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Chemical Composition, Antioxidant Activity, Functional, Pasting, and Thermal Properties of Selected Bean Flours

Janet Adeyinka Adebo

Centre for Cyber-Physical Food, Energy and Water Systems (CCP-FEWS), Faculty of Engineering and the Built Environment, University of Johannesburg, Auckland Park, Johannesburg, South Africa

Correspondence: Janet Adeyinka Adebo (janetaadex@gmail.com)

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ABSTRACT

This study investigated five commonly consumed flours—butter beans (BT) (*Phaseolus lunatus*), black beans (BB) (*Phaseolus vulgaris*), mung beans (MB) (*Vigna radiata*), haricot beans (HB) (*P. vulgaris*), and red kidney beans (RB) (*P. vulgaris*) for their physical properties, chemical composition, antioxidant activity, functional, pasting, and thermal properties. Color analysis revealed the highest lightness (L^*) values in HB (90.12) and BT (89.90) with redness (a^*) values highest in RB (2.46) and yellowness (b^*) values higher in MB (13.64) and BT (12.99). The protein content ranged from 17.75% to 24.35%, with the highest value found in MB. The fat content of the flours ranged from 0.5% to 1.10%, with MB having a significantly higher content. For the functional properties, RB exhibited the highest water absorption capacity (2.99 g/g), while HB had the highest oil absorption capacity (2.13 g/g); meanwhile, the bulk density ranged from 0.81 to 0.91 g/cm^3. MB recorded the highest total flavonoid and phenolic contents at 4.79-mg QE/g and 2.17-mg GAE/g, respectively. RB demonstrated the highest ABTS antioxidant activity (3.29-mg TE/g), followed by BB (2.83-mg TE/g). All flours had the same pasting temperature (95.10°C). Thermal properties varied, with HB showing the highest peak and end temperatures, while MB showed the highest gelatinization enthalpy. Scanning electron microscopy revealed structural differences among the flours, with MB exhibiting more compactness. These findings support the potential application and acceptability of these selected legumes as functional ingredients and promote their utilization for human consumption.

1 | Introduction

Legumes are integral to the economy, nutrition, and health, contributing to a sustainable future (Becerra-Tomás et al. 2018; Adebiyi et al. 2019). Legumes are deemed one of the first crops humans have grown and still serve as a staple for many cultures worldwide (Abobatta et al. 2022; Affrifah et al. 2023). Globally, legume seeds are used as cost-effective alternatives to protein. Some examples of legumes include red kidney beans, mung beans, black beans, pigeon peas, haricot beans, jack beans, Bambara groundnut, butter beans, and soybeans; however, some remain underutilized. These legumes have distinctive colors, shapes, sizes, and flavors that appeal to consumers. Legumes, including the underutilized varieties, are widely considered the most inexpensive plant-based source of protein, polyphenols, and carotenoids. They are low in fat and cholesterol and have a low glycemic index, providing a high-energy food option (Vilakazi et al. 2025). Legumes also contain essential minerals such as calcium, magnesium, potassium, iron, and essential amino acids (such as lysine), and considerable amounts of B vitamins, especially folate (Margier et al. 2018; Affrifah et al. 2023).

Pasting and thermal properties are recognized as the functional attributes of legumes that determine textural quality, processing behavior, and potential applications. The pasting and thermal properties are largely determined by the

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composition of starch and interactions between protein and starch, as well as granule morphology, all known to influence subsequent applications in soups, sauces, and baked goods. A study by Keskin et al. (2022) reported that awareness of legume ingredient characteristics such as protein denaturation, starch gelatinization, pasting behavior, and thermal properties can give a deeper understanding of their functionality and end-use applications. In addition, consuming legumes is positively associated with several health benefits, such as possessing hypoglycemic, antioxidant, hypocholesterolemic, antihypertensive, anticarcinogenic, anti-inflammatory, and antiatherogenic properties (Juárez-Chairez et al. 2022; Grdeń et al. 2023; Tawalbeh et al. 2023). Due to these nutritional and health benefits, legumes could serve as a low-cost ally against malnutrition, particularly in under-resourced communities (Samal et al. 2023; Sharif et al. 2024). Moreover, legumes are increasingly regarded as potential superfoods, contributing to the goal of achieving zero hunger at a time of critical need (Martín-Cabrejas 2019), especially with indications of chronic malnourishment in two of every five children (UNICEF/WHO/World Bank 2023).

These legumes may help address vital global challenges through the provision of sustainable alternatives to the protein deficiency issue, which is especially relevant in low-income countries where the availability of animal protein is limited. Accordingly, this would enable food manufacturers to create novel protein-based foods that are in high demand due to the current health and sustainability trend among consumers. Also, the assessment of both commonly used and underutilized varieties can unlock their industrial potential fully, thus promoting food security and aiding in achieving the UN's Sustainable Development Goal 2 (Zero Hunger).

Despite the well-accepted approval and importance of legumes as sustainable protein sources, knowledge gaps still exist regarding a comprehensive comparison of these five legume flours that are typically consumed in South Africa. Prior studies have focused on only one legume type and/or with limited parameters investigated, thus providing limited information for nutritionists and food producers to select the right legume for their applications. To the best of the author's knowledge, there is no reported comparative systematic analysis of the combined physical, functional, thermal, and antioxidant properties of butter beans, black beans, mung beans, haricot beans, and red kidney beans flours. Also, the relationship between functional properties and microstructural analysis of the abovementioned flours is lacking due to these current gaps that somewhat limit their use in industrial food production processes. This novel approach substantially overcomes these existing limitations by availing the simultaneous assessment of several crucial quality indicators, all critical for multi-industrial food processing operations.

Hence, this study focuses on the physical properties, chemical composition, phytochemical composition, antioxidant activity, functional, pasting, and thermal properties of five selected legume flours: butter beans, haricot beans, black beans, red kidney beans, and mung beans. These legumes were selected based on their varying nutritional properties and widespread consumption, representing both commonly used and underutilized legume species.

2 | Materials and Methods

2.1 | Materials

Five selected legumes, namely, red kidney beans (*Phaseolus vulgaris*), mung beans (*Vigna radiata*), black beans (*P. vulgaris*), haricot beans (*P. vulgaris*), and butter beans (*Phaseolus lunatus*) were purchased from Multi Snacks (Pty) Ltd., Cape Town, South Africa and Deli (Pty) Ltd., Johannesburg, South Africa. The grains were cleaned to remove debris or foreign objects and milled using a laboratory mill (Koninklijke Philips N.V., Eindhoven, Netherlands). The respective milled flours were sieved through 500-μm mesh (Analysette 3 Spartan, Fritsch GmbH, Idar-Oberstein, Germany) to obtain a uniform particle size distribution. After milling, the flour samples were kept in airtight containers, labelled, and stored at 4°C in a refrigerator for further analysis.

