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RESEARCH

Optimization of Lentils, Peas, and Beans-based Vegetable Burger Formulation Using D-optimal Mixture Design

Sonia Oukhmanou-Bensidhoum[1] · Hafida Merzouk[1] · Fatiha Brahmi[1] · Sofiane Dairi[1,2] · Nadia Bouaoudia[1,3] · Sabine Chabane[1] · Nabila Djerrada[1] · Khodir Madani[1] · Lila Boulekbache[1]

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Abstract

The growing request for plant-based meat substitutes reflects a global shift toward more sustainable, ethical, and health-promoting dietary practices. Legumes, due to their high protein and fiber content, are ideal for the formulation of such products. This study focused on the development of a plant-based burger made from lentils, peas, and black beans, with particular attention paid to optimizing ingredient proportions to achieve balanced nutritional, technological, and sensory properties. With this in mind, a three-component D-optimal mixture design was implemented. The assessment of the nutritional properties of the legume-based plant burger, both before and after cooking, revealed high protein (8.15%) and crude fiber (6.33%) contents. After cooking, the protein amount remained relatively stable, indicating good thermal stability of the protein matrix, but a marked decrease in fiber content was noticed. The cooking properties of the legume-based plant burger demonstrated a technologically stable formulation, suitable for ready-to-eat consumption. The product exhibited moderate cooking loss (13.10 ± 0.69%), along with minimal reductions in diameter (1.94 ± 0.22%) and thickness (7.75 ± 0.80%), indicating good structural integrity during cooking and effective shape retention. Lipid absorption remained controlled (19.62 ± 0.42%), while moisture retention (58.79 ± 1.08%) indicated a moderate water-holding capacity. These findings confirm the product's favorable thermal behavior. Rheological analysis showed that after cooking, the network of the burger became more elastic, which was confirmed by Scanning Electron Microscopy analysis (SEM), revealing a compact and homogeneous structure. To sum up, given its qualities and richness, especially in proteins, the elaborated vegetarian burger could constitute a substitute for the meat-based one.

Keywords Vegetable burger · Lentil · Pea · Black bean · Optimization · Mixture design

Introduction

Transitioning to plant-based diets enhances health by increasing fiber intake, aiding digestion, and supporting weight management while reducing saturated fat. It also significantly lowers diet-related land use, greenhouse gas emissions, and promotes animal welfare, making it an ecological priority [1].

Legumes, belonging to the Fabaceae family and known as pulses, are recognized in traditional medicine for their health benefits. They are rich in protein, have a low glycemic index, and contain compounds that are beneficial in the context of diabetes and cardiovascular disease [2]. Lentils, peas, and beans are rich in soluble fiber and resistant starch, which serve as prebiotics. Their consumption promotes beneficial gut bacteria growth, enhances short-chain fatty acid production, and contributes to improved gut and metabolic health [3]. Legume-based meat substitutes are a promising alternative to conventional meat, particularly in high-income countries, where consumption remains high. These products are specifically designed to replicate the sensory

✉ Fatiha Brahmi
fatiha.brahmi@univ-bejaia.dz

1 Faculty of Natural and Life Sciences, Laboratory of Biomathematics, Biochemistry, Biophysics and Scientometry, University of Bejaia, Bejaia 06000, Algeria

2 Department of Applied Microbiology and Food Sciences, Faculty of Nature and Life Sciences, University of Jijel, Jijel 18000, Algeria

3 Department of Microbiology and Biochemistry, Faculty of Sciences, University of M'sila, M'sila 28000, Algeria

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characteristics of meat while offering a comparable nutritional profile. Their development aims to encourage their adoption by flexitarian, vegetarian, or health-conscious consumers [4]. Chaudhary and Tremorin [5] showed that partial replacement of a lean beef burger with cooked lentil puree increased the nutrient density by ~ 20%, decreased the life cycle environmental footprint by ~ 33%, reduced the cost by 26%, and increased dietary fiber by 60 times. Shariati-Ievari et al. [6] reported the feasibility of formulating low-fat beef patties using 6% micronized gluten-free binder manufactured from lentil and chickpea flour and positive findings for their physicochemical characteristics and consumer acceptability. Abd-ELhak [7] found that incorporating whole white beans, whole lentils, and whole chickpeas into a vegetable burger enhanced in vitro the bioavailability of iron (Fe), zinc (Zn), calcium (Ca), potassium (K), and phosphorus (P). In terms of sensory rating, consumers appeared to prefer the tested vegetarian burgers.

