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BADJONA, Abraham <http://orcid.org/0000-0003-4759-7572>, BRADSHAW, Robert, MILLMAN, Caroline <http://orcid.org/0000-0003-4935-0477>, HOWARTH, Martin and DUBEY, Bipro <http://orcid.org/0000-0003-0396-9864>

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Influence of Dry and Steam Thermal Pretreatments on the Structural Properties and Flowability of Faba Bean Flours

Abraham Badjona[1] | Robert Bradshaw[2] | Caroline Millman[1] | Martin Howarth[1] | Bipro Dubey[1,3]

[1]Advanced Food Innovation Centre, Sheffield Hallam University, Sheffield, UK | [2]Bimolecular Research Centre, Sheffield Hallam University, Sheffield, UK | [3]School of Engineering and Built Environment, Sheffield Hallam University, Sheffield, UK

Correspondence: Abraham Badjona (a.badjona@shu.ac.uk)

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ABSTRACT

Faba beans are emerging as a promising alternative protein source for bakeries, snacks, cereals and ready-to-eat foods. The quality and consistency of such products depend strongly on the processing behaviour of their flours, including handling, storage, mixing and extrusion performance, all of which are governed by flour flow and structural characteristics. However, there is currently a lack of information on the structural and flow properties of thermally treated faba bean flours. This study aims to understand the influence of dry and steam-heating temperature (70°C–100°C for 15–45 min) on the physical, structural and flowability properties of faba bean flours. Moisture content consistently decreased with high drying temperatures and longer duration for dry heating and vice versa for steam treatment. Dry-treated samples exhibited reduced particle size (D_{50} = 14.5–18.9 μm), contributing to enhanced grindability but also increased cohesiveness. Fourier-transform infrared (FTIR) analysis revealed conformational changes in protein and starch domains, confirming that heating mode and moisture jointly influence molecular structure and powder behaviour. Flow indices (ff_c) classified dry-heated flours as cohesive to very cohesive (ff_c = 1.61–2.91), whereas steam-treated samples, particularly at 70°C for 15 min, were easy flowing (ff_c = 4.24). Principal component analysis explained 70.78% of the variance, distinguishing treatments based on moisture and flow attributes. These findings demonstrate that controlled thermal pretreatments can be used to tailor faba bean flour handling properties, facilitating their use in food manufacturing processes such as flour conveying, blending and hydration-based applications where powder flow and stability are critical.

1 | Introduction

Faba beans, a cool-seasonal crop from the Fabaceae family, are cultivated for both human and animal consumption (Chávez-Murillo et al. 2018). Whole faba beans typically contain nutrients such as protein, fat, carbohydrates, fiber and essential vitamins and minerals (Badjona et al. 2023). Due to their nutritional richness and functional properties, faba beans are increasingly studied and utilized in various food applications such as beverages, sausages and meat substitutes, serving as an alternative to conventional ingredients such as casein, whey and wheat protein (Badjona 2024). Faba bean seeds also contain flavonoids, phenolic compounds and other bioactive substances known for their potential health benefits, including neuroprotective, anticancer, antioxidant, hypocholesterolemic and antimicrobial properties (Ashraf et al. 2020; Badjona 2024).

While milling beans into flour can shorten cooking time compared to whole beans, it may still not align with consumer preferences for rapid preparation of high-quality foods. A potential approach to address this limitation is the pretreatment of whole seeds through thermal processing before milling, thereby enhancing their functionality as food ingredients. The preparation of prethermally treated bean flour primarily involves two

key processing steps: heating followed by milling. Heating methods are generally classified into moist–heat and dry-heat treatments. Moist-heat processing utilizes water, liquid or steam to transfer heat to the food matrix, whereas dry-heat treatment applies unsaturated hot air in the absence of moisture. It has been suggested that beans subjected to moist–heat treatment promote the gelatinization process, during which starch granules within the cotyledon cells absorb water and undergo expansion (Ovando-Martínez et al. 2011; Rovalino-Córdova et al. 2019). The subsequent processing step is milling, primarily aimed at reducing particle size. This reduction in particle size increases the total surface area, which has been associated with enhanced functional properties and improved digestibility (Byars et al. 2021; Rovalino-Córdova et al. 2019). Various physical properties are known to affect the behaviour of bulk flours (Schulze 2021). In general, an increase in particle size enhances powder flowability due to the reduced contact area between particles (Teunou et al. 1999). Additionally, the physicochemical constituents of flours play a crucial role in flow behaviour; for instance, fat content tends to increase cohesiveness, moisture promotes liquid bridge formation and capillary forces between particles, and higher protein levels can reduce flowability due to increased cohesiveness (Barone et al. 2019; Fitzpatrick et al. 2007). Plant protein-rich ingredients are commonly processed, transported and marketed in powder form (Badjona et al. 2025; Choe et al. 2022). Therefore, understanding their bulk handling properties is essential for various reasons, including preventing pipeline blockages and irregular flow, efficient powder mixing, optimizing packaging and ensuring desirable quality attributes for consumer applications. Given the growing interest in novel plant-based protein ingredients, further research is needed to better understand their processing and handling characteristics.