2.2 | Chemical Composition of Selected Bean Flours

The chemical composition of selected bean flours, such as crude ash, crude fiber, crude protein, crude fat, and moisture content was investigated using AOAC International methods 942.05, 978.10, 2001.11, 920.39, and 934.01. Furthermore, the total carbohydrate was calculated by difference (AOAC 2023).

2.3 | Color Profiles of Selected Bean Flours

The study ascertained the color profiles of the different legume flours using a chroma meter (CR 410, Konica Minolta Inc., Tokyo, Japan), calibrated using the required calibration plate before triplicate measurements for consistent values. Color parameters including yellowness (b^*), redness (a^*), and lightness (L^*) were recorded using the CIELAB system. The computed color metrics such as chroma (C^*), hue angle (H°), yellowness index (YI), and whiteness index (WI) were calculated using Equations (1)–(4), respectively (Adeyanju et al. 2025). The browning index was expressed using Equations (5) and (6) (Emerald et al. 2020).

$$\text{Chroma} = \sqrt{(a^*)^2 + (b*)^2} \tag{1}$$

$$\text{Hue } (H)\text{o} = \tan^{-1}\left(\frac{b*}{a*}\right) \tag{2}$$

$$\text{YI} = \frac{142.86b*}{L*} \tag{3}$$

$$\text{WI} = \sqrt{(100 - L*)^2 + (a*)^2 + (b*)^2} \tag{4}$$

$$\text{Browning index} = \frac{\left[100(y - 0.31)\right]}{0.17} \tag{5}$$

$$y = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \tag{6}$$

2.4 | Functional Properties of Selected Bean Flours

2.4.1 | Bulk Density (BD)

Fifty grams of the legume flours were each weighed into the 100-mL graduated cylinders to measure BD. The graduated cylinder was tapped several times to a consistent volume. The final volume was measured, and the BD was recorded. Subsequently, the BD (g/cm^3) was computed as the weight of the sample per volume of the sample after tapping (Adebiyi et al. 2016).

2.4.2 | Water and Oil Absorption Capacity (WAC and OAC)

One gram of each of the five legume flours and 10 mL of either distilled water (WAC) or oil (OAC) was added, vortexed (Model 36110740 Mixer, Darmstadt, Germany), and kept for 30 min at ambient temperature. Thereafter, the mixtures were centrifuged in a weighted centrifuge tube (Eppendorf 5702R, Merck, Darmstadt, Germany) at 2000 ×*g* for 10 min, and the supernatant was decanted. The results obtained were calculated on a dry basis as g of water/oil bound per g of flour sample (Adebiyi et al. 2016).

2.5 | Total Phenolic, Total Flavonoid, and Antioxidant Activity of Selected Bean Flours

2.5.1 | Extraction

The study extracted five different legume flours by employing the method of Mudau and Adebo (2025). Five milliliters of methanolic acid (1% hydrochloric acid in 80% methanol) was mixed into a 0.25-g flour sample in a centrifuge tube. The mixtures were homogenized, shaken for 2 h (Model 36,110,740 Mixer, Darmstadt, Germany), sonicated in an ultrasonic bath (AU 220, Argo Lab, Carpi, Italy), and agitated for 2 h. The samples were then centrifuged (Eppendorf 5702R, Merck) for 10 min at 4000 rpm. The supernatant was filtered into a 15-mL centrifuge tube and further analyzed.

2.5.2 | Total Phenolic Content (TPC)

A modified method by Arouna et al. (2020) was used to determine the TPC of the legume flours and evaluated using Folin–Ciocalteu reducing capacity. In sum, 10 μL of the sample extract was mixed with 50 μL of dilute Folin–Ciocalteu reagent and 50 μL of 7.5% sodium carbonate (Na_2CO_3). The mixture was incubated at 25°C in the dark for 30 min; thereafter, gallic acid (GA) standard solutions 0–0.2 mg/mL were prepared for the calibration curve, and absorbance was read using an Accuris SmartReader 96 microplate reader at 750 nm. The overall phenolic content was expressed as mg of GA equivalent per g sample (mg GAE/g).

2.5.3 | Total Flavonoid Content (TFC)

The TFC of the samples was estimated following the method used by Kewuyemi and Adebo (2024). Ten microliters of the extracts was added to "a 96-well microplate (Hirschmann Laborgerate GmbH & Co., Eberstadt, Germany)," and 10 μL of 2.5% $NaNO_2$, 30 μL of 1.25% $AlCl_3$, and 100 μL of 2% NaOH immediately thereafter. The plate was covered with aluminum foil and incubated in the dark for 30 min. The mixture volume (170 μL) and quercetin standard solutions (0–2.0 mg/mL) were read by a microplate absorbance reader (Accuris SmartReader 96, model: MR9600; Jersey, NJ, USA) at 450 nm. The TFC was calculated and expressed in the mg of quercetin equivalent per g sample (mg QE/g).

2.5.4 | ABTS [2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonate)] Free Radical Scavenging Activity Assay

The ABTS free radical scavenging activity was determined using the method of Sadh et al. (2017). An ABTS working solution was combined in a 96-well plate with extract solutions and allowed to incubate for 30 min at room temperature. The absorbance of the reaction mixture and blank was assessed at 734 nm using an Accuris SmartReader 96 microplate reader. ABTS radical scavenging activity percentage inhibition was calculated using the absorbance readings recorded.

2.6 | Pasting Properties of Selected Bean Flours

The method of Adeyanju et al. (2025) was applied to determine the pasting properties of the legume flours and measured using a Rheometer (Anton Paar MCR 72, Ostfildern, Austria). Briefly, each of the flour samples (3.4 g, db) was dispersed in distilled water and adjusted by weight to 34 g. The slurries were stirred at 960 rpm for 10 min to ensure even temperature (50°C) distribution and hydration. After that, the stirring rate was decreased to 160 rpm, and a temperature protocol from 50°C to 95°C in 15-min isotherm and the inverse way, 95°C to 50°C in 15 min was applied. The recorded pasting parameters include peak viscosity, peak time, peak temperature, holding strength, breakdown viscosity, final viscosity, setback viscosity, and trough viscosity, which were automatically computed and obtained from the rheometer software (RheoCompass).