Overall, it is worth noting that many plant-based meat substitute products to date are based on soy protein isolates and not whole legumes. On the other hand, despite rapid market growth, challenges remain in terms of formulation, nutritional quality, sensory acceptability, and consumer perception, making an in-depth study of ingredients, technological processes, and nutritional composition essential to support a sustainable food transition [4].

From this perspective, statistical methods, particularly optimization models, play a key role in the formulation of new products adapted to commercial scale. They make it possible to take into account consumer requirements and preferences, identify synergistic effects between ingredients, and predict the most effective combinations in terms of quality and cost. In this context, the present study is the first to report an optimized formulation of a vegetarian burger based on legumes, namely lentils, peas, and black beans from Algeria, using a D-optimal mixture design. Once the optimum formulation had been determined, the product's cooking properties were analyzed and its nutritional composition assessed before and after heat treatment in order to measure its impact on nutritional values. This burger was also characterized using rheological analysis and scanning electron microscopy (SEM), providing insights into the evolution of its microstructure and viscoelastic properties upon cooking.

Materials and Methods

The Supplementary Material contains a detailed explanation of the analytical techniques and experimental protocols.

Results and Discussion

Optimization of Vegetable Burger Formulation by D-mixture Design Approach

Sensory Scores of the Vegetable Burger

A D-optimal mixture design was used in this study to correlate the effect of formulation ingredients (X_1-Lentil, X_2-Peas, and X_3-Black beans) with the observed responses (Y_1-Color, Y_2-Aspect, Y_3-Odor, Y_4-Texture, Y_5-Taste, Y_6-Flavor/Savor, and Y_7-Overall acceptability). Eight formulations were suggested by the Design-Expert software, and runs were randomly set.

The findings revealed that the experimental runs had a significant ($p<0.05$) effect on the responses. In fact, color scores ranged from 3.8 to 4.65, and it was sample 6 that had the highest color score when 66% of lentils were added to the mixture. Otherwise, sample 7 had the lowest color score with 66% pea addition. Aspect scores ranged from 2.91 to 3.62, and the highest score resulted from high pea ingredient content. Odor scores ranged from 2.22 to 2.82, and sample 5, which presents a high content of lentil ingredient, gave the highest odor score. On the contrary, samples without black beans presented the lowest odor scores, such as samples 4 and 8. Texture was also affected by mixture composition, where the values ranged from 3.54 to 4.2. It was found that the presence of a pea sample increased texture acceptability, while the presence of a lentil decreased it. Taste scores ranged from 1.9 to 3.12. The presence of peas as an ingredient and, secondly, black beans gave the mixture a high taste score. The savor score ranged from 1.81 to 2.9, and it was the occurrence of peas as an ingredient and, secondly, black beans that gave the mixture a high savor score. Overall acceptability scores ranged from 5.81 to 7. The highest score was given to formulation 2, followed by formulation 6, when almost all of the combination is made up of peas and lentils. According to these observations, we could conclude that the two ingredients that significantly affect sensory attribute scores are peas and lentils. Yet, it is important to notice that these ingredients presented an antagonistic effect. Therewith, the black bean addition acts synergistically with the pea ingredient. Consequently, the reported desirability values ranged from 0.21 to 0.67, confirming the influence of the formulation composition on the selected responses.

Modeling and Analysis of D-optimal Mixture Experiments

The results demonstrated that all the models, such as color, aspect, odor, texture, taste, flavor, and overall acceptability, were highly reliable with R^2 of 0.994, 0.999, 0.994, 0.986, 0.986, 0.991, and 0.990, respectively. The linear models were also significant (p: 0.0161, 0.0018, 0.0155, 0.0356, 0.0341, 0.0212, and 0.0245, respectively), $p \leq 0.05$, which indicates that the model adequately describes the responses. At the same time, the adjusted R^2 values of all models are high enough to advocate their adequacy. Other parameters, including a high adjusted R^2 and the lowest CV of sensory attributes, showed that the flavor response was the most precise and reliable in the experiment. These models adequately represented the real relationship between the chosen parameters.

The three independent variables had effects on all the sensory attributes except the texture and savor, which were affected by both lentil and pea, and taste, which was affected by pea only. As for the overall acceptability characteristic, no significant linear and interactive effect of the three variables (X_1, X_2, X_3) was observed. However, only five attributes (color, aspect, odor, savor/flavor, and taste) were affected by their interactions (Supplementary Table S3).