Despite growing attention to faba bean flour functionality, little is known about how controlled thermal pretreatments influence flow and molecular structure, which are critical for industrial processing. Existing literature provides insights into the flow properties of other flour types, such as soybean (Lee and Yoon 2015), quinoa flour and rice flour (Alonso-Miravalles et al. 2020). Thus, the objective of this study was to evaluate and establish the relationship between the physical, structural and flow properties of thermally treated faba bean flour influenced by processing conditions. Therefore, the present study seeks to investigate the impact of dry and steam-heating conditions (temperature and time) on moisture profile and particle size distribution of faba bean flours. Additionally, structural changes induced by the thermal treatment were assessed with FTIR spectroscopy. Evaluation of flow behaviour through powder flowability metric was used and the application of multivariate statistical analysis for elucidation of the relationship between thermal processing and bulk powder properties was compared.

2 | Materials and Method

2.1 | Materials

Faba bean seeds were purchased from Whole Foods Earth (Kent, UK).

2.2 | Dehulling the Faba Bean Seeds

Faba bean seeds were dehulled by mechanically cracking whole seeds using a laboratory blender (Kenwood Blender, UK) operated at low speed (approximately 2000 rpm) for 30 s, followed by manual separation of the loosened seed coats from the cotyledons. The dehulled seeds were subsequently used to produce raw, steam-heated and dry-heated bean flour.

2.3 | Steam-Injection Processing (SF)

Two hundred grams of dehulled faba bean seeds were placed in a Retigo rotary O1011igPLUS oven (United Kingdom) and subjected to steam-assisted heating, where humidified air was introduced to maintain chamber temperatures of 70°C, 80°C and 100°C for 15, 30 and 45 min, respectively, for each temperature. Following thermal treatment, the samples were cooled to room temperature.

2.4 | Dry-Heat Processing (DF)

Two hundred grams of dehulled faba bean seeds were heated in an oven at temperatures of 75°C, 80°C, 85°C, and 90°C for 15, 30, and 45 min, respectively.

2.5 | Milling

Raw, dry-heated and steam-treated faba bean seeds were milled into flour using a vibratory disc mill (Retsch 200, Germany) set at 1200 rpm for 60 s.

2.6 | Physicochemical Properties of Raw Faba Bean Flour

The proximate composition of the raw faba bean flour used in this study was analysed in triplicate. Nitrogen content was determined using an Elementar Dumas system (Elemental, UK Ltd) with a conversion factor of N × 6.25 to estimate protein content. Fat content was measured through Soxhlet extraction using petroleum ether as the solvent. Moisture content was determined by drying the samples at 105°C, while ash content was quantified after incineration at 550°C. Carbohydrate content was estimated using the difference method (Horwitz 2006).

The condensed tannin was determined according to the method described by Price et al. (1980) and (Bento et al. 2021). A standard curve of (0–30 mg/mL) was used for quantification and the concentration of condensed tannins was calculated and expressed in mg CE/g. Water holding capacity (WHC) and oil holding capacity (OHC) were assessed by mixing 1 g of flour with 10 mL of distilled water or sunflower oil, followed by vortexing for 30 min. The mixtures were then centrifuged at 3000 rpm for 30 min. WHC and OHC were expressed as grams of water or oil absorbed per gram of flour (Chandra et al. 2015). The colour properties of the flour were evaluated using a colorimeter (CR-400, Minolta, Japan), measuring lightness (L*), redness (a*) and yellowness (b*). The

instrument was calibrated against a standard white tile prior to measurements (Cappa et al. 2025).

2.7 | Moisture Profile Analysis

The moisture content of the treated samples was determined in replicates using an infrared moisture analyzer MB120 (OHAUS Europe, Switzerland).