2.7 | Thermal Properties of Selected Bean Flours

A differential scanning calorimeter (DSC) system integrated with *STARe* software (CH-8606, Mettler Toledo, Greifensee, Switzerland) was used to evaluate the thermal properties of the legume samples using the modified method of Adeyanju et al. (2025). Ten milligrams (dry weight) of the sample was weighed into the DSC pan, 30-μL distilled water was added, and the pan was sealed afterwards. The sealed pan was allowed to equilibrate for 24 h at ambient temperature, and the scanning process occurred between 25°C and 140°C at a rate of 10°C per min. Indium ($T_p = 156.6$°C, 28.5 J/g) served as the calibration standard, with an empty pan used as the reference. Onset temperature (T_o), end set temperature (T_e), peak temperature (T_p), and gelatinization enthalpy (ΔHgel) were measured.

2.8 | Scanning Electron Microscopy (SEM) of Selected Bean Flours

The study employed the method of Adebiyi et al. (2016) for the SEM of the selected bean flours. The flour samples were placed on aluminum stubs using a carbon coater (Quorum Q150TE, QuorumTechnologies, UK) for spray coating with a thin carbon film. Thereafter, the samples were taken to the chamber of the SEM specimen and run through an electron beam vacuum using an SEM (Vega Ash-utd, TESCAN, Czech Republic). The SEM images were obtained at 250× magnification.

2.9 | Statistical Analysis

Triplicate experimental data obtained were computed for the mean value, one-way analysis of variance (ANOVA) and means separated subsequently using Duncan multiple range test at $p \leq 0.05$ significance (IBM *SPSS Statistics*, ver. 29.0, Armonk, NY, USA). The Shapiro–Wilk test was used to confirm the data normality, and Levene's test was used to verify the homogeneity of variance prior to ANOVA analysis.

3 | Results and Discussion

3.1 | Chemical Composition of Selected Bean Flours

The percentage protein content ranged from 17.75% to 24.35%, with no significant ($p \leq 0.05$) differences between BT and RB (Table 1). The highest protein value was recorded in MB and the lowest in HB. This observation was in agreement with an earlier study that recorded a high protein content of 22.63% to 25.84% in MB (Idris et al. 2025). Similarly, Shimelis and Rakshit (2005) obtained protein levels ranging from 17.96% to 22.07% in HB varieties, which are in line with the current study's obtained values. According to Du et al. (2014), the protein content of 10 commercial legume flours ranged from 22.37% to 28.05%. As mentioned in Singh et al. (2022), legume proteins are generally between 15.5% and 42%, which is reportedly higher than several other commodities such as poultry, which falls between 18% and 25%; meat, between 15% and 30%; cereal crops, between 8% and 15%; and eggs, between 12% and 13%, depending on the specific item and preparation method (USDA 2023). The high protein content (17.75%–24.35% w/w) of these legume flours makes them suitable for protein isolate production in the food industry. From the data, MB, which has the highest protein content (24.35% w/w), appears to be the most promising legume for protein production. In addition to some sensitive consumers who incline towards alternative protein foods that are free from soy, the protein isolate from these legumes may offer an alternative that is allergen-free or less allergenic than soy protein isolate. However, it is important to note that allergenicity can still occur with any legume, although the risk is typically lower compared to soy (Smits et al. 2023). To mitigate such risk, careful investigation of the allergenicity assessment, cross-reactivity, and subsequent labeling, where applicable, is required.

The observed moisture content of legume flours was between 8.77% and 10.52%, with no significant ($p \leq 0.05$) differences between BT and BB, while MB (8.77%), HB (10.52%), and RB (10.19%) showed significantly different values (Table 1). These differences may be attributed to seed coat permeability, water holding capacity, and hygroscopic properties, which vary between species depending on their protein and carbohydrate compositions. Our results are in agreement with those reported by Du et al. (2014) on various legume varieties. The moisture content of the legume flours was less than 14%, a level known to inhibit microbial growth and enhance storability. The fat content of the selected legumes ranged from 0.5% to 1.10%, with MB showing significantly higher content. All values were low, consistent with the typical low-fat nature of some legumes (Tucker 2023).

BT had the highest level of crude ash (3.98%), while MB had the lowest value (3.04%). Flours with higher ash content could enhance minerals in the diet, especially when incorporated into food products with low ash (Millar et al. 2019), such as maize (1.93%) (Adeniyi and Ariwoola 2019), rice (0.7%) (Summpunn et al. 2023), and wheat (0.55%) (Bodor et al. 2024). Higher ash content of $> 1\%$ is a distinctive attribute of pulse flours (Locali-Pereira et al. 2022). According to Cauvain (2015), bakers typically consider flour with an ash content of $> 1\%$ to be of inferior quality, especially for the production of white bread. This is because the elevated ash levels, containing nongluten proteins and dietary fibers, can interfere with gluten development by weakening the protein network during dough formation through disintegration and dilution effects (Czaja et al. 2020). The total carbohydrate content ranged from 56.59% to 63.52%. MB has a lower carbohydrate content of 56.59%, which corresponds with its higher fat (1.10%) and protein (24.35%) contents, while HB's higher carbohydrate content (63.52%) aligns with its lower protein content (17.75%). The latter sample with higher carbohydrate

TABLE 1 | Chemical composition (% w/w) of selected bean flours.

Sample	Moisture	Crude protein	Crude ash	Crude fat	Crude fiber	Carbohydrate
BT	9.95 ± 0.01^{b}	19.00 ± 0.52^{b}	3.98 ± 0.25^{c}	0.60 ± 0.02^{b}	3.90 ± 0.22^{a}	62.57 ± 0.54^{c}
MB	8.77 ± 0.22^{a}	24.35 ± 0.08^{d}	3.04 ± 0.25^{a}	1.10 ± 0.02^{d}	6.15 ± 0.78^{b}	56.59 ± 0.89^{a}
BB	9.95 ± 0.31^{b}	21.12 ± 0.09^{c}	3.67 ± 0.04^{bc}	0.75 ± 0.02^{c}	5.29 ± 0.35^{ab}	59.22 ± 0.43^{b}
HB	10.52 ± 0.14^{d}	17.75 ± 0.10^{a}	3.31 ± 0.08^{ab}	0.65 ± 0.02^{b}	4.25 ± 0.30^{a}	63.52 ± 0.29^{d}
RB	10.19 ± 0.01^{bc}	19.04 ± 0.07^{b}	3.65 ± 0.24^{bc}	0.50 ± 0.02^{a}	4.81 ± 1.23^{ab}	61.81 ± 0.85^{c}

Note: Each value is a mean of triplicates. Means with no common letters within a column significantly differ ($p \leq 0.05$).
Abbreviations: BB, black bean; BT, butter bean; HB, haricot; MB, mung bean; RB, red kidney bean.

content could contribute to the supply of calories in products that could be developed from it.

