. The electromagnetic waves in the frequency range of 300–3000 MHz, generated by a magnetron, involve heating by impinging on the dielectric properties of food material [18]. Frictional heat, generated by dipole rotation of water molecules and ionic conduction, causes the heating of food material during processing [19, 20]. Microwave roasting eliminates the limitations of conventional roasting, such as temperature control, temperature distribution, and hygiene, causing significant changes in the nutritional quality of food. It is a novel method of roasting that is more concerned with selective heating, quicker start-up, lower processing time, quality of end product, better sensory attributes, and food hygiene [21–23]. The short roasting period in a microwave, compared to traditional roasting, improves the quality of food products and proves to be a less time-consuming and energy-efficient process [24, 25]. Additionally, the development of roasted flavor and its retention create distinctive tastes and aromas that increase consumer acceptability [9, 10]. The high-power density for a short time reduces the yeast and mould count and brings microbial reduction to increase the safety and hygiene aspect of spices [21, 26], which reflects the industrial potential of microwave roasting in the decontamination and processing of spices.

The investigation of the effect of roasting on different physical properties, such as size, sphericity, density, and surface area, is important in the design of packaging material, handling, transportation, and storage systems [27]. Color is an important physical parameter in human perception to accept or reject a product [28]. Textural properties such as hardness, fracturability, and rupture energy are important parameters for designing equipment for grinding, milling, mixing, etc. Grinding is the essential operation of the spice industry to convert into powder form. It increases the surface area of spices, ultimately increasing the availability of nutrients, taste, and flavor components [29, 30], and reduces the cost of packaging, transportation, and storage [31]. The inside-out volumetric heating causes rapid removal of moisture from food, and expansion of geometry tends to change the properties of the seed [23]. Particle size distribution plays an important role in quality control and influences organoleptic properties (texture, mouth feel, etc.) and storage stability of the product. These properties help in the design and simulation of process parameters and equipment to ensure the higher quality of the end product for better consumer acceptability.

Considering the limited studies on the roasting of black pepper (Figure 1) and its effect on the physical and textural properties of spices and particle size distribution, the present study was designed to observe the effect of microwave roasting parameters such as microwave power and exposure time on the physical and textural properties of black pepper seed and particle size distribution of roasted black pepper powder.

2. Materials and Method

2.1. Sample Collection. Black pepper (var. Wayanadan, extra-bold) with a brownish-black color and a shriveled surface was procured from Cropnrich Agri. Pvt. Ltd., Pariyaram, Wayanad, Kerala, through SPIISRY, an online sales outlet of ICAR-IISR, Kozhikode, Kerala (India). The pepper seeds were cleaned manually, and broken, foreign matter, split, and deformed were removed. The initial moisture content of black pepper seed was determined using the standard method (AOAC, 2005). The graded samples were packed in aluminum pouches (thickness: 70 microns) and kept in a desiccator for further processing and analysis.

2.2. Roasting of Black Pepper. Roasting of the graded sample was performed using the laboratory-scale microwave (CE104VD, 2,450 MHz, Samsung, India), having maximum input power and rated power output of 1,400 W and 900 W, respectively. Samples (50 g) were placed in a glass petri dish (155 mm diameter), and roasting was performed at three different power levels (300, 450, and 600 W) for three different time intervals (5, 10, and 15 min). An unroasted sample was used as a control to compare the effect of roasting on different properties of black paper.

The levels of microwave energy and exposure time were selected based on the preliminary trials as per the specifications of the laboratory-scale oven (CE104VD, 2,450 MHz, Samsung, India). After roasting, samples were allowed to cool in a desiccator, packed, and kept in an airtight container at room temperature until further analysis.

The microwave dosage (kWh g^{-1}) supplied to the black pepper seeds was calculated using the following [32]

$$\mathrm{MD}(\mathrm{kWhg}-1)=\frac{\text{Microwave Power (W)}\times\text{Exposure Time (min)}}{\text{Initial Weight of Sample (g)}\times 1000\times 60}. \tag{1}$$

2.3. Effect of Roasting on Properties of Black Pepper Seeds

2.3.1. Physical Properties. The physical dimensions of control (unroasted) and roasted black pepper were determined by picking 100 seeds randomly from each treatment and measuring their three principal dimensions, namely, major (a), intermediate (b), and minor (c) axes, using a digital micrometer screw gauge (Least count: 0.001 mm) [27]. The geometric mean diameter (D_g, mm), aspect ratio (R_a), sphericity (ϕ), and surface area (S, mm^2) were calculated using the following equations ((2)–(5)) [27]. The average bulk density (BD) of the control and roasted black pepper seeds was determined using the standard test weight procedure described by Nimesh and Sharanagat [33]. The seeds were poured into a known volume measuring cylinder and tapped manually (10 times) to fill the pore spaces, followed by weighing. The BD of seeds was measured using Eq. (6). A hundred seeds were randomly counted from a batch of control and each roasted treatment using the seed counter (INOSAW, Osaw Industrial Products Pvt. Ltd., S6709, India) and were used to calculate the W_{100} as described by Sharanagat et al. [27].