2.8 | Particle size distribution

Particle size distribution of milled flours was analysed using a Mastersizer 3000 laser diffraction analyzer (Malvern, UK) with a dry sampling system (Olakanmi et al. 2024). Measurements were conducted under nonspherical sample analysis conditions, with a refractive index of 1.53, an absorption index of 0.001 and a background measurement time of 10 s. Sample measurement lasted 15 s, with an obscuration range of 0.1%–6%, air pressure at 4 bar and a feed rate of 30%. Each replicate used approximately 0.2 g of sample. Reported parameters included span, $D_{10,3}$ and $D_{50,3}$.

2.9 | Fourier-transform infrared (FTIR) spectroscopy

Infrared spectra were collected in triplicate for all samples using attenuated total reflectance FTIR spectroscopy (ATR-FTIR) (CA, USA) within a wavenumber range of 4000–650 cm^{-1} (Cappa et al. 2025). Each spectrum was recorded with 32 scans at a resolution of 4 cm^{-1}. Additionally, the spectral analysis of raw and heat treated faba bean samples focused on the protein regions, using a wavenumber range of 1200–1900 cm^{-1}.

2.10 | Powder Flowability

The flow properties of the flour samples were assessed using a powder flow tester (PFT 610, Brookfield Engineering Labs, UK). Data acquisition was performed following the standard procedure using Powder Flow Pro V1.3 software (Padhi and Dwivedi 2022). A maximum applied stress of ~15 kPa was used for all measurements.

2.11 | Statistical data analysis

Each treatment condition was conducted in triplicate ($n = 3$) using independent batches of thermally treated faba bean seeds prepared under identical processing conditions and mixed. The data generated was analysed using origin and excel software. Unless otherwise stated, results are expressed as mean ± standard deviation from triplicate analysis. Prior to multivariate analysis, all quantitative variables (e.g., moisture content, particle size parameters, flow indices and FTIR band intensities) were normalized. Principal component analysis (PCA) was then performed on the normalized dataset to identify major sources of variance and visualize treatment-related groupings. Hierarchical cluster analysis (HCA) was conducted using the Ward's linkage method with Euclidean distance as the similarity measure to classify samples based on spectral and physicochemical similarities. The resulting dendrograms and score plots were generated using OriginPro 2019 (OriginLab, USA).

The statistical significance of the differences between the control and treated samples was assessed using One-way Analysis of Variance (ANOVA), followed by Tukey's HSD post hoc test. All analyses were performed using OriginPro 2019. Differences were considered statistically significant at $p < 0.05$.

3 | Results and Discussion

3.1 | Physicochemical Properties of the Dehulled Faba Bean Flour

The physicochemical properties of the dehulled faba bean flour used in this study are presented in Table 1. The moisture content was 10.35%, comparable to values reported by Mattila et al. (2018), but slightly higher than those noted by Millar et al. (2019), likely due to differences in seed variety, cultivation and postharvest storage. The flour had an ash content of 3.03%, aligning with Millar et al. (2019), and a fat content of 1.15%, which falls within the range reported by Mattila et al. (2018). Protein content was 29.09%, consistent with Nosworthy et al. (2018), but lower than values reported by Mattila et al. (2018) and higher than those by Millar et al. (2019). Carbohydrate content was 56.38%. Condensed tannins and total phenolics were 0.14 mg CE/g and 57.80 mg GAE/100 g, respectively, both lower than values reported for other varieties (De Angelis et al. 2021). Colour measurements yielded L*, a* and b* values of 91.78, 6.17, and 2.82, respectively. The OHC and WHC were 0.74 and 1.13 g/g.

TABLE 1 | Physicochemical and functional properties of raw faba bean flour used in the present study.

Constituent	Faba bean flour
Moisture content (%)	10.35 ± 0.19
Protein (%)	29.09 ± 0.03
Dry matter (%)	89.65 ± 0.19
Ash (%)	3.03 ± 0.02
Fat (%)	1.15 ± 0.15
Carbohydrate (%)	56.38 ± 0.03
Energy (kJ/100 g)	352.23 ± 0.07
Condensed tannins (mg CE/g)	0.14 ± 0.01
Total phenolic content (mg GA/100 g)	57.80 ± 0.21
OHC (g/g)	0.74 ± 0.01
WHC (g/g)	1.13 ± 0.08
Colour parameters	L* = 91.78 ± 0.86
	a* = 6.17 ± 0.86
	b* = 2.82 ± 0.20

Note: Data presented as means values ± SD ($n = 3$). L* Lightness; a* Red-green axis; b* Yellow-blue axis.