3.2 | Color Profiles of Selected Bean Flours

Table 2 delineates the color profiles for different types of legumes, demonstrating statistically significant differences ($p \leq 0.05$) among the legume samples. The lightness (L^*) values ranged from 82.66 to 90.12, with HB exhibiting the highest value (90.12), followed by BT (89.90). Given that L^* in HB and BT indicated brighter colors, it is possible to associate them with better appearance and higher market value. Both RB (82.66) and BB (82.81) had the lowest values. These two legumes (HB and BT) also show the highest values for the whiteness index (WI), while samples with the lowest L^* values correspondingly showed the lowest WI values. Wodajo et al. (2021) reported that the L^* values of different HB varieties ranged from 26 to 81. The authors further emphasized that the brightness and color of the seed are part of the main quality parameters of the common bean.

The a^* and b^* positive values ($+a^*$ and $+b^*$) are typically associated with red and yellow hues, respectively (Pandiselvam et al. 2023), while the negative values ($-a^*$) indicate green and blue ($-b^*$) colors (Jaramillo-Sánchez et al. 2018). The redness (a^*) values were as follows: RB (2.46), BB (1.32), HB (0.91), BT (0.20), and MB (−2.37); thus, the legumes (RB and BB) with the lowest L^* values exhibited high values in a^*. RB has a reddish color characteristic, which would lead to a higher a^* value, thereby indicating more redness on the red-green spectrum. The MB sample with a negative a^* value indicated a greenish hue. MB and BT had the highest yellowness (b^*) values, while BB and RB displayed the lowest. Such low values in BB might be due to this legume having a very dark color with minimal yellow tones. Since b^* was higher in MB and BT, the YI was higher in MB and BT.

The chroma (C^*) was higher in the MB and BT, signifying vivid colors, with the lowest values in BB and RB (Table 2), suggesting less intense coloration. Higher chroma values correspond with the higher color intensity of samples, which consumers can discern (Pathare et al. 2013). The yellow index ranged from 8.32 to 22.22 and was higher in MB (22.22) and BT (20.64). WI values displayed a similar pattern with lightness values; HB (86.42) flour had the highest whiteness indices, followed by BT flour (83.55). These lighter-colored flours demonstrate higher visual appeal, which is crucial for applications such as bakery products and dairy analogs, as consumers usually associate light colors with quality and freshness. In contrast, the lowest whiteness indices were noted for MB (80.70) and RB (80.99) as shown in Table 2. The darker color of the RB flour is mainly due to the increased anthocyanin content present in the seed coat of the seeds, which naturally darkens the flour. The variability in color parameters occurs based on the natural peculiarity of such pigment's concentration in respective legume flours: While anthocyanins create the darker hue of the RB, carotenoids contribute to the yellowness observed in MB and BT.

The browning index was higher in BT (15.40) and MB (14.44), and the lowest value was observed in BB (7.02). According to Demircan and Velioglu (2024), visual appeal is sustained with a lower browning index, eliminates unwanted color changes, and offers insights into the nutritional value and phenolic compounds. The hue angle (h) ranged from −1.40° to 1.56°, indicating that the seeds showed colors within the red-yellow spectrum. The hue angle can reveal the presence of the natural colors that influence consumer perceptions of the quality of legumes. During assays, a higher hue angle shows a less yellow character (Pandiselvam et al. 2023). Hence, the authors further conclude that BT, which has a lower a^* value, results in a higher hue value. These color parameters are crucial for assessing the quality and freshness of legumes and controlling market value by serving as indicators of consumer appeal that affect quality control and marketing (Demircan and Velioglu 2024). Correspondingly, genetic variability and environmental factors can influence the color of legumes (Parker et al. 2024).

3.3 | Functional Properties of Selected Bean Flours

The BD, OAC, and WAC of the selected bean flours are presented in Table 3. The BD of MB was 0.91 g/cm^3, which was significantly higher ($p \leq 0.05$) than that of BB, HB, RB (0.83 g/cm^3), and BT (0.81 g/cm^3). The higher BD in MB indicates that the flour was denser compared to flours from other legumes, suggesting that it may require more compact and durable packaging material during storage (Awuchi et al. 2019). On the other hand, low BD has an advantage in the formulation of a high-quality complementary diet or products (WHO 2003), with lighter and airier textures, improving palatability and digestibility for infants or young children. This also allows for better blending and nutrient distribution, ensuring a uniform diet that is less taxing

TABLE 2 | Color profile of selected bean flours.

Sample	L^*	a^*	b^*	Chroma	Yellow index	Whiteness index	Browning index	Hue angle
BT	89.90 ± 0.01^{d}	0.20 ± 0.02^{b}	12.99 ± 0.01^{d}	12.99 ± 0.01^{d}	20.64 ± 0.02^{d}	83.55 ± 0.01^{d}	15.40 ± 0.01^{e}	1.56 ± 0^{e}
MB	86.34 ± 0.01^{c}	-2.37 ± 0.02^{a}	13.43 ± 0.02^{e}	13.64 ± 0.02^{e}	22.22 ± 0.03^{e}	80.70 ± 0.02^{a}	14.44 ± 0.02^{d}	-1.40 ± 0^{a}
BB	82.81 ± 0.01^{b}	1.32 ± 0.01^{d}	4.82 ± 0.01^{a}	5.00 ± 0^{a}	8.32 ± 0.01^{a}	82.10 ± 0^{c}	7.02 ± 0^{a}	1.30 ± 0^{c}
HB	90.12 ± 0.02^{e}	0.91 ± 0.01^{c}	9.26 ± 0.01^{c}	9.31 ± 0^{c}	14.68 ± 0.01^{c}	86.42 ± 0.01^{e}	11.33 ± 0.01^{b}	1.47 ± 0^{d}
RB	82.66 ± 0.01^{a}	2.46 ± 0.02^{e}	7.42 ± 0.01^{b}	7.82 ± 0^{b}	12.82 ± 0.02^{b}	80.99 ± 0.01^{b}	11.37 ± 0^{c}	1.25 ± 0^{b}

Note: Each value is a mean of triplicates. Means with no common letters within a column significantly differ ($p \leq 0.05$).
Abbreviations: a^*, redness/greenness; b^*, yellowness; BB, black bean; BT, butter bean; HB, haricot; L^*, lightness; MB, mung bean; RB, red kidney bean.