$$D_g=\sqrt[3]{abc}, \tag{2}$$

$$\mathrm{R_a}=\frac{\mathrm{b}}{\mathrm{a}}, \tag{3}$$

$$\phi=\frac{\sqrt[3]{abc}}{\mathrm{a}}, \tag{4}$$

$$S=\pi Dg^2, \tag{5}$$

$$BD=\frac{\text{Weight of seeds (kg)}}{\text{Volume of container }(\mathrm{m}^3)}, \tag{6}$$

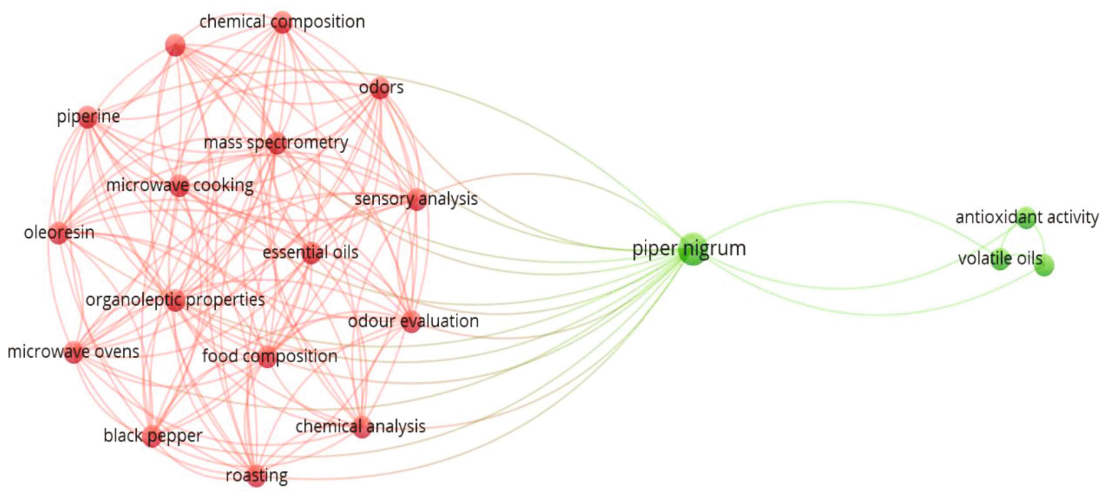


Figure 1: Network diagram of bibliometric literature review of roasting of black pepper.

where *a*, *b*, and *c* are the major, intermediate, and minor axes, respectively.

2.3.2. Color Analysis. Hand-held chroma meter (Konica Minolta, CR-400, Japan) was used to determine the effect of roasting on the color of black pepper. The color parameters (L^*: lightness/darkness, a^*: redness/greenness, and b^*: yellowness/blueness) were measured as described by Sharanagat et al. [34]. Color parameters were used to calculate the total color difference (ΔE) and browning index (BI) using equations (7) and (8), respectively.

$$\Delta E = \sqrt{(L_1^* - L_0^*)^2 + (a_1^* - a_0^*)^2 + (\mathrm{b}_1^* - \mathrm{b}_0^*)^2}, \quad (7)$$

$$\mathrm{BI} = \frac{100 \times (X - 0.31)}{0.17}, \quad (8)$$

where L_1, a_1, and b_1 are the values for roasted sample. L_0, a_0, and b_0 are the values of control sample

$$x = \frac{(a^* + 1.75L^*)}{5.64\,L^* + a^* - 3.01b^*}. \quad (9)$$

2.3.3. Textural Properties. A texture analyzer (Stable Micro Systems, TA-HDplusC, UK) was used to observe the texture profile of control and roasted black pepper. Before analysis, the height and force calibration were performed, and the samples were subjected to 50% compression using a cylindrical probe (75 mm diameter) and 30 kg load cell. The other parameters like trigger force (5 g), pretest speed (1 mm/sec), test speed (1 mm/sec), and posttest speed (5 mm/sec) were set for analysis [27]. Textural parameters such as hardness and fracturability were determined by analyzing the texture profile analysis (TPA) graph.