3.2 | Moisture Profile

The initial moisture content (MC) of the untreated faba bean flour was 10.35% ± 0.19^{fg}. Moisture content is an important indicator that influences the stability, flowability, handling behaviour and stability of food materials (Thamarsha et al. 2024). As shown in Table 2 and Figure 1, dry-heated (DF) samples consistently exhibited lower moisture contents (7.01%–9.53%), while steam-treated (SF) samples showed markedly higher moisture levels (10.73%–15.59%). All DF flours resulted in a statistically significant decrease in MC compared to the raw flour ($p < 0.05$). This is a result of convective moisture evaporation, where the high-temperature, low-humidity environment provides a strong thermodynamic driving force for the diffusion of water vapor out of the faba bean matrix. The MC consistently decreased with increased treatment severity (temperature and time), with the lowest final MC recorded at 7.01% ± 0.21^{k} (DF90°C;45 min). Within the DF group, samples with the same superscript, such as DF75°C, 15 min (9.53% ± 0.11^{gh}) and DF75°C, 30 min (9.48% ± 0.02^{gh}) were not statistically different.

Conversely, all SF flours exhibited a statistically significant increase in moisture content compared to the raw flour, due to the direct mass transfer of water vapor into the faba bean matrix. The steam environment ensures the particle surface is saturated, leading to condensation and absorption. This process results in the highest recorded moisture values, such as 15.59% ± 0.69^{a}(SF70°C,45 min), which was statistically significantly higher than all other treatments, including the raw flour. This difference in final moisture content between the high-moisture content SF group and the low-moisture content DF group is the fundamental driver for the contrasting physical and flow properties observed. A similar observation was made by Choe et al. (2022) upon thermally treating bean flours.

3.3 | Particle Size Distribution

Particle size distribution is a critical parameter influencing the functional properties of flours, including hydration characteristics, flow and handling behaviour, rheology and pasting behaviour (Islam et al. 2024). The particle size distribution of raw and thermally treated faba beans flours for 30 min is present in Figure 2 and as shown in Table 2. In this work, the values of span, $D_{10,3}$, $D_{50,3}$ and span are reported in Table 2. The $D_{50,3}$, representing the volumetric median diameter, is commonly used as an indicator of powder cohesiveness (Zhang et al. 2012). As indicated in Table 2, both processing conditions contributed to the difference in part in particle size parameters (span, $D_{10,3}$ and $D_{50,3}$). For example, raw faba bean showed a $D_{10,3}$ value of 14.50 μm, a $D_{50,3}$ of 35.30 μm and a span value of 9.56. The

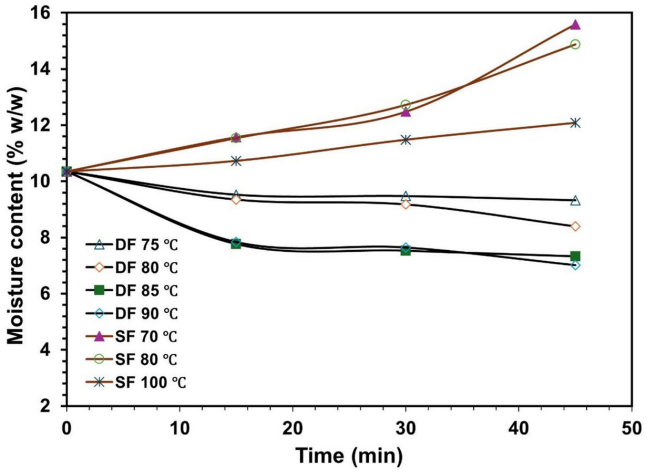

FIGURE 1 | Moisture content of raw, dry-heated (DF) and steam-injected (SF) faba bean flours over treatment time.

TABLE 2 | Physical properties of dry-heated and steam-injected faba bean seeds. Dry-heated (DF) and steam-injected (SF) faba bean flours.