TABLE 3 | Functional properties, total phenolic, total flavonoid, and antioxidant activity of selected bean flours.

Sample	BD (g/cm^3)	WAC (g/g)	OAC (g/g)	TPC (mg GAE/g)	TFC (mg QE/g)	ABTS (mg TE/g)
BT	0.81 ± 0.01^{a}	2.88 ± 0.01^{c}	1.58 ± 0.02^{a}	1.29 ± 0.08^{a}	4.58 ± 0.01^{a}	1.26 ± 0.19^{a}
MB	0.91 ± 0.01^{c}	2.10 ± 0.02^{a}	1.62 ± 0.03^{b}	2.17 ± 0.37^{b}	4.79 ± 0.09^{b}	1.48 ± 0.13^{a}
BB	0.83 ± 0.01^{b}	2.70 ± 0.03^{b}	1.77 ± 0.02^{c}	1.16 ± 0.22^{a}	4.56 ± 0^{a}	2.83 ± 0.17^{b}
HB	0.83 ± 0.01^{b}	2.93 ± 0.03^{d}	2.13 ± 0.01^{e}	0.93 ± 0.28^{a}	4.56 ± 0.03^{a}	1.60 ± 0.17^{a}
RB	0.83 ± 0.01^{b}	2.99 ± 0.02^{e}	1.94 ± 0.01^{d}	0.91 ± 0.05^{a}	4.56 ± 0.02^{a}	3.29 ± 0.28^{c}

Note: Each value is a mean of triplicates. Means with no common letters within a column significantly differ ($p \leq 0.05$).
Abbreviations: ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); BB, black bean; BD, bulk density; BT, butter bean; HB, haricot; MB, mung bean; OAC, oil absorption capacity; RB, red kidney bean; TFC, total flavonoid content; TPC, total phenolic content; WAC, water absorption capacity.

on the digestive system and supports better nutrient absorption (Onweluzo and Nwabugwu 2009; Balasubramanian et al. 2014).

The WAC of the legume flours ranged from 2.10 to 2.99 g/g, with significant ($p \leq 0.05$) differences. RB had the highest WAC (2.99 g/g), while MB recorded the lowest (2.10 g/g). According to Awuchi et al. (2019), an increase in the WAC of flour may be attributed to enhanced amylose solubility and leaching, as well as the degradation of the starch crystalline structure. Similarly, in comparison to other legumes, the higher WAC in RB may be due to its hydrophilic properties. Hydrophilic properties, such as polysaccharides, are more prevalent in flours with a high WAC (Pereira et al. 2025). The higher WAC of flours signifies better performance as it impacts their functional and sensory properties during food preparation (Wani et al. 2019). Du et al. (2014) reported WAC levels of 1.22, 1.67, and 1.61 g/g in MB, RB, and BB, respectively, which are different from the values obtained in this study. HB had the highest OAC, with significant ($p \leq 0.05$) differences among the samples. OAC plays a significant role in the functional properties of flours as it enhances mouth feel and retains flavor. The type of protein, particle size, protein and starch contents, as well as surface nonpolar amino acid side chain ratios, influence the OAC of legume varieties (Sathe et al. 1982; Chau et al. 1997; Bala et al. 2020). Both WAC and OAC in legumes were higher than those in wheat flour (Chandra and Samsher 2013; Ozolina et al. 2024). This study also confirmed higher WAC in RB (2.99 g/g) and OAC of HB (2.13 g/g), both exceeding values reported for wheat flour (1.08–1.46 g/g) in previous studies (Chandra and Samsher 2013; Kumar et al. 2021; Msugh et al. 2024). Thus, this enables better dough handling and improves the texture of baked goods. Studies have suggested that typical WAC values should be in the range of 1.0–3.0 g/g to ensure optimal cohesiveness, dough hydration, and handling properties in baked goods, while OAC values of 1.0–2.0 g/kg are generally sufficient to facilitate fat emulsification, improve dough lubricity, texture, and overall quality of baked goods (Bojňanská et al. 2012; Akissoé et al. 2025). These natural functional properties are clean-label solutions that could not be obtained by any synthetic emulsifier.

3.4 | Total Phenolic, Total Flavonoid, and Antioxidant Activity of Selected Bean Flours

The TPC of various selected bean flours ranged between 0.91- and 2.17-mg GAE/g (Table 3), indicating the antioxidant potential of the flours. There were no significant ($p \leq 0.05$) differences between RB, HB, BB, and BT. The TPC of HB (0.93-mg GAE/g) was similar to that of RB (0.91-mg GAE/g), while BT (1.29-mg GAE/g) was comparable to BB (1.16-mg GAE/g), and MB exhibited the highest TPC among the flour samples (Table 3). The higher TPC in MB may be due to its greenish seed coat, which contains elevated levels of polyphenols. A study by Ahmmed et al. (2020) reported that MB had the highest TPC compared to three other legume varieties, namely, lentil, anchor, and chickpea, which are in agreement with the findings of this study. Another study examined the TPC in different types of MB (Yusnawan et al. 2019). The TPC in the dull group ranged from 3.97- to 6.58-mg GAE/g, which was slightly higher than that of the shiny green group, which ranged from 3.74- to 5.20-mg GAE/g (Yusnawan et al. 2019). These differences were linked to genotype and seed pigmentation. Also, the TPC levels in 26 kidney bean varieties reportedly ranged from 0.25- to 3.79-mg GAE/g (Kan et al. 2017). Among the kidney bean cultivars, the colors of Taiguoshuangqingjiadou (TGSQJD) and Honghuaqingjiajiadou (HHQJJD) were similar to red kidney beans, and their TPCs were 0.92- and 0.97-mg GAE/g, respectively (Kan et al. 2017). The TPC findings corroborate with values measured in RB in this study.