2.3.4. Particle Size Distribution (PSD). Grinding of control and roasted black pepper seeds was performed using an automatic hammer mill (Rathi Pumps Pvt. Ltd., Haryana, India) with sieve no. 1 (0.5 mm). A 100 g sample was taken in the hammer mill for dry milling of black pepper seeds. Particle size analysis of control and roasted black pepper powder was performed using sieve analysis. The sample was passed through a set of sieves ranging from 300, 250, 210, 180, 150, 105, 75, and 38 μm and pan for 20 min using an electronic sieve shaker (Macro Scientific Works Pvt. Ltd., Delhi). The sample retained on each screen was collected and weighed to calculate the mass fraction and percent retained on each screen. The average particle size was calculated using eq. (10) [30]. The particle size distribution (PSD) of the black pepper powder was observed in the form of D_{10}, D_{50}, D_{60}, and D_{90}, which indicate the total percentiles of particle sizes below the values of 10%, 50%, 60%, and 90%, respectively, in a cumulative size distribution [35–37], and coefficient of uniformity (CU) and span which indicate the width of distribution [38] were calculated using eqs. (11) and (12), respectively.

$$L_2 = \sum_{i=1}^{n} d_i x_i, \quad (10)$$

$$\mathrm{Span} = \frac{(D_{90} - D_{10})}{D_{50}}, \quad (11)$$

$$\mathrm{CU} = \frac{D_{60}}{D_{10}}, \quad (12)$$

where

L_2 is the average particle size of powder after grinding (μm); d_i is the average aperture of the sieves (μm); and x_i is the mass fraction of the sample retained on each sieve.

2.4. Statistical Analysis. Two-way analysis of variance (ANOVA) was used to analyze the data using SPSS software (SPSS 25.0, SPSS Inc., Chicago, IL). The analyses were performed in triplicate, and the results were represented as the mean ± standard deviation. The statistically significant differences in the individual parameter and treatment combinations were determined at a significance level of $p < 0.05$ using Tukey's test.

3. Result and Discussion

3.1. Geometric Mean Diameter (D_g), Sphericity (ϕ), Surface Area (S), and Aspect Ratio (R_a). The black pepper seeds (moisture content: d.b.13.60 ± 0.15%) were roasted, and the different physical properties, viz., D_g, ϕ, S, and R_a were determined (Table 1). The physical properties are dependent upon the principle dimensions of the seed. An increase in microwave dosage led to the expansion of the seed's axial dimensions (major, intermediate, and minor axis). A significant ($p < 0.05$) increase was observed in D_g, i.e., 12.75% (300 W, 15 min), 16.14% (450 W, 15 min), and 20.46% (600 W, 15 min) (Table 1). The highest and lowest D_g were observed for the sample roasted at 600 W for 15 min (6.283 ± 0.31 mm) and the control sample (5.216 ± 0.21 mm), respectively. Similarly, the sphericity (ϕ) of all the roasted samples was higher than the control sample. The highest ϕ (0.927 ± 0.02) was recorded at 450 W for 5 min, whereas the lowest ϕ (0.883 ± 0.05) was recorded for the control sample. The overall increase in the ϕ at initial roasting conditions might be due to the higher expansion of smaller dimensions, and the later decrease in ϕ with higher roasting power and time might be due to severe roasting treatment, which caused shrinkage to the product [39]. The nonsignificant ($p \geq 0.05$) variation observed in the ϕ of roasted black paper might be due to the uneven dimensional expansion of black paper with the different roasting conditions. The increase in sphericity value with respect to control indicated that the roasted seeds tend towards a spherical shape, which generally indicates ease of rolling on a surface [39]. The surface area (S) of black pepper significantly ($p < 0.05$) increased from 12% to 45% upon roasting and varied in the range of 85.560 ± 6.98 mm^2 (control) to 124.262 ± 12.23 mm^2 (600 W, 15 min). It is an area of heat and mass transfer that could influence the reactions taking place inside the product during roasting. The increase in the surface area might be due to void space created in the cell matrix and expansion of the starchy endosperm when exposed to microwave energy [39]. The aspect ratio (R_a) was observed in the range of 0.846 ± 0.08 to 0.909 ± 0.07. A nonsignificant ($p \geq 0.05$) change was observed with respect to roasting parameters (roasting power and roasting time). All the roasted samples showed higher aspect ratio values than the control sample. The minimum R_a (0.853 ± 0.07) was obtained for the control sample, whereas the maximum R_a (0.914 ± 0.04) was obtained for the samples roasted at 450 W for 15 min. The initial increase in the R_a might be due to the expansion of black pepper seed along width and thickness compared to length. Later, prolonged exposure to high power caused cracks in seeds and tends to uneven expansion in geometric dimensions [39]. The increase in R_a was due to the expansion of geometric dimensions along the width and thickness compared to length.

