Ohmic Heating as an Emerging Technology for the Improvement of the Techno-Functional Properties of Common Bean Flour †

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Abstract: The common bean (Phaseolus vulgaris L.) is one of the most important food legumes because of its high availability and low cost. It has also been associated with preventing and reducing noncommunicable diseases. Because of this, the application of processing technologies has grown to improve common beans’ nutritional and bioactive profiles. The processing of the raw material directly influences its techno-functional properties. The objective of this work was to demonstrate the advantages of ohmic heating over traditional cooking on common bean flours in regard to their techno-functional characteristics and antinutritional factors. The results of ohmic heating did not show significant differences compared with traditional cooking; however, ohmic heating obtained higher values in foaming capacity and emulsifying. In addition, it did not modify the protein solubility profile and reduced trypsin inhibitors by 25.42 to 57.44%. This suggests that ohmic heating could be an alternative to conventional treatments and reducing processing time, with greater energy efficiency, not presenting nutrient leaching.

Keywords: ohmic heating; common bean; techno-functionality

1. Introduction

The FAO classifies the common bean as an essential food legume for human consumption and fundamental for food security. It represents one of the most important protein sources for about 500 million people in Africa, America, and the Caribbean [1]. Beans are also an important source of dietary fiber, vitamins, minerals, and phytochemicals.

In addition, bean consumption has been associated with preventing several chronic noncommunicable diseases, such as obesity, diabetes, and cardiovascular diseases [2]. Despite their importance in human nutrition, beans contain compounds that impede the digestion and absorption of specific components. These include enzyme inhibitors such as trypsin, chymotrypsin, α-amylase, phytic acid, saponins, and lectins. Most antinutritional factors are eliminated during cooking; however, excessive heat treatment causes
decreased lysine availability, resulting in reduced protein quality [3] and affecting the techno-functional characteristics of the beans.

These technofunctional properties are physicochemical characteristics, which in legume flours mainly depend on the presence and behavior of proteins and carbohydrates in the food matrix [4]. These properties are found by the composition and molecular structure of the individual components and the interactions that are sought between them. These physicochemical characteristics are influenced by the type of processing and have a direct impact on the final quality of the product.

Recently, ohmic heating has proven to be an alternative for food processing with advantages over other technologies due to rapid and uniform heating, which translates into reduced processing time, uniform distribution of heat in food, and energy efficiency of 90% [5]. In addition, it allows the conservation of the nutritional constituents of the raw material. This heating occurs when an electric current passes through food, causing an increase in the temperature inside it due to the resistance offered by the food to the passage of electric current (Joule effect). The amount of heat generated is directly related to the electric current, the applied voltage, and the electrical resistance [5], so the following factors must be considered: the amount of water and ions, the shape and size of the particles, the viscosity, and other feed characteristics [6]. Blanching, evaporation, dehydration, fermentation, extraction, sterilization, and pasteurization are some applications of ohmic heating in foods [7]. However, it is mainly applied in products with high viscosity or in foods immersed in liquid [8] to promote the passage of electric current, so there has been limited research on understanding the effects produced in solid matrices. Therefore, the objective of this work was to investigate the advantages of ohmic heating over traditional cooking in bean flours by evaluating and comparing the techno-functional characteristics and anti-nutritional factors of bean flours prepared with each method.

2. Materials and Methods

2.1. Biological Material

Seeds of common black bean (*Phaseolus vulgaris* L.), variety San Luis, harvested in 2017 from Zacatecas, Mexico, donated by the National Institute of Agricultural and Livestock Forestry Research (INIFAP, Mexico City, Mexico), were used.

2.2. Ohmic Heating Cooking (OH)

The beans were soaked in water (1:1 ratio) for 12 h before cooking. A batch-type ohmic heater was used. The OH setup was composed of a variable transformer (220 VAC, 60 Hz, VARIAC, Cleveland, OH, USA), a temperature controller (Series 981, Watlow, St. Louis, MO, USA), and two panel meters (Model MT4W, Autonics, Korea) to obtain voltage and current values. The OH chamber consisted of a nylamide cylindrical cell (10 cm in diameter by 6 cm in width) with stainless steel electrodes and a glass insulated type T thermocouple.