The TFC results are similar to that of TPC (Table 3), with no significant ($p \leq 0.05$) differences between RB, HB, BB, and BT. The study observed the highest TFC values in MB, ranging from 4.56- to 4.79-mg QE/g. The degree of maturity, extraction method, seed coat color between cultivars, and environmental and genetic factors could influence the variation in TPC and TFC (Zhao et al. 2014; Multescu et al. 2024). Findings from a study conducted in Portugal on the TFC of different bean samples and their cultivars for the 2013 and 2014 harvest years reported ranges from 0.80- to 4.33-mg CE/g (2013) and 0.91 to 4.02-mg CE/g (2014), respectively (Carbas et al. 2020). In particular, the cranberry, black, and red kidney cultivars exhibited higher phenolic composition than the uncolored cultivars (navy and butter beans) (Carbas et al. 2020).

Antioxidants can differ in how they respond based on the particular type of oxidant or radical source (Multescu et al. 2024). As a result, no specific approach can fully encompass the mode of action of all radical sources or antioxidants in a complex system, such as foods (Prior et al. 2005). The ABTS values ranged from 1.26- to 3.29-mg TE/g (Table 3). RB had the highest ABTS value (3.29-mg TE/g) followed by BB (2.83-mg

TE/g), HB (1.60-mg TE/g), MB (1.48-mg TE/g), and BT (1.26-mg TE/g). Complex composition, such as vitamins, active polysaccharides, microelements, amino acids, and proteins, may influence the antioxidant capacity of legumes (Zhao et al. 2014). Studies have reported that high antioxidant activities occur in legumes with a dark seed coat, such as lentils, adzuki bean, and black soybeans (Ha et al. 2021; Kumar et al. 2023; Pathiraja et al. 2023; Tung et al. 2024) This outcome could be attributed to the presence of high levels of phenolic-related compounds, mostly condensed tannins and anthocyanins (Ha et al. 2021; Kumar et al. 2023; Pathiraja et al. 2023; Tung et al. 2024).

3.5 | Pasting and Thermal Properties of Selected Bean Flours

The pasting properties of the flours were measured using a rheometer (Anton Paar MCR 72, Ostfildern, Austria). Amylographs (Rapid Visco Analyzer [RVA] and Brabender Visco-Amylograph [BVA]) and paste cells incorporated with a rheometer are conventionally used for pasting behavioral analysis (Keskin et al. 2022), with these studies concluding that precise rheometric measurements have more benefits than RVA/BVA for investigating the properties of starch, as they do not disrupt the gel structure during measurement (Tsutsui et al. 2005; Ahmed 2012). Such rheometers ensure improved accuracy regarding shear rate and temperature control and viscosity measurements and allow detailed reproduction of viscoamylographic curves, better comprehension of starch gelatinization processes, and might be a reliable screening tool for obtaining datasets at potentially lower error margins for minor characterization of legume flour (Ahmed et al. 2008).

Figure 1 depicts the rheometric pasting properties results. Pasting temperatures of the selected legumes were the same (95.10°C). The peak times for MB (33.14 min), BB (33.14 min), HB (33.16), and RB (33.16 min) were slightly higher than for BT (32.98 min). Peak time reflects the required time for starch to fully gelatinize. The trough viscosity of the legume flours varied significantly ($p \leq 0.05$), ranging between 165.67 and 899.07 cP. HB exhibited the highest values, while BT exhibited the lowest. According to Wani et al. (2012), the formation of amylose–lipid complexes and the rate of amylose leaching and granule swelling denote trough viscosity. The peak (710.20 cP) and final (899.53 cP) viscosities were highest in HB, followed by MB (Figure 1). Interestingly, MB had lower peak (591.0 cP) and final (1060.0 cP) viscosities than flours from various sources (Liu et al. 2006). However, the values above are higher than those observed in the current study. Peak viscosity is an indication of the maximum swelling capacity and water-binding capacity of the starch granules. The highest peak viscosity in HB suggests a very high granule expansion with hydration. This could be due to the composition of starch and protein-starch interaction. MB also showed high peak viscosity (298.50), but the value is lower than 710.20 cP. It corresponds with the slightly loose and more expanded structure that was observed in the SEM image (Figure 3C). The final viscosity is an indicator of the ability of starch molecules to reassociate during cooling and a high retrogradation potential. Retrogradation characterizes the gelling ability of starch sources and is vital in the use of sauce, and bakery fillings.

The setback viscosity is usually calculated as the difference between final and trough viscosities. It further indicates the extent of starch retrogradation that occurs during the cooling process. The HB has a higher setback, followed by the MB, signifying higher structural recovery and gelling ability. The breakdown