3.2. Bulk Density and 100-Grain Weight. The bulk density (BD) is an important parameter that influences the packaging requirement of a product [40]. The effect of microwave roasting at different power levels and exposure time caused significant ($p < 0.05$) changes in the BD (Table 1). BD decreased with an increase in roasting power and time and varied in the range of 500.97 kg/m^3 (control) to 251.38 kg/m^3 (600 W for 15 min). The BD decreased with an increase in microwave power and time. It might be associated with a simultaneous reduction in weight due to rapid moisture removal with roasting and increases in the volume of the sample due to pressure buildup within the seed [41]. In addition to that, the removal of moisture with an increase in the degree of roasting reduced the W_{100} and was found to vary from 7.55 ± 0.38 to 5.63 ± 0.18 g. The major losses in weight are contributed by the rapid removal of moisture present in the product, whereas the release of volatile flavor compounds during roasting share a smaller contribution to weight loss [42]. A similar justifications were stated by Schoeman and Manley [43] for oven and forced convection continuous tumble (FCCT) roasting (180°C for 140 s) of wheat; Sharanagat et al. [27] for microwave (450, 600, and 900 W for 5, 10, and 15 min) and sand roasting (180, 200, and 220°C for 5, 10, and 15 min) of chickpea; and Sharanagat et al. [34] for microwave-roasted (300, 450, and 600 W for 5, 10, and 15 min) sorghum.

3.3. Color Analysis. Color is an important variable in roasting, indicating the degree of roasting, caramelization, and browning reactions [23, 44]. Color analysis of control and roasted black pepper seed is presented in Table 2. The color values of black pepper seeds were less affected due to inside-out heating during microwave roasting. The color values L^*, a^*, b^*, ΔE, and BI varied in the range of 22.82 ± 0.02 to 17.76 ± 0.08, 2.48 ± 0.09 to 0.56 ± 0.02, 3.26 ± 0.13 to −0.75 ± 0.04, 0.96 ± 0.03 to 5.30 ± 0.19, and 30.97 ± 0.73 to 4.8 ± 0.33, respectively. The decrease in L^* value was observed with an increase in roasting power and roasting time, indicating an inverse relationship between the L^* value and the degree of roasting. Similarly, a decrease in the a^* and b^* values was observed with an increase in the roasting level. The decrease in a^* and b^* indicates the decrease in redness and yellowness, respectively, with an increase in the roasting of black pepper. The loss in redness might be associated with the protein denaturation and thermal disintegration of pigment complexes [45, 46], whereas the loss in yellowness with higher microwave dosage might be associated with the production of darker color at higher temperature [46, 47]. The lowest value of a^* (0.56 ± 0.02) and b^* (−0.75 ± 0.04) was observed in the sample roasted at 600 W for 15 min, whereas the highest value of a^* (2.48 ± 0.09) and b^* (3.26 ± 1.26) was observed in the sample roasted at 300 W for 5 min and 450 W for 5 min, respectively. A similar decrease in a^* and b^* also reported by Suri et al. [45] for black cumin (*Nigella sativa* L.) seed oil upon dry air and infrared roasting. The decrease in the L^* value is attributed to the chemical reactions of phenolic compounds and the formation of Maillard products during roasting. A similar trend was observed by Bagheri et al. [48] for infrared-hot air roasting (air temperature: 100 and 120°C, IR power: 130 W, 165 W, and 200 W for 10, 20, and 30 min) of peanut kernels and Dhua et al. [49] for microwave roasting (600 W for 5 min) of pigmented wheat.

The findings were also supported by Fernando et al. [44] and Zhang et al. [50] for the infrared roasting of chilli and

Table 1: Effect of roasting on physical properties of black pepper seeds.