The beans were ohmically heated from room temperature until reaching 110 °C and then held at this temperature for 10 min and 15 min. A temperature controller (Series 981, Watlow, St. Louis, MO, USA) was used at a constant voltage of 60 V. Once the samples had been processed, they were dried in a dehydrator at 50 °C for 48 h, ground (Coffee Mill), and sieved through a No. 60 mesh to obtain the flour. All ohmic flours were stored in 50 mL Corning™ tubes at 4 °C until use.

2.3. Traditional Cooking (TC)

The beans were cooked using a “traditional” process [9]. A 1:5 (w/v) ratio was placed and boiled for 2.5 h. The beans and the cooking broth were dehydrated at a temperature of 50 °C for 48 h. The dehydrated beans were ground in a coffee grinder and sieved with a No. 60 mesh. Traditionally cooked flours were stored in 50 mL Corning tubes at 4 °C until use.
2.4. Crude (C)

The raw sample was ground in a coffee grinder and sieved with a No. 60 mesh. Flours were stored in 50 mL Corning tubes at 4 °C until use.

2.5. Water Absorption Index (WAI)

The WAI was determined with 5 g of dehydrated flour mixed in 30 mL of distilled water in a previously weighed 50 mL centrifuge tube. The sample was vortexed for 1 min and centrifuged at 3000× g for 10 min at 25 °C. The supernatant liquid was discarded, the tubes were drained for 10 min on a paper towel, and the tube was weighed. Results are expressed as grams of water retained per gram of dry solids (g/g) [10].

2.6. Oil Absorption Capacity (OAC)

The OAC was determined with 10 mL of vegetable oil added to 1 g of each flour in a previously weighed 50 mL centrifuge tube. The suspension was stirred for 2 min, allowed to stand at 28 °C for 30 min, and then centrifuged at 15,000× g for 20 min. The supernatant was decanted and discarded. Oil droplets adhering to the centrifuge tube were removed with cotton wool, and then the tube was weighed. The result was calculated and is expressed as the volume of oil absorbed per gram of flour (mL/g) [10].

2.7. Emulsifying Capacity (EmC)

One gram of each flour was mixed with 20 mL of water and stirred for 15 min. The pH was adjusted to 7, and distilled water was added until a final volume of 25 mL was obtained. Subsequently, 25 mL of corn oil was added in a blender and mixed for 3 min. Subsequently, the sample was centrifuged at 1300× g for 5 min. The emulsion is expressed in percentage terms as the height of the emulsified layer for the total liquid [10].

2.8. Foaming Capacity (FC)

This analysis was performed using 2 g of sample mixed with 100 mL of water in a blender (550 watts/15,000 rpm) for 5 min. Afterward, they were transferred to a 200 mL cylinder, and the final volume was measured after 30 s of pouring. FC is expressed as the percentage increase in volume compared with the original volume [11].

2.9. Least Gelation Concentration (GC)

The GC was performed using suspensions at 4%, 8%, 12%, and 14% (w/v) prepared in distilled water. Five mL of each mixture was taken, and placed in a hot bath at 100 °C for 1 h, subsequently cooled in an ice bath for 1 h. Clot strength was evaluated by inverting the tube. The lowest protein concentration that formed a stable gel (remained in an inverted test tube) was considered the LGC [11].

2.10. Quantification of Soluble Proteins

The bean samples were defatted before analysis. After that, distilled water was added in a ratio of 1:10 (sample/water), and the pH was adjusted to 8.5 with 1 M NaCO. The mixture was stirred (200 rpm) for 2 h at room temperature and then centrifuged at 10,000× g at 4 °C for 20 min. The supernatant was stored under refrigeration, and distilled water was added to the pellet at a ratio of 1:5 (w/v). The sample was stirred for 2 h and centrifuged at 10,000× g at 4 °C for 20 min. Both supernatants were mixed, and the pH was adjusted to 4.4. This sample was left under stirring for 2 h and then centrifuged at 10,000× g at 4 °C for 20 min. Protein isolates were stored at −80 °C [12].

Approximately 2 mg of these isolates were weighed, and the protein concentrations were quantified with the Pierce™ BCA Protein Assay Kit (Thermo, Scientific, Waltham, MA, USA).
2.11. Lectin Quantification

Extraction of the lectins in the flour was carried out using a phosphate buffer solution (5 mM K2HPO4 and 0.15 M NaCl pH 7.4). First, 0.1 g of bean flour was weighed, 10 mL of phosphate buffer was added, and the sample was left under continuous stirring for 18 h. Afterward, the mixture was centrifuged at 12,000 × g, and the supernatant was used for the hemagglutination test. Hemagglutinating activity is expressed in units of hemagglutinin/mg protein. Hemagglutinin units were defined as the inverse of the last dilution that showed positive agglutination [13].