Sample treatment	Moisture content (%)	Dry matter (%)	Span	$D_{10,3}$ (μm)	$D_{50,3}$ (μm)
Raw bean	10.35 ± 0.19^{fg}	89.65 ± 0.19	9.56 ± 0.03^{ab}	14.5 ± 0.25^{b}	35.3 ± 0.68^{a}
DF 75°C;15 min	9.53 ± 0.11^{gh}	90.47 ± 0.11	11.01 ± 3.13^{a}	12.7 ± 0.97^{c}	40.10 ± 3.75^{a}
DF 75°C;30 min	9.48 ± 0.02^{gh}	90.52 ± 0.02	8.40 ± 3.99^{ab}	9.86 ± 0.07^{d}	27.40 ± 0.85^{b}
DF 75°C;45 min	9.33 ± 0.20^{h}	90.67 ± 0.20	8.57 ± 1.44^{ab}	4.58 ± 0.05^{e}	24.10 ± 0.32^{bc}
DF 80°C;15 min	9.35 ± 0.11^{h}	90.65 ± 0.11	6.58 ± 0.44^{abc}	4.30 ± 0.17^{a}	27.60 ± 0.60^{b}
DF 80°C;30 min	9.18 ± 0.24^{hi}	90.82 ± 0.24	7.57 ± 0.20^{abc}	3.55 ± 0.05^{f}	27.40 ± 0.35^{b}
DF 80°C;45 min	8.4 ± 0.06^{ij}	91.60 ± 0.06	9.84 ± 0.46^{ab}	4.58 ± 0.40^{e}	35.30 ± 6.32^{a}
DF 85°C;15 min	7.77 ± 0.10^{jk}	92.23 ± 0.10	8.63 ± 0.42^{ab}	3.12 ± 0.12^{fg}	21.20 ± 0.25^{cd}
DF 85°C;30 min	7.53 ± 0.10^{jk}	92.47 ± 0.10	9.49 ± 1.43^{ab}	2.42 ± 0.05^{gh}	18.70 ± 0.40^{cde}
DF 85°C;45 min	7.33 ± 0.38^{k}	92.67 ± 0.38	9.49 ± 0.25^{ab}	2.42 ± 0.03^{gh}	18.70 ± 0.23^{cde}
DF 90°C;15 min	7.84 ± 0.15^{jk}	92.16 ± 0.15	3.06 ± 0.08^{c}	1.65 ± 0.05^{hi}	16.40 ± 0.64^{de}
DF 90°C;30 min	7.84 ± 0.15^{jk}	92.35 ± 0.15	3.05 ± 0.07^{c}	1.45 ± 0.01^{i}	14.50 ± 0.15^{e}
DF 90°C;45 min	7.01 ± 0.21^{k}	92.99 ± 0.21	5.76 ± 0.30^{bc}	2.13 ± 0.04^{hi}	18.90 ± 0.15^{cde}

Note: $D_{50,3}$(μm) = particle size below which 50% of sample volume is found.
Note: Span = measurement of the width of the distribution calculated as: $(D_{90,3}-D_{10,3})/D_{50,3}$.

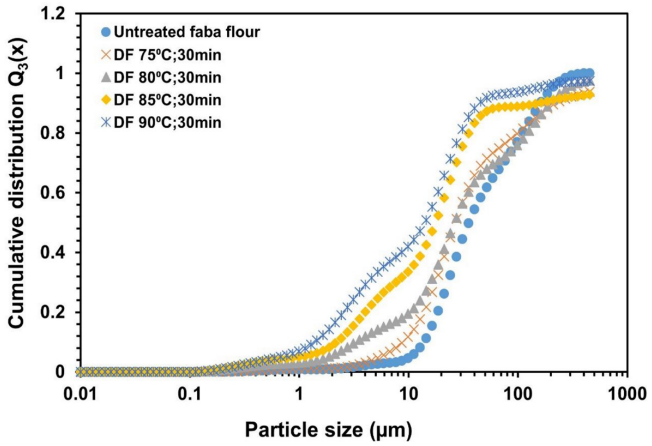

FIGURE 2 | Cumulative mass distribution Q_3 as a function of particle size for untreated faba bean flour, and dry-heated faba bean flours at different temperatures for 30 min. Dry-heated (DF) and steam-injected (SF) faba bean flours.

thermal treatments resulted in statistically significant changes in particle size parameters across all samples compared to the raw faba bean flour. $D_{50,3}$ initially increased to 40.10 ± 3.75^{a} µm (DF75°C;15 min), which was statistically similar to the raw flour. This initial change may be attributed to the hardening and densification of the particles due to moisture loss (low MC), promoting the formation of hard agglomerates during milling that resist fracture. However, at prolonged treatment times (e.g., DF75C;45 min), the $D_{50,3}$ decreased to 24.10 ± 0.32^{bc} µm, which was statistically smaller than the raw flour. This suggests that prolonged dry heating caused sufficient structural modification to make the seeds more susceptible to fragmentation during subsequent milling, leading to a reduction in particle size. The difference in particle size parameters of dry-heated faba bean seeds was observed among all samples (the particle size of moist treated samples were not analysed due to difficulty in their measurement). These differences in particle sizes might be partially explained by drying temperature, incubation time and partially explained by the seed cell wall hardness (Córdova-Noboa et al. 2021).