Power (W)	Time (min)	Microwave dosage (kWh g^{-1})	Major axis, a (mm)	Intermediate axis, b (mm)	Minor axis, c (mm)	D_g (mm)	R_a	ϕ	S (mm^2)	BD (kg/m^3)	W_{100} (g)
Control	0	0	5.926 ± 0.46^{ax}	5.028 ± 0.22^{ax}	4.775 ± 0.26^{ax}	5.216 ± 0.21^{ax}	0.853 ± 0.07^{ax}	0.883 ± 0.05^{ax}	85.560 ± 6.98^{ax}	500.97 ± 8.85^{dz}	7.55 ± 0.38^{cz}
300	5	0.00050	6.08 ± 0.23^{by}	5.375 ± 0.32^{by}	5.164 ± 0.23^{by}	5.525 ± 0.21^{by}	0.884 ± 0.05^{by}	0.909 ± 0.3^{by}	95.970 ± 7.39^{by}	463.67 ± 4.85^{cy}	7.44 ± 0.34^{cy}
	10	0.00100	6.28 ± 0.41^{byz}	5.572 ± 0.32^{byz}	$5.429 \pm 0.29b^{z}$	5.745 ± 0.28^{bz}	0.890 ± 0.06^{by}	0.917 ± 0.04^{by}	103.852 ± 10.07^{bz}	429.62 ± 6.90^{cx}	7.18 ± 0.34^{cxy}
	15	0.00150	6.41 ± 0.40^{bz}	5.700 ± 0.28^{bz}	5.572 ± 0.24^{bz}	5.881 ± 0.25^{bz}	0.891 ± 0.06^{by}	0.919 ± 0.04^{by}	108.806 ± 9.33^{bz}	$403.20 \pm 9.30^{c\alpha}$	6.86 ± 0.10^{cx}
450	5	0.00075	6.256 ± 0.43^{by}	5.622 ± 0.53^{cy}	5.343 ± 0.55^{by}	5.724 ± 0.28^{cy}	0.899 ± 0.07^{by}	0.915 ± 0.05^{by}	103.508 ± 17.12^{cy}	366.49 ± 2.40^{by}	6.78 ± 0.27^{by}
	10	0.00150	6.407 ± 0.33^{byz}	5.799 ± 0.32^{cyz}	5.577 ± 0.26^{bz}	5.915 ± 0.24^{cz}	0.906 ± 0.05^{by}	0.924 ± 0.04^{by}	110.025 ± 9.06^{cz}	364.41 ± 4.54^{bx}	6.65 ± 0.23^{bxy}
	15	0.00225	6.536 ± 0.31^{bz}	5.971 ± 0.34^{cz}	5.703 ± 0.27^{bz}	6.058 ± 0.27^{cz}	0.914 ± 0.04^{by}	0.927 ± 0.02^{by}	$115..468 \pm 10.38^{cz}$	$340.38 \pm 3.82^{b\alpha}$	6.52 ± 0.13^{bx}
600	5	0.00100	6.502 ± 0.32^{cy}	5.870 ± 0.34^{dy}	5.603 ± 0.25^{cy}	5.978 ± 0.26^{dy}	0.903 ± 0.04^{by}	0.920 ± 0.02^{by}	112.426 ± 9.93^{dy}	348.43 ± 0.28^{ax}	6.54 ± 0.40^{ay}
	10	0.00200	6.718 ± 0.53^{cyz}	6.059 ± 0.42^{dyz}	5.763 ± 0.36^{cz}	6.165 ± 0.39^{dz}	0.904 ± 0.05^{by}	0.919 ± 0.03^{by}	119.809 ± 15.36^{dz}	276.06 ± 4.84^{ax}	5.97 ± 0.27^{axy}
	15	0.00300	6.845 ± 0.52^{cz}	6.135 ± 0.35^{dz}	5.918 ± 0.30^{cz}	6.283 ± 0.31^{dz}	0.909 ± 0.07^{by}	0.920 ± 0.05^{by}	124.262 ± 12.23^{dz}	$251.38 \pm 4.22^{a\alpha}$	5.63 ± 0.18^{ax}

Values are given as means ± standard deviation. Superscripts a, b, c, and d indicate a significant difference between power, whereas superscripts x, y, z, and α indicate a significant difference between time. Dg: geometric mean diameter; R_a: aspect ratio; ϕ: sphericity; S: surface area; BD: bulk density; W_{100}: 100-grain weight.

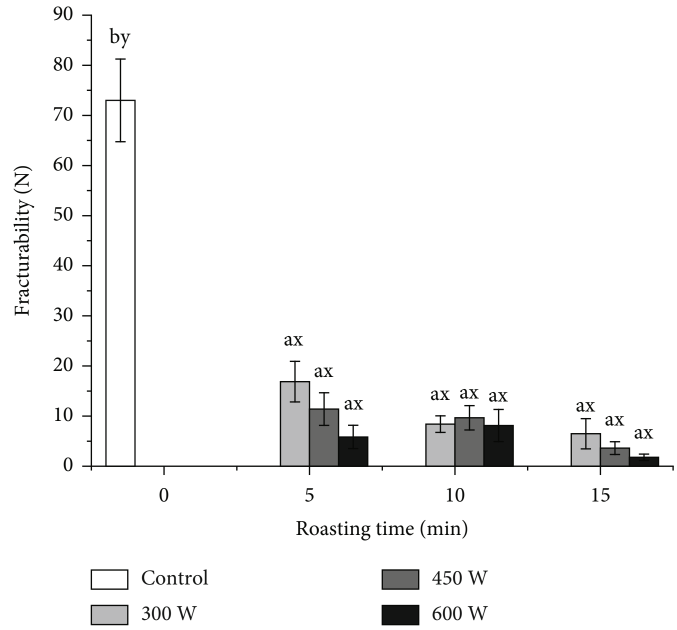
Table 2: Color analysis of control (unroasted) and roasted black pepper seed.