The fitted sensory models were described by the following equations with significant terms:

$$Y_1\,(\text{Color}) = 3.99X_1 + 3.83X_2 - 6.63X_3 + 1.40X_1X_2 + 17.06X_1X_3 + 15.43X_2X_3 \quad (1)$$

$$Y_2\,(\text{Aspect}) = 2.96X_1 + 2.56X_2 + 5.90X_3 + 2.25X_1X_2 - 4.73X_1X_3 - 0.21X_2X_3 \quad (2)$$

$$Y_3\,(\text{Odor}) = 3.43X_1 + 2.30X_2 + 3.42X_3 - 2.14X_1X_2 - 2.65X_1X_3 + 0.26X_2X_3 \quad (3)$$

$$Y_4\,(\text{Texture in mouth}) = 3.98X_1 + 4.03X_2 + 3.36X_3 - 1.0X_1X_2 - 1.08X_1X_3 + 2.17X_2X_3 \quad (4)$$

$$Y_5\,(\text{Tatse}) = 0.80X_1 + 3.36X_2 + 6.72X_3 + 1.35X_1X_2 - 2.34X_1X_3 - 6.25X_2X_3 \quad (5)$$

$$Y_6\left(\frac{\text{Savor}}{\text{Flavor}}\right) = 4.76X_1 + 5.21X_2 + 3.98X_3 - 10.07X_1X_2 - 7.26X_1X_3 - 8.31X_2X_3 \quad (6)$$

$$Y_7\,(\text{Overall acceptability}) = 5.836X_1 + 6.28X_2 - 12.05X_3 + 1.04X_1X_2 + 26.53X_1X_3 + 26.92X_2X_3 \quad (7)$$

Where X_1-Lentil, X_2-Pea, X_3-Black bean.

According to the equations, both independent variables, lentil and pea, have a significant effect on most sensory attributes of burgers (≤ 0.0001 and ≤ 0.05, respectively), whereas black bean had a weak effect. The lentil/pea interaction significantly influenced aspect, odor, and savor/flavor (p: 0.0030*, 0.0267*, and 0.0045*, respectively). The variation of texture in the mouth, taste, and overall acceptability characteristics were not affected by this interaction. A significant interactive effect between lentil and black bean was observed only on color and aspect properties (p: 0.0049*, 0.0055*, respectively). Color, appearance, and flavor are crucial for marketability and consumer acceptance [4].

Equation 2 to 7 show a significant positive linear impact of lentil and pea (≤ 0.0001 and ≤ 0.05, respectively) on the color, aspect, taste, and overall acceptability of plant-based burgers, likely due to water-soluble lentil components that protect color and delay lipid oxidation [8]. These findings align with the work of Li and Ganjyal [9], which reported higher juiciness, texture, and overall acceptability in hamburgers with 6% lentil flour compared to meat controls. Whilst no significant differences in flavor or aroma were observed. Infrared heat-treated lentil flour also improved flavor acceptability, likely by reducing off-flavors. Similar conclusions were reached by Senna et al. [10], who demonstrated the positive linear effect of pea protein and confirmed lentil flour's role in preserving color. Bhat and Pathak [11] prepared spaghetti with flours from green peas, yellow peas, chickpeas, and lentils. Increasing the proportion of legume flour (up to 30%) improved pasta firmness, legume flavor, and color intensity **(**$p < 0.0001$). For black bean seeds, a positive effect was observed on aspect, odor, and flavor ($p < 0.0001$). This agrees with Bhat and Pathak's [11] results, where black beans highly improved the flavor, juiciness, and texture of pasta.

Validation of Optimal Formulation

Optimized conditions for a 100 g burger were 6 g (0.10) of lentils, 43.2 g (0.72) of peas, and 10.8 g (0.18) of black beans. These conditions allowed reaching a global desirability value of 0.87, which very satisfactory formulation. In these conditions, the optimized values (Supplementary Table S4) showed that there weren't any significant differences ($p \geq 0.05$) in parameters when comparing the predicted and the measured values. These approaches indicate that the optimization process could successfully be applied for predicting formulation parameters, which demonstrates the accuracy of the predicted models.

Proximate Composition and Physicochemical Characterization of the Optimized Legume-based Burger

The properties of raw and cooked optimized legume-based burgers are illustrated in Supplementary Table S5.