2.12. Quantification of Trypsin Inhibitors

Trypsin inhibitory activity was measured as residual tryptic activity, using BAPNA (Nα-Benzoyl-DL-arginine 4-nitroanilide hydrochloride) as substrate. Total trypsin inhibitory activity was expressed as TIU per mg of sample (TIU/mg) [12].

2.13. Statistical Analysis

All measurements were carried out as separate duplicate experiments. The data are expressed as the mean ± standard deviation (SD), and the ANOVA analysis and the comparison of means were performed using a Tukey HSD test (α = 0.05) for all treatments. All statistical analyses were carried out in the JMP® 8.0 program.

3. Results and Discussion

3.1. Water Absorption Index (WAI)

The WAI values obtained for ohmic heating flours (OH) were 2.90 and 2.91 g water/g sample for OH10 and OH15, respectively (Figure 1a). This result represents a significant increase in absorption of 29% over that of the raw product. Besides this, no significant differences were found among thermal treatments (3.14 g water/g sample for traditional) (Figure 1a) and other studies [14,15]. Furthermore, consistently with results reported in other studies, this finding indicated the complete cooking of beans [14]. These results may be mainly due to the albumin fraction, which, when applying electric current, can cause the ionization of the SH groups, making them more reactive, or a partial denaturation, causing a higher concentration of polar groups (carboxyl, COOH, and amide, NH2, groups) [16] generated by electric current, resulting in better interaction with water.

![Figure 1](image-url)

Figure 1. Techno-functional properties of bean flour processed by ohmic heating (OH10: 110 °C/10 min, OH15: 110 °C/15 min) and traditional processing (TC). Each value represents the mean of two replicates ± DS. Values with the same letter are not different from each other (Tukey α = 0.05).
3.2. Oil Absorption Capacity (OAC)

Oil pick-up was 0.86 and 0.90 mL of oil/g sample for OH10 and OH15 (Figure 1b), respectively. The differences found were not significant between flours obtained from raw conditions and traditional cooking, with 0.94 and 0.95 mL of oil/g sample, respectively, coinciding with other results [15]. By modifying the orientation of the hydrophilic charges towards the outside, the treatment could cause the hydrophobic amino acids to be oriented towards the inside of the structure. According to this, it can be inferred that there were fewer nonpolar side chains available in the protein molecules of flour [15], which decreased their ability to bind to oil. Another option is that starch-protein interactions were fostered, which may have influenced the phenomenon of reduced oil absorption [4]. This would allow obtaining fried products with reduced fat.

3.3. Emulsifying Capacity (EmC)

The EmC of flours processed by OH ranged from 42 to 45% (Figure 1c). In comparison with TC, OH showed no differences. These results agreed with other studies on other cooking methods [17,18] and represented an approximate increase of 15% over the raw product (Figure 1c). Although the compact and rigid structure of globulins, the main protein fraction of beans, does not make them proteins with good potential for emulsifying/foaming functions in the raw product [19], the results found indicate that the samples processed by ohmic heating developed and improved this property. This was closely related to their water absorption capacity, since if they had lower absorption, the amount of available water would not be enough to maintain the dispersion of the fat, which did not increase significantly over the crude product.

3.4. Foam Capacity (FC)

Figure 1d shows the results obtained for the FC. OH samples obtained the highest FC, a phenomenon contrary to that reported previously [14], where heat treatment almost eliminated this capacity due to denaturation and/or solubilization of albumin, so it can be said that OH affects albumin less. Furthermore, as already mentioned, proteins determine important hydrodynamic functional properties such as WAI and OAC and colloidal properties such as FC, but these are also modified by the carbohydrates and dietary fiber present in beans [14].

3.5. Least Gelation Concentration (GC)

Gelation properties observed for bean flours at different flour concentrations are shown in Table 1. Complete gelation for OH was at a concentration of 8%. These results showed gelation at concentrations lower than those reported in other studies [14,18] in which the minimum gelation concentration was 12% for flours to which some thermal process was applied. This could be explained by the fact that, as mentioned before, the electric current could modify the conformation of the proteins, promoting protein-protein interaction and creating networks of intertwined polypeptides where water is trapped.