Power (W)	Time (min)	Microwave dosage (kWh g^{-1})		Color values L^*	a^*	b^*	ΔE	BI
Control	0	0		$22.82 \pm 0.02^{c\alpha}$	2.47 ± 0.17^{dz}	2.41 ± 0.11^{bz}	—	25.87 ± 1.07^{by}
	5	0.00050		22.32 ± 0.14^{bz}	2.48 ± 0.09^{by}	$3.06 \pm 0.08^{b\alpha}$	0.96 ± 0.03^{ax}	29.92 ± 0.03^{bz}
300	10	0.00100		20.86 ± 0.09^{by}	2.16 ± 0.02^{by}	2.35 ± 0.03^{by}	1.96 ± 0.10^{ay}	26.35 ± 0.18^{by}
	15	0.00150		20.08 ± 0.25^{bx}	1.49 ± 0.11^{bx}	1.50 ± 0.06^{bx}	2.75 ± 0.20^{az}	19.80 ± 0.19^{bx}

Table 2: Continued.

Power (W)	Time (min)	Microwave dosage (kWh g^{-1})		Color values L^*	a^*	b^*	ΔE	BI
	5	0.00075		22.22 ± 0.21^{bz}	2.44 ± 0.08^{cy}	$3.26 \pm 0.13^{b\alpha}$	1.11 ± 0.06^{ax}	30.97 ± 0.73^{cz}
450	10	0.00150		20.50 ± 0.17^{by}	2.41 ± 0.01^{cy}	2.36 ± 0.04^{by}	2.31 ± 0.16^{ay}	27.65 ± 0.01^{cy}
	15	0.00225		19.62 ± 0.36^{bx}	1.86 ± 0.06^{cx}	1.87 ± 0.14^{bx}	3.16 ± 0.40^{az}	23.67 ± 0.94^{cx}
	5	0.00100		21.71 ± 0.14^{az}	1.90 ± 0.10^{ay}	$2.67 \pm 0.19^{a\alpha}$	1.35 ± 0.09^{bx}	26.45 ± 1.26^{az}
600	10	0.00200		$20.10 \pm 0.15a^{y}$	1.81 ± 0.03^{ay}	1.79 ± 0.09^{ay}	2.68 ± 0.17^{by}	22.62 ± 0.79^{ay}
	15	0.00300		17.76 ± 0.08^{ax}	0.56 ± 0.02^{ax}	-0.75 ± 0.04^{ax}	5.30 ± 0.19^{bz}	4.18 ± 0.33^{ax}

Values are given as means ± standard deviation. Superscripts a, b, c, and d indicate a significant difference between power, whereas superscripts x, y, z, and α indicate a significant difference between time. L^*, a^*, and b^* represent lightness/darkness, redness/greenness, and yellowness/blueness, respectively, ΔE: total color difference; BI: browning index.



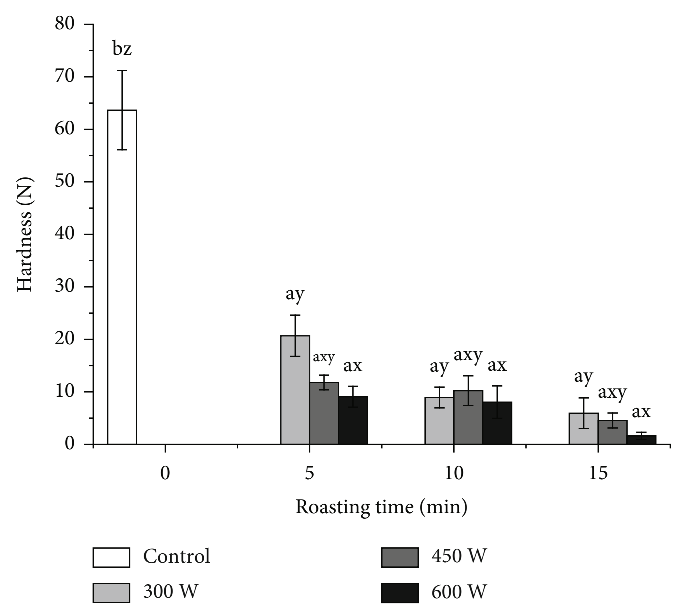


Figure 2: Effect of roasting on textural properties of black pepper. (a) Fracturability and (b) hardness. Superscripts a and b indicate a significant difference between power, whereas superscripts x, y, and z indicate a significant difference between time.

chilli seeds. They also reported the decreasing trend of L^*, a^*, and b^* values for roasting chilli and chilli seeds above 160°C for 30-40 min. The decrease in the b^* value of sesame seed upon roasting above 180°C was reported by Berk et al. [51], but on the contrary, increase in the a^* value with respect to roasting. It might be due to loss in yellowness and the formation of brown pigments at high temperatures.