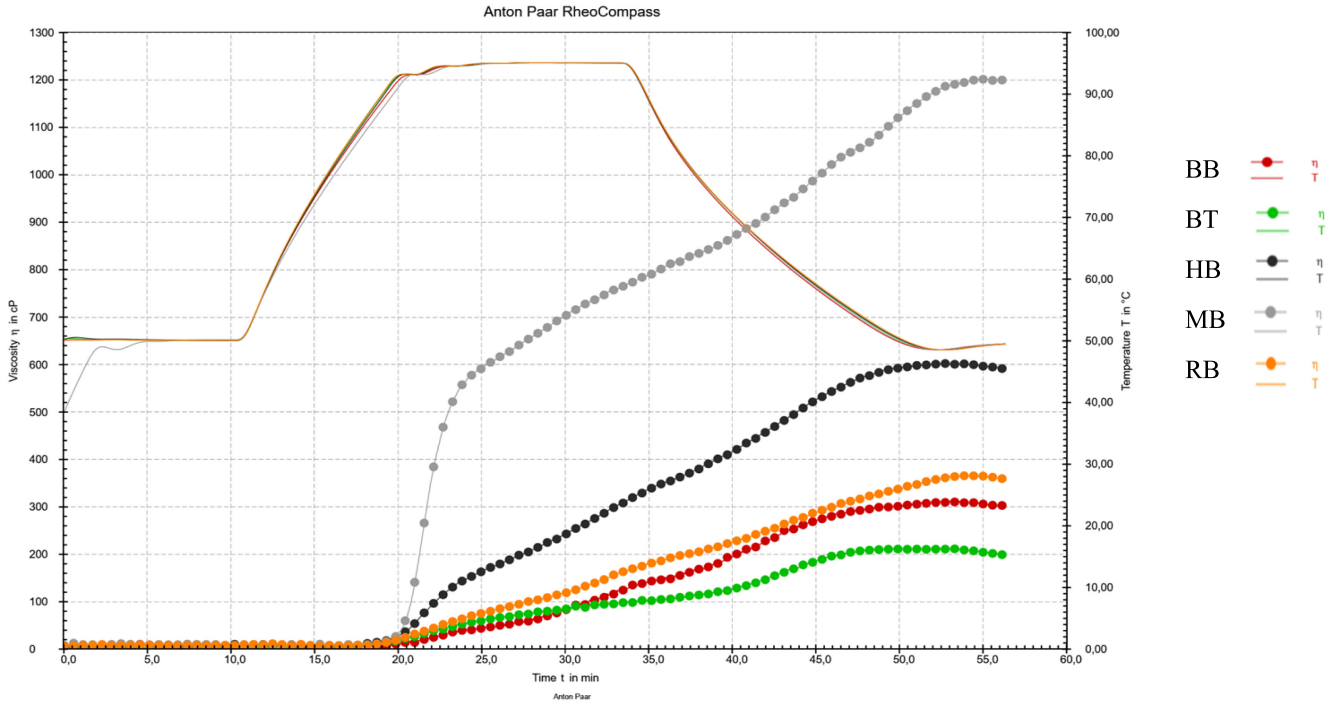


FIGURE 1 | Pasting profile of selected bean flours. Butter beans (BT), black beans (BB), mung beans (MB), haricot beans (HB), and red kidney beans (RB).

viscosity of flour from the different legume varieties ranged from 0.11 to 1.42 cP, and no significant ($p \leq 0.05$) differences were observed (Figure 1). The breakdown of the MB and RB flours was the lowest, which could suggest that the flours have strong shearing resistance and good pasting stability. A study on various legume varieties has shown that the small RB flour breakdown was the lowest and ascribes this outcome to strong shearing resistance and good paste stability (Du et al. 2014). Moreover, Wang et al. (2020) found that higher breakdown viscosity in flour can withstand heat. Findings from this study indicated that HB flour displays higher swelling, stability, and an adequate level of retrogradation, while MB and RB provide strong resistance to breakdown. This finding is useful in designing legume flours for specific food applications based on their pasting behavior.

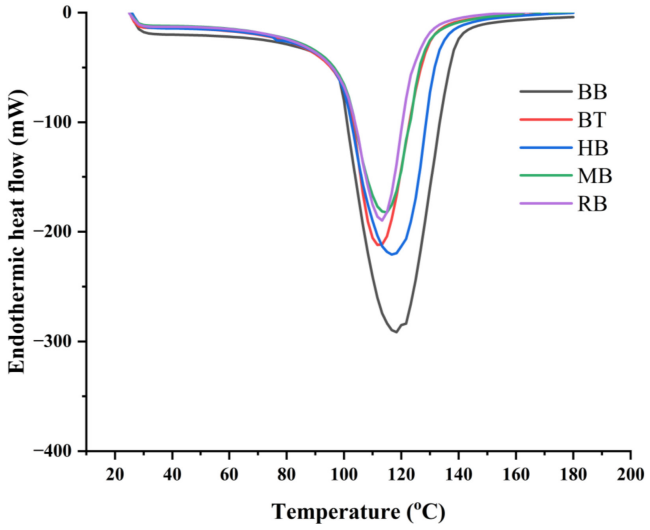


FIGURE 2 | Thermal properties of selected bean flours determined by differential scanning calorimetry (DSC). The figure reflects the thermal curve for butter beans (BT), black beans (BB), mung beans (MB), haricot beans (HB), and red kidney beans (RB).

The thermal properties of legume flours as determined by DSC (Figure 2) provide critical insights into the behavior of starch gelatinization of the investigated samples. The gelatinization parameters include onset temperature (T_o), peak temperature (T_p), end set temperature (T_e), and gelatinization enthalpy change (ΔH_G). The T_o ranged from 88.29°C to 96.92°C, with BB showing the highest value and MB the lowest. No significant differences ($p \leq 0.05$) in the T_o of the different legume flours were observed. The differences in the T_o of legume starches are attributed to an interplay between degree of crystallinity, proportion of the outer "A" branches of amylopectin, and lipid-complexed amylose chains (Hoover and Ratnayake 2002). The T_p was highest in HB (113.08°C) and lower in MB (109.90°C), BB (108.74°C), BT (107.39°C), and RB (107.38°C). The T_p signifies the rate of