The uncooked legume-based burger (ULBB) has a moisture content of 53.22 ± 0.30%, which is a little lower than the 58–62% moisture level of extruded plant-based burgers [12]. The ULBB ash content was low, 1.72 ± 0.04% but similar to that of the formulated spreadable dairy matrix with kidney bean milk-like extract [13]. Its lipid content, measured at 13.68%, importantly places the ULBB at a level comparable to some meat products (22 g/100 g) [14]. With an 8.15% protein level, the ULBB falls into the higher range of marketed plant-based alternatives (8.9–20 g/100 g) [14]. In terms of crude fiber (6.33%), the ULBB stands out significantly, exceeding the levels observed in most commercially available plant-based substitutes (2.17 g/100 g) [15]. This elevated fiber content can be attributed to the formulation, which is primarily based on fiber-rich legumes, notably peas and lentils. Indeed, peas have a total fiber content ranging from 19.8% to 31.4%, and lentils, slightly lower, with values between 17.8% and 21.8% [9]. Thus, the combined use of these legumes could explain the high fiber content observed in the formulated burger. In the present study, the carbohydrate content of raw ULBB hamburgers was estimated at 16.90%, slightly higher than values reported in the literature (7–15 g/100 g) [14]. The pH-formulated burger was nearly neutral. Colorimetry of the ULBB exhibits values of L^* = 60.05, a^* = 8.25, and b^* = 19.18 and revealed a golden and luminous hue. The L^* value suggests a light appearance, while the a^* and b^* components indicate a warm coloration. The hue angle (h° = 66.77) and chroma (c^* = 20.87) confirm this warm tone. These values fall within the range typically observed in puffed legume-based products (L^* = 55–62) [16]. During cooking, the ULBB undergoes several chemical transformations. A relative moisture loss of 41.0% is observed, primarily due to water evaporation under heat. The ash content remains stable, indicating the preservation of mineral elements, which are unaffected by cooking temperatures. The lipid content increases significantly (+ 143.42%), largely due to oil absorption during frying, a process that enhances fat content [17]. Meanwhile, the protein content remains generally stable post-cooking. The crude fiber content, however, drops drastically (–73.46%) due to the thermal degradation of complex polysaccharides; heat breaks down glycosidic bonds. There was a rise of carbohydrate level after cooking, reaching 23.2%. The gelatinization of starch during cooking, which modifies the structure of carbs, may account for this augmentation [18]. The pH decreased slightly (6.88 → 6.80) after cooking ($p < 0.05$), but remained within the ideal range (6.7–7.0) [19].

In terms of color, cooking results in a marked decrease in brightness (L^*: − 44.3%), accompanied by a decrease in the yellow component (b^*: − 14.1%) and chroma (c^*: − 9.58%). Conversely, the red component (a^*) shows a modest increase. However, none of these changes are statistically significant. These shifts reflect the intensity of Maillard and caramelization reactions, which lead to the formation of brown pigments known as melanoidins, giving cooked products their characteristic appearance. Furthermore, the reductions in chroma (c^*) and hue angle (h°) indicate an overall darkening and diminished color saturation, consistent with the accumulation of these transformation products [16].

Cooking Properties of the Optimized Legume-based Burger

For all samples, the cooking loss (Supplementary Table S6) of a legume-based burger (13.10 ± 0.69%) is considered moderate, lower than that reported for beef burgers [20]. Compared to plant-based alternatives, this loss is slightly higher than that observed by Basati and Hosseini [21] for soy-based burgers (11.33 ± 0.13%), but remains lower than other similar formulations, such as those of Shahiri Tabarestani et al. [22], with 22.2 ± 0.63%. As pointed out by Ko et al. [23], moisture release during heating is the main cause of cooking loss, which can lead to a reduction in post-cooking yield [24]. This phenomenon can be explained by the fact that the protein network of the plant product didn't collapse entirely during heating: as the proteins had already been denatured, the porous matrix remained intact. The porous matrix thus retained a sufficiently solid structure to retain liquids. In addition, the plant-based wafers contained polymeric ingredients such as methylcellulose and modified starch, renowned for their ability to bind and retain water by forming porous networks [25].

The diameter reduction rate measured for the legume-based burger developed is 1.94 ± 0.22%, which is considerably lower than that of beef-based burgers, showing significantly higher shrinkage rates: 22.84 ± 1.29% according to Polizer-Rocha et al. [26], and slightly lower than several plant analogues documented in the literature. The meatless soy burger analyzed by Shahiri Tabarestani et al. [22] reached a value of 2.11 ± 0.39%. Ayalew et al. [24] reported a shrinkage of 2.81 ± 0.17% for a lupin protein-based meat analog.

Thickness reduction after cooking is an essential indicator of the structural stability of plant-based meat substitutes. The formulated legume-based burger showed a thickness reduction of 7.75 ± 0.8%, a value significantly lower than that reported for an analog made from lupin protein (13.09 ± 0.43%) [24].