Total color difference (ΔE) and browning index (BI) were calculated to observe the overall color difference and observe the development of brown color pigments with respect to roasting. The ΔE was significantly ($p < 0.05$) affected by the roasting power and time. An increase in overall color change (0.96 ± 0.03 to 5.30 ± 0.19) was observed upon roasting due to the non-enzymatic browning during roasting. The extension of browning depicted by BI shows the optimum roasting condition at which browning begins [52]. The BI increased at lower roasting time (300, 450, and 600 W for 5 min) compared to the control, but later increased exposure to microwave energy reduced the BI. No studies have been reported on the effect of roasting on the color analysis of black pepper; however, an increasing trend for the BI was reported for different grains and nuts, *viz.*, peanuts (Hybridized IR hot air rosting: Air temperature—100 and 120°C; IR power: 130 W, 165 W, and 200 W for 10, 20, and 30 min)

Table 3: Effect of roasting on the particle size distribution of black pepper powder.

Power (W)	Time (min)	Microwave dosage (kWh g^{-1})	D_{10} (μm)	D_{50}(μm)	D_{60} (μm)	D_{90} (μm)	Mean size (μm)	Span	Coefficient of uniformity (CU)
Control	0	0	49.63 ± 0.22^{ax}	109.68 ± 0.85^{ax}	141.15 ± 1.20^{ax}	227.86 ± 1.03^{ax}	121.72 ± 0.71^{ax}	1.62 ± 0.01^{cz}	2.84 ± 0.02^{bz}
	5	0.00050	66.03 ± 5.01^{bz}	112.80 ± 3.17^{by}	140.08 ± 1.25^{by}	227.25 ± 1.83^{ax}	127.81 ± 2.38^{by}	1.43 ± 0.07^{by}	2.13 ± 0.15^{ax}
300	10	0.00100	66.09 ± 1.49^{bz}	$118.10 \pm 2.98^{b\alpha}$	146.11 ± 4.19^{bz}	227.20 ± 4.23^{axy}	131.55 ± 1.11^{bz}	1.36 ± 0.01^{bx}	2.21 ± 0.11^{axy}
	15	0.00150	73.93 ± 1.44^{by}	123.49 ± 0.53^{bz}	147.54 ± 0.50^{bz}	225.76 ± 1.75^{ay}	132.31 ± 0.55^{by}	1.23 ± 0.03^{by}	1.99 ± 0.04^{ay}
	5	0.00075	79.14 ± 0.30^{cz}	133.84 ± 0.15^{cy}	153.61 ± 0.19^{cy}	224.68 ± 0.57^{ax}	138.50 ± 0.33^{cy}	1.09 ± 0.00^{ay}	1.94 ± 0.01^{ax}
450	10	0.00150	79.36 ± 0.16^{cz}	$144.80 \pm 0.46^{c\alpha}$	162.06 ± 0.36^{cz}	234.15 ± 1.14^{axy}	144.26 ± 0.43^{cz}	1.07 ± 0.00^{ax}	2.04 ± 0.00^{axy}
	15	0.00225	72.66 ± 0.45^{cy}	136.90 ± 0.61^{cz}	155.90 ± 0.44^{cz}	221.11 ± 1.45^{ay}	136.37 ± 0.28^{cy}	1.09 ± 0.01^{ay}	2.15 ± 0.01^{ay}
	5	0.00100	82.16 ± 0.28^{cz}	136.61 ± 1.19^{dy}	155.37 ± 0.99^{cy}	231.45 ± 1.97^{bx}	139.01 ± 0.90^{cy}	1.09 ± 0.00^{ay}	1.89 ± 0.01^{ax}
600	10	0.00200	84.67 ± 0.43^{cz}	$151.90 \pm 1.26^{d\alpha}$	164.65 ± 1.01^{cz}	229.06 ± 1.59^{bxy}	146.14 ± 0.65^{cz}	0.95 ± 0.00^{ax}	1.95 ± 0.01^{axy}
	15	0.00300	70.88 ± 0.01^{cy}	135.74 ± 1.08^{dz}	160.49 ± 3.77^{cz}	246.53 ± 0.50^{by}	135.03 ± 0.53^{cy}	1.29 ± 0.00^{ay}	2.27 ± 0.05^{ay}

Values are given as means ± standard deviation. Superscripts a, b, c, and d indicate a significant difference between power, whereas superscripts x, y, z, and α indicate a significant difference between time. D_{10}, D_{50}, D_{60}, and D_{90} indicate total percentiles of particle sizes below the values of 10%, 50%, 60%, and 90%, respectively, in cumulative size distribution.