Compared to raw faba bean flours, drying at high temperature had smaller $D_{50,3}$. This phenomenon can be attributed to the decreased seed hardness with less cohesiveness compared to the raw counterparts due to the lower moisture content of dry-heated bean seeds (Perera et al. 2023) (Table 2), which could be easier to grind into flour. In both raw and dry-heated samples, a similar particle size distribution was observed and the particle size at the major peak was close to 25 µm, representing the size of free protein, cell wall materials and damaged starch granules (Jiang et al. 2021). Bhandari (2013) reported particle size ranges of 100 to 5000 µm for cereal and soy flours, which are notably larger than those observed in milk or coffee powders.

In general, fine powders tend to exhibit higher cohesiveness and reduced flowability, whereas powders with larger particle sizes typically flow more easily Teunou et al. (1999) due to a lower surface area available for the development of interparticle cohesive forces (Fitzpatrick et al. 2007). In relation to the span values, all the samples had values ranging from 3.05 to 11.01, indicating that some of the treated flours such as dried 75°C,15 min and dried 75°C,15 min consisted of a wide range of particle sizes while the other dry-heated samples were more homogeneous comparatively. Wider particle size distributions in powders can complicate handling, as smaller particles may occupy the voids between larger ones, thereby increasing surface contact and enhancing interparticle cohesion (Bian et al. 2015).

3.4 | Structural Changes Using ART-FTIR

The application of FTIR provides valuable insight into the molecular interaction between protein, starch and other cellular compounds and provides useful information on conformation change in bean flours after thermal treatment. FTIR spectra were obtained for bean flours in their native, moist treated and dry heat processed forms across the spectra range (4000–400 cm^{-1}) are shown in Figures S1 and S2. Spectral variations were detected in these regions for both dry and moist heating relative to the raw flour. The peak at approximately ~3278 cm^{-1} in thermally treated flours corresponds to the stretching vibrations of free, inter- and intramolecular O–H, attributed to hydrogen bond formation (Díaz et al. 2019). The peak observed at 996–1000 cm^{-1} is attributed to C–O–H bending within the carbohydrate region. No shifts in wavenumber or absorbance were detected in the moist-heated and dry-heated samples. Previous studies have associated this band with the ordered crystalline structure of starch (Díaz et al. 2019). Therefore, the lack of changes to wavenumber shift in the moist-heated and dry-heated samples may indicate the maintenance of the ordered crystalline structure of starch. However, the magnitude of these peaks increases with increasing heating during which could be attributed to the reduction moisture content and concomitant increase in dry matter content in the case of dry heating and the reverse in the case of steam treatment. On the other hand, FTIR spectra at the shoulders ~1022 cm^{-1} indicate disordered/amorphous starch. Thus, the ratio of absorbances at 1022/995 cm^{-1} is often used to understand the degree of order in starch (Sevenou et al. 2002). In this region, moist–heat and dry heat caused an increase in peak intensity. The peaks observed from 2929 to 2923 cm^{-1} are related to lipids. No major alterations were also observed in this region. Overall, changes in peak intensity were observed in moist and dry-heated faba bean flours in the protein, starch and less in the lipid regions as shown in Figure 3.

Peak ranging from 1900 to 1200 $cm^{-1}$are commonly associated with the amide groups of proteins (Badjona et al. 2024; Vargas et al. 2021). Observable changes in peak wavenumber and intensity after moist and dry heating were observed compared to raw faba bean flour as shown in Figure 4. As a result of the applied thermal treatments, significant variations in spectral intensity were observed among the treated samples within the 1200–1900 cm^{-1} region (Figures 3 and 4). Regarding steam treatments, the presence of steam facilitated greater unfolding of protein molecular structures, while the mild temperature likely enhanced molecular mobility. In contrast, the limited water availability and high temperatures used in dry-heated flours induced protein damage and structural rearrangements, leading to the contraction of their tertiary structure (Chávez-Murillo et al. 2018). Protein is a primary macronutrient in beans, and understanding its structure is crucial for elucidating