Shrinkage that commonly occurs during cooking is due to protein denaturation and the release of trapped water and fat [27].

The fat absorption rate during frying measured for the legume-based veggie burger is 19.62 ± 0.42%, which is significantly higher than the values reported by Soltanizadeh and Ghiasi-Esfahani [28] for a low-fat meat burger (12%) and lower than that reported by Modi et al. [29] for a buffalo meat burger containing legume flours as binders (28.6%–68.3%). During frying, water evaporates from the crust and is replaced by moisture migrating from the core of the food, thereby maintaining the vapor flux, and the crust must remain permeable to allow this process. As steam escapes, it creates voids that facilitate oil penetration, highlighting the critical role of the food's moisture content in determining fat absorption [28].

The moisture retention value observed in this study (58.79 ± 1.08%) reflects a moderate water-holding capacity. This result aligns with the range reported for low-fat beef burgers by Selani et al. [30], indicating comparable moisture content. However, it remains lower than the values reported for meat-free burgers (68.2–74.77%) by Shahiri Tabarestani et al. [22]. This difference may be attributed to the structural properties of plant dietary fibers commonly found in meat alternatives. The insoluble fibers, mainly cellulose and hemicellulose, possess water- and fat-retention capacities that are influenced by their molecular arrangement. In legumes, cellulose forms hydrogen-bonded microfibrils, and longer fibers have shown greater fat-binding potential. When interacting with hemicellulose, cellulose contributes to a porous fiber network with increased surface area, which enhances the retention of both moisture and lipids [27]. Moreover, Shariati-Ievari et al. [6] demonstrated that the dietary fiber content in chickpea and lentil flours played a key role in improving moisture retention in cooked low-fat beef burgers.

Viscoelasticity Analysis of Raw and Cooked Legume-based Burgers

To better understand the effect of cooking on the texture of legume-based burgers, their rheological properties were measured. The storage modulus (G′) as a function of angular frequency shows a marked increase after cooking that varied from 914.54 to 3937.40 Pa at 1 Hz (Supplementary Figure S2A). This change reflects the development of a firmer, predominantly elastic structure. An increase in the loss modulus (G″) after cooking (Supplementary Figure S2B) from 1433.1 to 1787.4 Pa at 1 Hz is observed but to a lesser extent than G′. As a result, the phase angle (tan δ) decreases sharply, from 1.57 in the raw burger to 0.45 in the cooked burger (Supplementary Figure S2C). A tan δ value greater than 1 reflects a predominantly viscous behavior, as is the case for the raw burger. In contrast, a value less than 1 reveals a predominantly elastic character for the cooked product. The complex shear modulus (G*) also increases after cooking from 1700.05 to 4324.11 Pa at 1 Hz (Supplementary Figure S2D).

These observations are consistent with those of Dunne et al. [31], who showed, by studying the textural and rheological characteristics of animal meats and their plant-based analogues, that the increase in viscoelastic modules (G′, G″, and G*) reflects the formation of solid protein networks, which are essential for obtaining a firm and consistent texture. Similarly, De Angelis et al. [32], working with mung bean proteins, found that heat treatment above 70 °C leads to a significant increase in the complex modulus (G*), resulting from the combination of starch gelatinization and protein gelation, which together create a more stable three-dimensional network. These elements explain, in this study, the increase in G′, G″, and G*, as well as the decrease in tan δ after cooking, reflecting the formation of denser and more elastic protein and starch networks, which are responsible for the overall strengthening of the matrix.

SEM Analysis of Raw and Cooked Legume-based Burgers

SEM observations (Fig. 1) highlight clear differences between legume-based burgers before and after cooking. In the raw sample (Fig. 1A and C), the surface appears heterogeneous, poorly cohesive, and weakly organized. Well-separated particles can be distinguished, interspersed with numerous empty spaces. At high magnification, we observe spherical shapes, probably related to starch granules. Fibrous or filamentous areas were also noticed, which could correspond to fragments of cell walls or protein networks in the process of organization.

Conversely, the cooked sample (Fig. 1B and D) reveals a denser and more homogeneous texture, with a clear reduction in interstitial spaces. The starch granules appear partially swollen or slightly deformed, a sign of gelatinization caused by heat. The proteins, on the other hand, denature and then assemble to form a continuous network capable of enveloping the starch and fibers [18, 32]. Frying also promotes oil absorption since it seeps into the areas freed up by water evaporation, thereby contributing to the reduction of interstices and the enhancement of the matrix's compactness [28].