Table 1. Gelation capacity of bean flours processed with different treatments.

<table>
<thead>
<tr>
<th>Suspension Concentration</th>
<th>4%</th>
<th>8%</th>
<th>12%</th>
<th>14%</th>
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<tr>
<td>Sample</td>
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<td>OH10</td>
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OH10: 110 °C/10 min, OH15: 110 °C/15 min. TC: traditional cooking, C: crude. X: complete gelation, —: no gelation.
3.6. Quantification of Soluble Proteins

Figure 2a shows the protein content of bean flours. Flours processed by OH had protein concentrations between 30 and 33 g of soluble protein/100 g of sample. These values did not present an essential statistical difference between the raw and TC samples. The concentrations obtained in OH flours were higher than those reported in other studies for different bean varieties [12]. Generally, decreased protein solubility would be expected because of thermal processing. Because of protein denaturation and subsequent aggregation [20], however, a considerable reduction was not found in any case. This factor has been considered the essential in the techno-functional properties of bean flour, since most of the proteins to which such effects are attributed, such as albumin and globulins, are soluble [21]. OH10 flour had the best technology and functionality conditions and had a high concentration of soluble proteins.

![Figure 2a](image)

Figure 2. (a) Protein concentration and (b) trypsin inhibition for each flour sample. OH10: 110 °C/10 min, OH15: 110 °C/15 min, TC: traditional cooking, C: crude. Each value represents the mean of two replicates ± DS. Values with the same letter are not different from each other (Tukey α = 0.05).

3.7. Quantification of Trypsin Inhibitors

Figure 2a shows the trypsin inhibitor content for all flours analyzed. A concentration of 19.72 ± 1.29 UIT/mg was obtained for the raw product. The OH process showed a significant reduction in trypsin inhibition of about 25% compared with the raw flour. It has been reported that by the nature of the matrix reaching a temperature of 110 °C, the union of ions with the proteins can occur. It has also been reported that cross-links may occur during denaturation because of temperature, which can significantly alter the thermal stability of proteins, resulting in better resistance to heat [22], which could result in a lower reduction in inhibitor content in comparison with TC. Despite this, it has been reported that a concentration of at least 18.1 TIU/mg of trypsin inhibitors is needed to form complexes [23]. Each of the OH treatments had lower concentrations than this.

3.8. Quantification of lectins

The raw bean flour presented a higher concentration of hemagglutination (688.17 hemagglutination/mg protein), which agreed with that reported in the literature [12,24], compared with the samples subjected to heat treatment (TC and OH), in which hemagglutinin was not detectable. These results showed that after thermal processing, hemagglutination was not observed [24]. The process OH ensured the inactivation of these antinutritional compounds, which could be a change in conformation caused by the reorientation of charges by the electric current described above, causing the protein to no longer be structurally available.

4. Conclusions

OH bean flour showed techno-functional characteristics similar to those of traditional bean flour.

Common bean flours processed by OH showed the highest values for EmC and FC compared with the conventional method. For the antinutritional compounds, no lectins...
were detected in any of the treatments, there was a reduction in the trypsin inhibitors, and there were no changes in the solubility profile of the proteins for both processes.

These results suggest that the processing of beans by OH could be an innovative alternative to obtaining bean flours with the advantage of reduction in processing time (10 min vs. 2 h), which in the long run would also represent significant financial savings. In addition, it did not present leaching of the nutritional compounds of the beans, since they could not be lost in the cooking broth, and had the additional advantage of having technofunctional characteristics similar to those obtained by conventional treatment.

The OH bean flours obtained could be used as ingredients in the formulation of new functional products, which could translate into increased consumption and production of this legume.

**Author Contributions:** I.L.-B. carried out the experimental work and data curation and wrote the first draft; B.-A.M. carried out part of the work; F.D.-C. carried out part of the experimental work; L.M. and G.L.-P. contributed to data curation and editing of the paper; E.M.-S. carried out the experimental work, wrote the draft, and edited the paper; A.K.R.-J. carried out the experimental work; M.G.-M. conceived the idea, supervised the work, administrated the project, and edited the paper. All authors have read and agreed to the published version of the manuscript.

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