[48], sorghum (Microwave roasting: 300, 450, and 600 W for 5, 10, 15 min) [34], yellow, black, and purple wheat (Microwave roasting: 600 W for 5 min, pan roasting: 115 ± 5°C for 90 s, and sand roasting: 175 ± 5°C for 60 s) [49], black rice (Microwave roasting: 300, 600, and 900 W for 5, 10, and 15 min) [39].

3.4. Textural Properties. The texture parameters like fracturability and hardness were observed to evaluate the change in the textural properties of black pepper due to roasting. Fracturability refers to the tendency of a material to fracture or break when subjected to mechanical forces, whereas hardness refers to the resistance of a material to deformation or penetration. Both are important textural properties of spice as they determine their brittleness and ease of fragmentation during grinding and their prominent effect on grinding energy [53]. The decreasing trend for fracturability and hardness was observed under different roasting conditions (Figure 2). Increase in the roasting power from 300 W to 600 W and exposure time from 5 min to 15 min, resulted in a decrease in fracturability (72.99 ± 14.30 N to 1.78 ± 1.09 N) and hardness (63.65 ± 13.08 N to 1.61 ± 1.19 N). This could be attributed to a rapid reduction in moisture content, breakdown of internal bonds, and microstructural changes because of volumetric heating when exposed to microwave energy. The decrease in fracturability positively correlated with a decrease in hardness, with an increase in power/temperature and roasting time owing to the formation of more crumbled and fragile kernels with a reduction in moisture content and an increase in internal pressure at high temperature [41, 54]. The findings were correlated with Nikzadeh and Sedaghat [55] for electric oven roasting of pistachio nut (90, 120, and 150°C for 30 min), Murthy et al. [56] for sand roasting of wheat (300 ± 10°C for 15–18, 25–30, and 80–100 s), Suri et al. [47] for peanut kernels, Mohammadi Moghaddam et al. [57] for pistachio nut/kernel, Arjun et al. [58] for makhana seeds, and Sharanagat et al. [27] for roasted chickpea.

3.5. Particle Size Distribution (PSD). The particle size distribution of spices impacts the release of flavor and aroma and also ensures the consistency and uniformity of the product [59]. If black pepper is used as seasoning, then particle size distribution becomes important as coarser particles have noticeable crunch and texture. The PSD was more distinguishable with respect to roasting power and time compared to control (Table 3). The increase in the D_{10}, D_{50} (median), D_{60}, and mean size was observed and varied in the range of 49.63 ± 0.22 to 84.67 ± 0.43 μm, 109.68 ± 0.85 to 151.90 ± 1.26 μm, 140.08 ± 1.25 to 164.65 ± 1.01 μm, and 121.72 ± 0.71 to 146.14 ± 0.65 μm, respectively, with a reduction in span factor and CU from 1.62 ± 0.01 to 0.95 ± 0.01, and 2.84 ± 0.02 to 1.89 ± 0.01, respectively, indicating coarser powder formation with narrow PSD with respect to roasting. The initial decrease in D_{90} was observed at lower roasting conditions and further increased with respect to high roasting conditions. The inverse relation of PSD and span factor was reported by Kong et al. [38] and Khaleel et al. [37]. The current data can be supported with the findings of Jeong et al. [60] for the roasted ginseng powder. They reported that ginseng roasted at 180°C up to 15 min showed a decreasing pattern for particle size due to destruction in starch granules and starch-protein interactions, but prolonged exposure for over 18 min caused a significant increase in particle size due to flocculation.

4. Conclusion

Microwave roasting significantly influenced the physical and textural properties of black pepper seeds and also varied the powder's particle size distribution. Roasting increased the geometric mean diameter, sphericity, aspect ratio, and surface area of seeds, whereas a significant reduction was observed in bulk density and 100-grain weight. The change in the color values upon roasting significantly increased the total color difference, indicating a gradual change in the appearance upon roasting. The reduction in hardness and fracturability makes the seeds more friable and may break down at lower grinding energy with increased mean particle size. The reported results will be useful for the roasted spice processing operations such as grinding, blending, and packaging. Therefore, understanding the effect of roasting on the physical textural properties is crucial for optimizing the roasting conditions and designing processing instruments to achieve the best-desired product.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

Authors do not have any known conflict of interest.

Acknowledgments

All the authors gratefully acknowledge the financial assistance and infrastructural support from the National Institute of Food Technology Entrepreneurship and Management, Kundli, Haryana.

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