Conclusion

The present investigation is intrigued by how lentils, peas, and black beans could be functional ingredients for developing a vegan burger rich in nutrients. Interestingly, the application of the D-optimal mixture design, based on sensory evaluation, proved an effective approach to optimize the formulation considering these vegetables. This approach enabled the identification of the ideal combination of lentils, peas, and black beans within the 60 g legume fraction of the 100 g burger, with respective proportions of 6 g (10%), 43.2 g (72%), and 10.8 g (18%). The characterization of the legume-based meat substitute burger highlights a balanced and nutrient-rich formulation, particularly in fiber and protein. Its techno-functional properties during cooking, including moderate mass loss, reflect good structural stability, likely due to the presence of functional ingredients capable of retaining water. The minimal reduction in diameter and thickness also indicates effective preservation of the product's shape and volume, which are

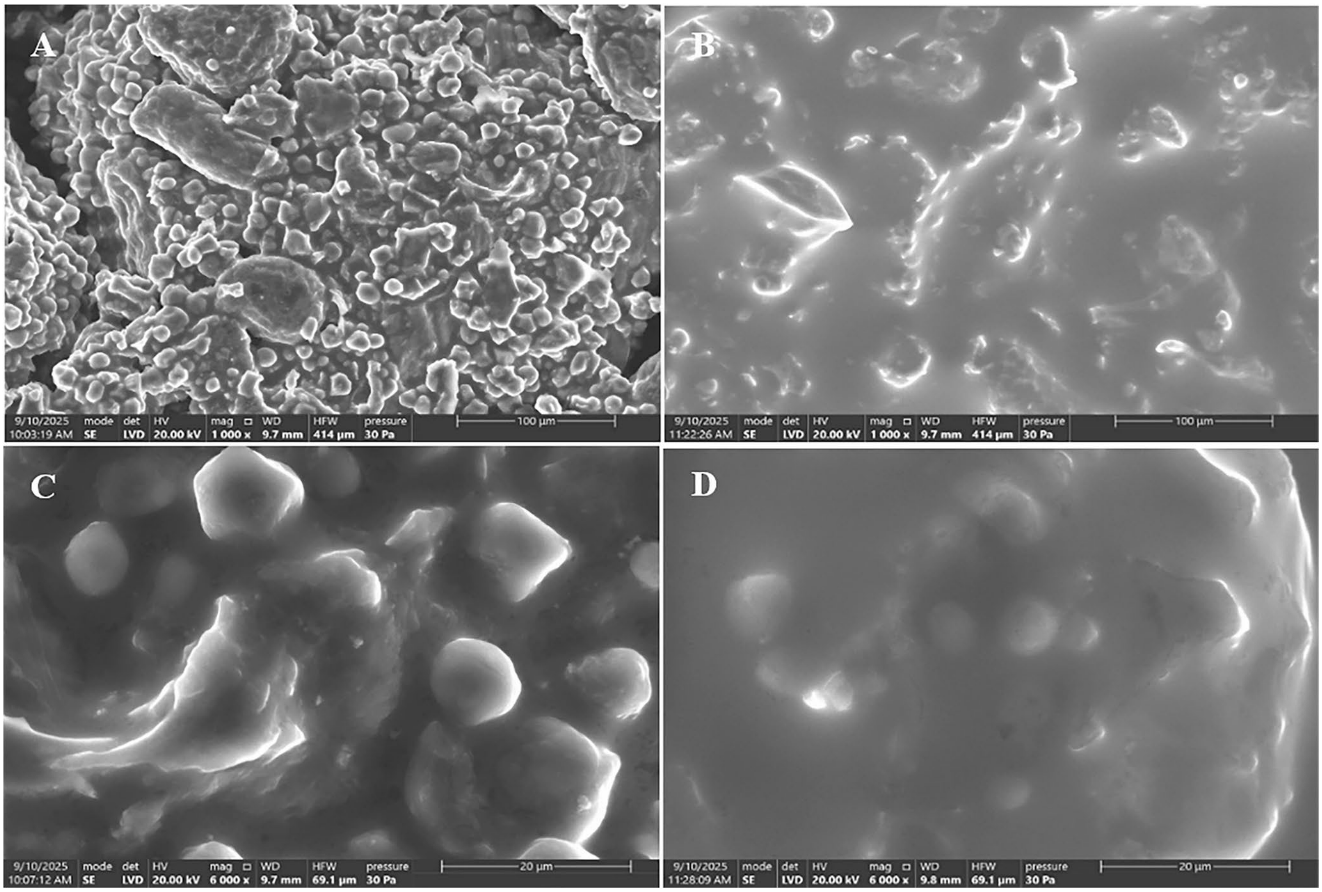

Fig. 1 SEM micrographs of legume-based burgers: (**A**) raw burger at 1000×, (**B**) cooked burger at 1000×, (**C**) raw burger at 6,000×, and (**D**) cooked burger at 6000×