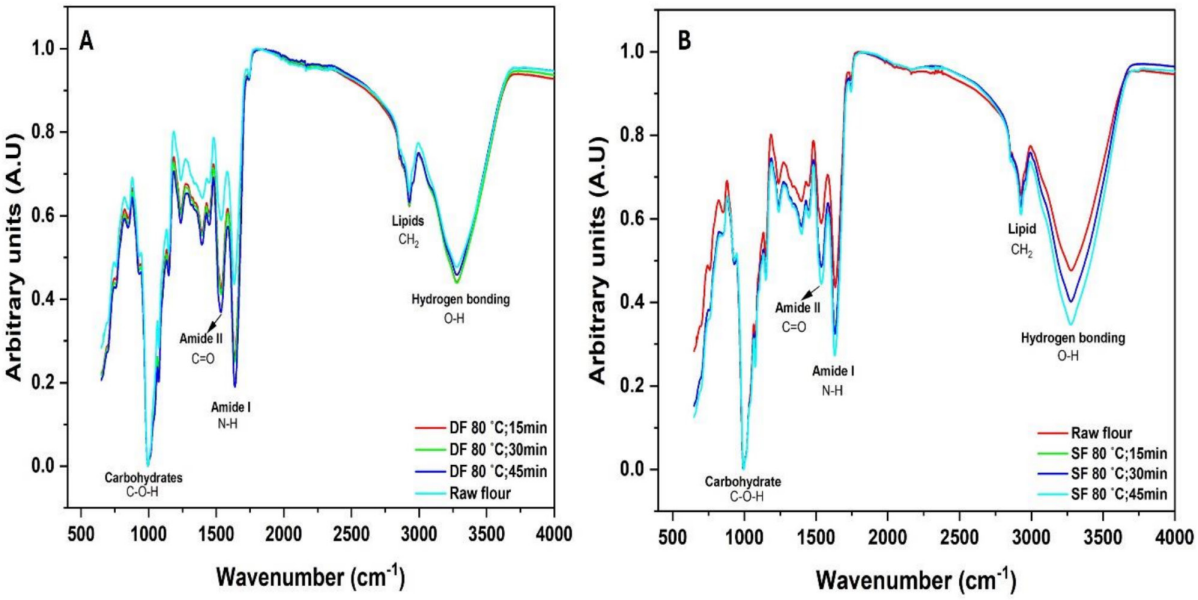

FIGURE 3 | FTIR spectra of raw, moist and dry-heated faba bean flour. (A) Dry-heated bean flours (DF) at 80°C; (B) steam-heated bean flour (SF) at 80°C from 15–45 min. Functional groups, and regions that correspond to nutrients, are shown below the full FTIR spectra.