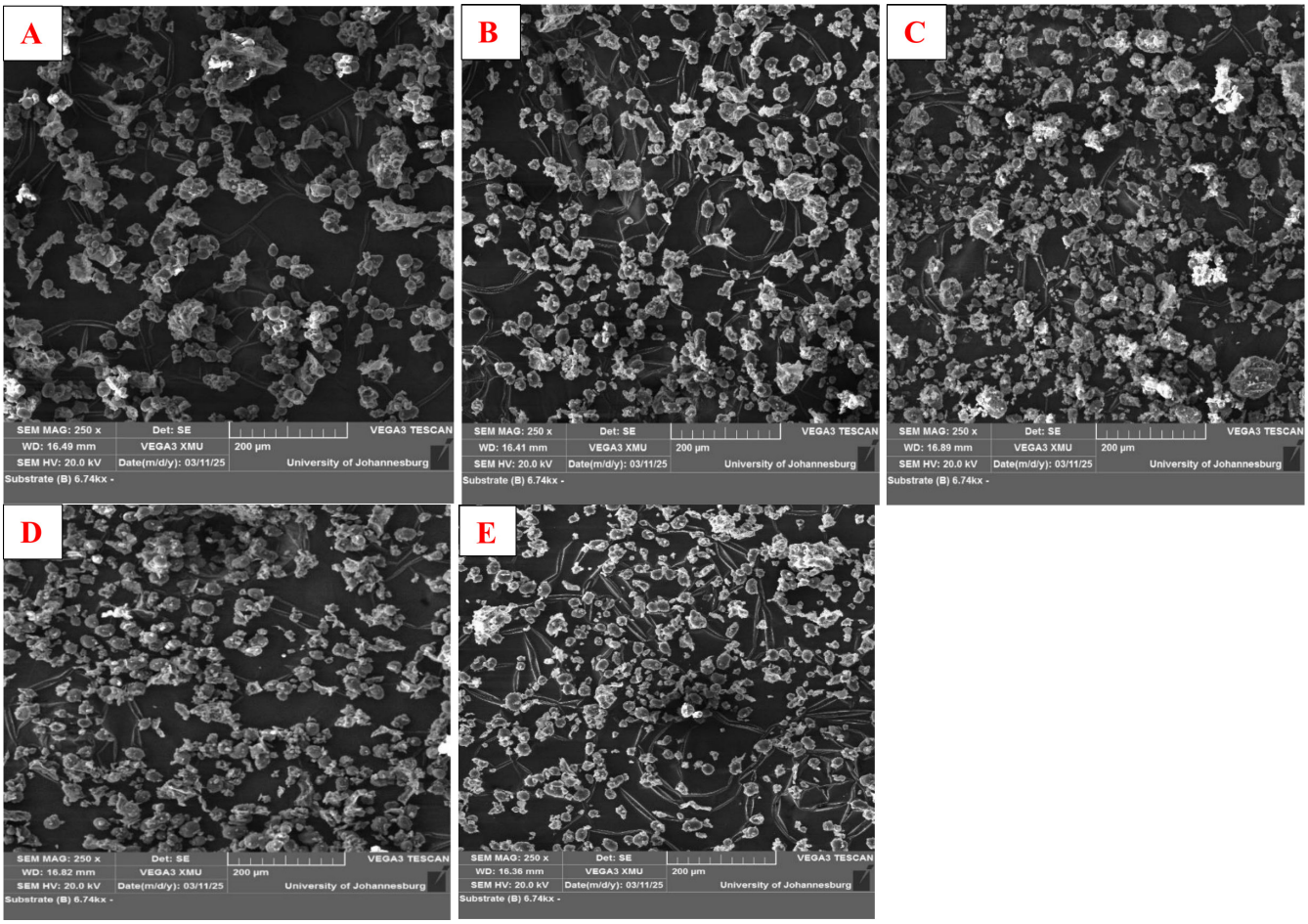


FIGURE 3 | Scanning electron microscopy (SEM) images of selected bean flours. The figure shows (A) butter beans (BT), (B) black beans (BB), (C) mung beans (MB), (D) haricot beans (HB), and (E) red kidney beans (RB) at 250× magnification.

maximum gelatinization or denaturation, and the temperature at which 50% of the molecules have experienced a thermal transition (Sánchez-Arteaga et al. 2014).

The T_e ranged from 117.91°C to 137.67°C, with the lowest value observed in BB and the highest in HB, which also exhibited the highest T_p and T_e values at 113.08°C and 137.67°C, respectively. The ΔH_G of the flours obtained from the different legume varieties ranged from 2234.9 to 4334.31 J/g, with MB displaying the highest value and RB the lowest. Lower ΔH_G values can be linked to partial disruption of starch crystallites or dissimilarity of starch and lipid interactions. For example, higher ΔH_G values in MB and higher T_p values in HB as compared to BB, similar to BT, can be linked to the relatively higher structural integrity and crystallinity of their starches. Hasjim et al. (2013) and Guo et al. (2023) reported that the distribution of starch granules, size as well as shape, are factors that affect ΔH_G and contribute to the transition temperatures of the flours. The lowest values for T_o, T_p, conclusion temperature (T_c), and ΔH_G signify that less energy is required to disrupt the intermolecular bonds in the starch granules for effective gelatinization (Kaur and Singh 2006). The thermal stability properties of these legumes are suitable for applications of processed food where animal proteins may unfavorably denature.

The correlation between the thermal behavior of the legume flours and their pasting behavior seems to emphasize the possible correlation with the importance of the functional behavior of the flours during processing. The pasting temperatures, which were all at 95.10°C (Figure 1), were within the range of the onset temperatures, 88.29°C–96.92°C, as shown in Figure 2. This observation implies that it is at this point of temperature that starch granules begin to swell and absorb more water to develop some viscosity. The MB with a higher gelatinization enthalpy (4334.31 J/g) did have the second-highest peak viscosity (298.50 cP), as HB has the highest peak viscosity (710.20 cP). In that regard, this can be linked to factors beyond the crystalline order that contributed to the pasting behavior. Despite HB having moderately high ΔH_G (2446.02 J/g), it had the highest final (899.53 cP) and trough (899.07 cP) viscosities; this demonstrated that viscosity development was contributed during heating by factors such as granule integrity and protein-starch interactions. HB showed a correlation between thermal stability, indicated by higher *Te* values, and MB and RB showed paste stability, reflected in lower breakdown viscosity. These legume flours under thermal stress maintained structural integrity, resulting in viscosity profiles during heating and cooling.

3.6 | SEM of Selected Bean Flours

The study compared the SEM images of the different legume varieties by investigating their structural changes. According to the micrographs of the legume flours in Figure 3, their structures display smaller and asymmetrical particles, with these differences probably indicating protein and fiber particles. The starch granule surfaces are not smooth in all the flour samples and are of different sizes, thus indicating the existence of starch granules from different biosynthesis levels (Ravi and Harte 2009). BT flour (Figure 3A) showed a relatively loose arrangement of particles with conspicuous gaps between them. BB (Figure 3B) also displayed a visible space between particles and a porous structure. MB (Figure 3C) showed a more compact microstructure, indicating a higher degree of cohesiveness than the other legume varieties, which might impact its functional properties, such as water retention capacity, and during processing on the rheological behavior.

As shown in Figure 3D,E, the compactness level was intermediate for HB and RB, and the particles had a moderate distance from each other. Such structural legume flour characteristics might also be related to the functional properties presented earlier (Table 3), whereas the differences in the WAC and OAC of these legume species might be caused by differing microstructure arrangements. In addition, the SEM images suggest that the legume flour samples exhibit varying degrees of compactness related to BD differences (Table 3), wherein MB had the highest BD (0.91 g/cm^3), and the other legume flours had BD values of 0.83 g/cm (BB, HB, and RB) and 0.81 g/cm (BT). The images further suggest that, except for the more compact MB flour, the different legume varieties may exhibit similar behavior during processing (soaking and drying). These processing steps are necessary and significantly influence the processing characteristics and the end-product quality of food formulations incorporating these legume flours.

4 | Conclusion

The five selected legumes investigated in this study have distinct functional properties that make them suitable for various food applications. The primary consideration is that choosing legumes by their functionality tends to produce more viable results than treating all legumes as interchangeable protein sources. For example, mung beans are suitable where high protein is required, red kidney beans are integrated into products that demand water retention, and haricot beans are recommended for use under thermal treatment. In practice, food industries can use the obtained data to develop structurally and functionally superior products. This symbolizes the shift from viewing other legumes as inadequate replacements to considering them as enhancers and structuring agents in promoting protein-source diversification. The results imply that it is now possible to identify individual potential uses for some legumes, thus promoting high-accuracy scientific progress in improved legume-derived food products. Future studies should explore traditional and novel food processing techniques and reinvestigate the analysis in this study. In addition, developing food products from these legumes and their consumer acceptability should be considered.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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