essential criteria for visual and sensory acceptability. Thermal treatment had a marked influence on the rheological properties, resulting in the development of a reinforced viscoelastic network. SEM observations confirmed these effects by revealing a more compact and homogeneous structure after cooking. Overall, the consistency between rheological, microstructural, and nutritional results supports the potential of this burger as a credible plant-based alternative to meat products.

It's worth noting that this study has some limitations. Reproducibility may be affected by the controlled laboratory conditions, which differ from industrial processes. In addition, the optimization focused only on selected legumes (lentils, peas and, black beans), without considering other plant protein sources or functional ingredients that could improve product quality.

Future research should adapt the optimal formulations for commercial applications, considering factors such as production scale, texture after freezing, and cooking time. It will also be essential to evaluate shelf life, lipid oxidation, and microbiological stability, as well as to conduct comprehensive sensory tests to ensure consumer acceptance. In addition, studies on amino acid profiling and in vitro digestibility could provide deeper insights into the nutritional and functional properties of the developed burgers.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Gibbs J, Cappuccio FP (2022) Plant-based dietary patterns for human and planetary health. Nutrients 14:1614
2. Grdeń P, Jakubczyk A (2023) Health benefits of legume seeds. J Sci Food Agric 103:5213–5220. https://doi.org/10.1002/jsfa.12585
3. Kadyan S, Sharma A, Arjmandi BH et al (2022) Prebiotic potential of dietary beans and pulses and their resistant starch for aging-associated gut and metabolic health. Nutrients 14:1726
4. Andreani G, Sogari G, Marti A (2023) Plant-based meat alternatives: technological, nutritional, environmental, market, and social challenges and opportunities. Nutrients 15:452
5. Chaudhary A, Tremorin D (2020) Nutritional and environmental sustainability of lentil reformulated beef burger. Sustainability 12:6712. https://doi.org/10.3390/su12176712
6. Shariati-Ievari S, Ryland D, Edel A et al (2016) Sensory and physicochemical studies of thermally micronized Chickpea (Cicer arietinum) and green lentil (Lens culinaris) flours as binders in Low-Fat beef burgers. J Food Sci 81(5):S1230–S1242. https://doi.org/10.1111/1750-3841.13273
7. Abd ELhak NA (2021) Preparation and evaluation of different nutritive vegetarian burger for females and women. Egypt J Food Sci 49:107–123
8. Khazaei H, Subedi M, Nickerson M (2019) Seed protein of lentils: current status, progress, and food applications. Foods 8:391
9. Li C, Ganjyal GM (2017) Chemical composition, pasting, and thermal properties of 22 different varieties of peas and lentils. Cereal Chem 94:392–399
10. Senna C, Soares L, Egea MB, Fernandes SS (2024) The techno-functionality of Chia seed and its fractions as ingredients for meat analogs. Molecules 29:440
11. Bhat ZF, Pathak V (2011) Effect of black bean (*Vigna mungo*) on the quality characteristics of oven-roasted chicken seekh kababs. J Stored Prod Postharvest Res 2:15–23
12. Boukid F (2021) Plant-based meat analogues: from niche to mainstream. Eur Food Res Technol 247:297–308. https://doi.org/10.1007/s00217-020-03630-9
13. Kurbanova I, Lauciene L, Serniene L (2025) The physicochemical and sensory profiles of spreadable dairy matrix obtained from kidney bean milk-like extract and cow milk blends. Scifood 19:292–308
14. Romão B, Botelho RBA, Torres ML et al (2023) Nutritional profile of commercialized plant-based meat: an integrative review with a systematic approach. Foods 12:448
15. Gerber S, Masters W (2022) Nutrient composition of plant-based substitutes for animal-sourced foods: evidence from packaged and processed meats in 30 countries. Curr Dev Nutr 6:485
16. Bhuiyan MHR, Liu L, Samaranayaka A, Ngadi M (2025) Characterization of pea composites and feasibility of heat-modulated meat analogs production. Food Chem 463:141282. https://doi.org/10.1016/j.foodchem.2024.141282
17. Ruiz-Méndez M-V, Velasco J, Lastrucci AS, Márquez-Ruiz G (2024) Lipid quality changes in French fries, chicken croquettes, and chicken nuggets fried with high-linoleic and high-oleic sunflower oils in domestic deep fryers. Foods 13:2419
18. Ai Y, Jane J (2024) Understanding starch structure and functionality. Starch in food. Elsevier, pp 55–77Ai Y, Jane J (2024) Understanding starch structure and functionality. Starch in food. Elsevier, pp 55–77 https://doi.org/10.1016/B978-0-323-96102-8.00018-8
19. Dasiewicz K, Szymanska I, Opat D, Hac-Szymanczuk E (2024) Development and Characterization of Hybrid Burgers Made from Pork and Multi-Ingredient Plant Mixtures and Protected with Lactic Acid Bacteria. Appl Sci 14:2076–3417Dasiewicz K, Szymanska I, Opat D, Hac-Szymanczuk E (2024) Development and Characterization of Hybrid Burgers Made from Pork and Multi-Ingredient Plant Mixtures and Protected with Lactic Acid Bacteria. Appl Sci 14:2076–3417 https://doi.org/10.3390/app14146272
20. Trujillo-Mayol I, Madalena C, Sobral M, Viegas O et al (2021) Incorporation of avocado Peel extract to reduce cooking-induced hazards in beef and soy burgers: A clean label ingredient. Food Res Int 147:110434. https://doi.org/10.1016/j.foodres.2021.110434
21. Basati A, Hosseini SE (2018) The Effects of Adding Xanthan and Carboxy Methyl Cellulose on Cooking and Sensory Characteristics of Soya Burger. 8(1):59–64
22. Shahiri Tabarestani P, Kashiri M, Maghsoudlou Y et al (2022) Effect of *opuntia* pulp as a clean label ingredient on techno-functional properties of meat-free burger. Int J Food Sci Technol 57:3982–3989. https://doi.org/10.1111/ijfs.15657
23. Ko HJ, Wen Y, Choi JH (2021) Meat analog production through artificial muscle fiber insertion using coaxial nozzle-assisted three-dimensional food printing. Food Hydrocolloids 120:106898
24. Ayalew DB, Abera BD, Adiss YL (2024) Effect of roasting temperature and soaking time on the nutritional, antinutrional and sensory properties of protein-based meat analog from lupine. Heliyon 10:e33122. https://doi.org/10.1016/j.heliyon.2024.e33122
25. Vu G, Zhou H, McClements DJ (2022) Impact of cooking method on properties of beef and plant-based burgers: appearance, texture, thermal properties, and shrinkage. J Agric Food Res 9:100355. https://doi.org/10.1016/j.jafr.2022.100355
26. Polizer-Rocha YJ, Lorenzo JM, Pompeu D et al (2020) Physicochemical and technological properties of beef burger as influenced by the addition of pea fibre. Int J Food Sci Technol 55:1018–1024. https://doi.org/10.1111/ijfs.14324
27. Pietrasik Z, Sigvaldson M, Soladoye OP, Gaudette NJ (2020) Utilization of pea starch and fibre fractions for replacement of wheat crumb in beef burgers. Meat Sci 161:107974. https://doi.org/10.1016/j.meatsci.2019.107974
28. Soltanizadeh N, Ghiasi-Esfahani H (2015) Qualitative improvement of low meat beef burger using Aloe vera. Meat Sci 99:75–80. https://doi.org/10.1016/j.meatsci.2014.09.002
29. Modi VK, Mahendrakar NS, Narasimha Rao D, Sachindra NM (2004) Quality of Buffalo meat burger containing legume flours as binders. Meat Sci 66:143–149. https://doi.org/10.1016/S0309-1740(03)00078-0
30. Selani MM, Shirado GAN, Margiotta GB et al (2016) Effects of pineapple byproduct and canola oil as fat replacers on physicochemical and sensory qualities of low-fat beef burger. Meat Sci 112:69–76. https://doi.org/10.1016/j.meatsci.2015.10.020
31. Dunne RA, Darwin EC, Medina VAP (2025) Texture profile analysis and rheology of plant-based and animal meat. Food Res Int 205:115876
32. De Angelis D, Opaluwa C, Pasqualone A et al (2023) Rheological properties of dry-fractionated mung bean protein and structural, textural, and rheological evaluation of meat analogues produced by high-moisture extrusion cooking. Curr Res Food Sci 7:100552. https://doi.org/10.1016/j.crfs.2023.100552