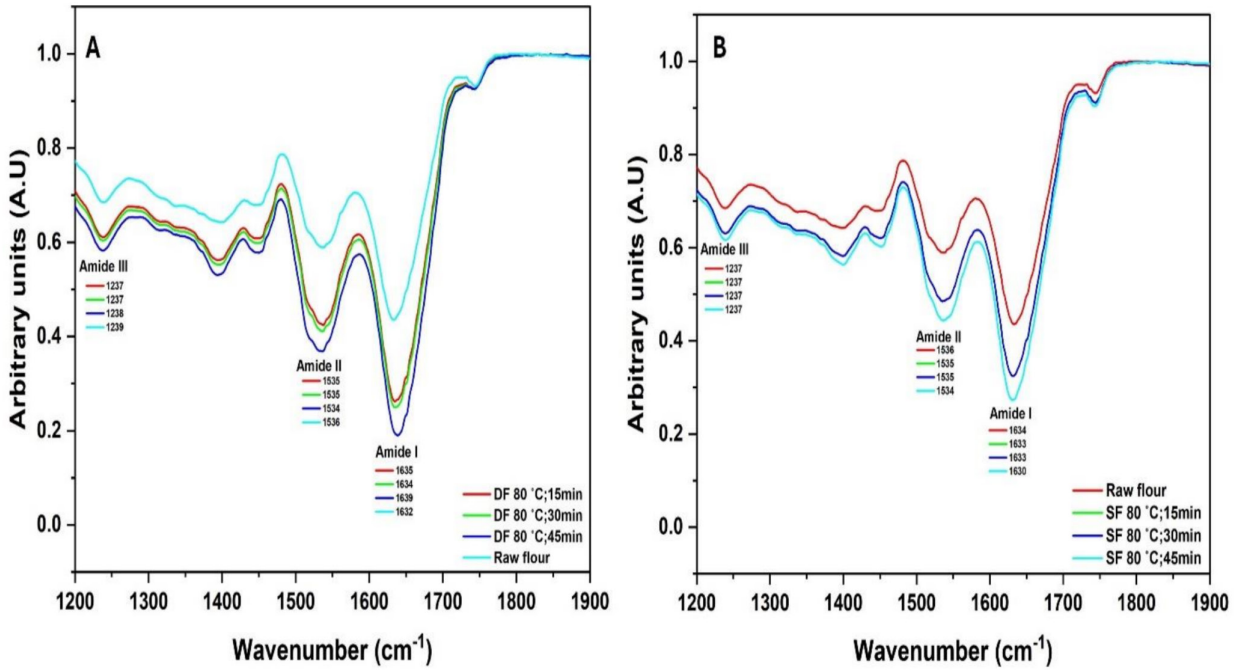

FIGURE 4 | FTIR spectra of raw, moist-heated and dry-heated faba bean flour. (A) Dry-heated bean flour at 80°C; (B) moist-heated bean flour at 80°C from 15 to 45 min (SF 80 C for 15 and 30 min overlap in spectra). Functional groups and regions that correspond to nutrients are shown below the full FTIR spectra.

its functionalities and digestibility (Deng et al. 2020). The amide I and II bands are the major bands used to study conformational modification. Between the two amide bands, the amide I band is particularly important in terms of understanding the secondary structure of protein (Gulzar et al. 2024). Substantial changes caused by moist–heat and dry heat were observed in the amide I, II and III regions. Previously, studies have confirmed that three peaks having wavenumbers at ~1634, ~1652 and ~1688 cm^{-1} were assigned as β-sheet, α-helix and aggregates, respectively (Candoğan et al. 2020; Carbonaro et al. 2012). One study found that the β-sheet adversely affects protein digestibility by forming intermolecular β-sheet aggregates upon heating (Carbonaro et al. 2012). Earlier studies have indicated that the α-helix and β-sheet secondary structures of proteins are crucial in determining the rate of protein digestion, which subsequently impacts functional properties such as gel strength, emulsification and foaming abilities (De La Rosa-Millán 2017).

In general, both moist and dry-heat pretreatments induced structural changes in the resulting faba bean flours,

particularly in relation to protein and starch conformation. Steam treatment led to enhanced protein unfolding due to the plasticizing effect of water and moderate heat, as evidenced by increased amide I and II peak intensities. This may improve protein digestibility and solubility, which are critical for nutritional and functional performance in food systems. In contrast, dry heat caused a reduction in peak intensities, likely due to dehydration and thermal stress. For starch, both treatments affected the relative intensity of bands associated with crystalline (995 cm^{-1}) and amorphous (1022 cm^{-1}) regions, with increased amorphous content suggesting partial disruption of native starch granule order. These transitions are particularly relevant for processing behaviours like gelation, hydration and thermal stability. Lipid-associated peaks remained relatively stable, indicating thermal resistance or minimal lipid oxidation.

3.5 | Multivariate Molecular Spectral Analysis for ATR-FTIR Spectra

HCA facilitates the visualization of grouping and subgrouping patterns within the spectra. The results of HCA analyses based on full spectra and the fingerprint region (1900–1200 cm^{-1}) acquired from different thermally treated faba bean seeds and duration are shown in Figure 5A,B, respectively. The HCA demonstrated intragroup similarity among the samples and formed clusters within each group. Spectral range differences were identified by analysing corresponding regions across all samples. As shown in Figure 5A, application of full spectra range (4000–400 cm^{-1}), clear classification was observed raw faba bean flour and treated faba bean flours. Four main clusters were obtained based on full spectra analysis with raw faba bean flour mostly associated with steam-treated faba bean flours especially SF 70°C, 15 min. However, discrepancies were observed as DF 90°C, 15 min was also found to be closely associated with raw faba bean flour. In general, HCA was able to discriminate between dry and steam-heated faba bean flours using the full FTIR spectra regions.

In the case of HCA analysis based on protein fingerprint regions (1900–1200 cm^{-1}) (Figure 5B.), a different discrimination was observed compared to the full spectra regions. According to similarity, six groups were observed in comparison with raw flour. This grouping reflects that the treatment temperature and duration had a significant effect on the fingerprint regions when faba bean seeds were thermally treated. Raw faba bean flour was distinctly separated from dry treated flours, while dry-treated samples were separated on the basis of temperature and time. Similarly, in the cases of steam-treated faba bean flours, there were three distinct clusters as observed in Figure 5A,B. Interestingly, steam flour SF at 70°C and 80°C at 15, 30 and 45 min were classified together with untreated faba bean flour. This could be attributed to the

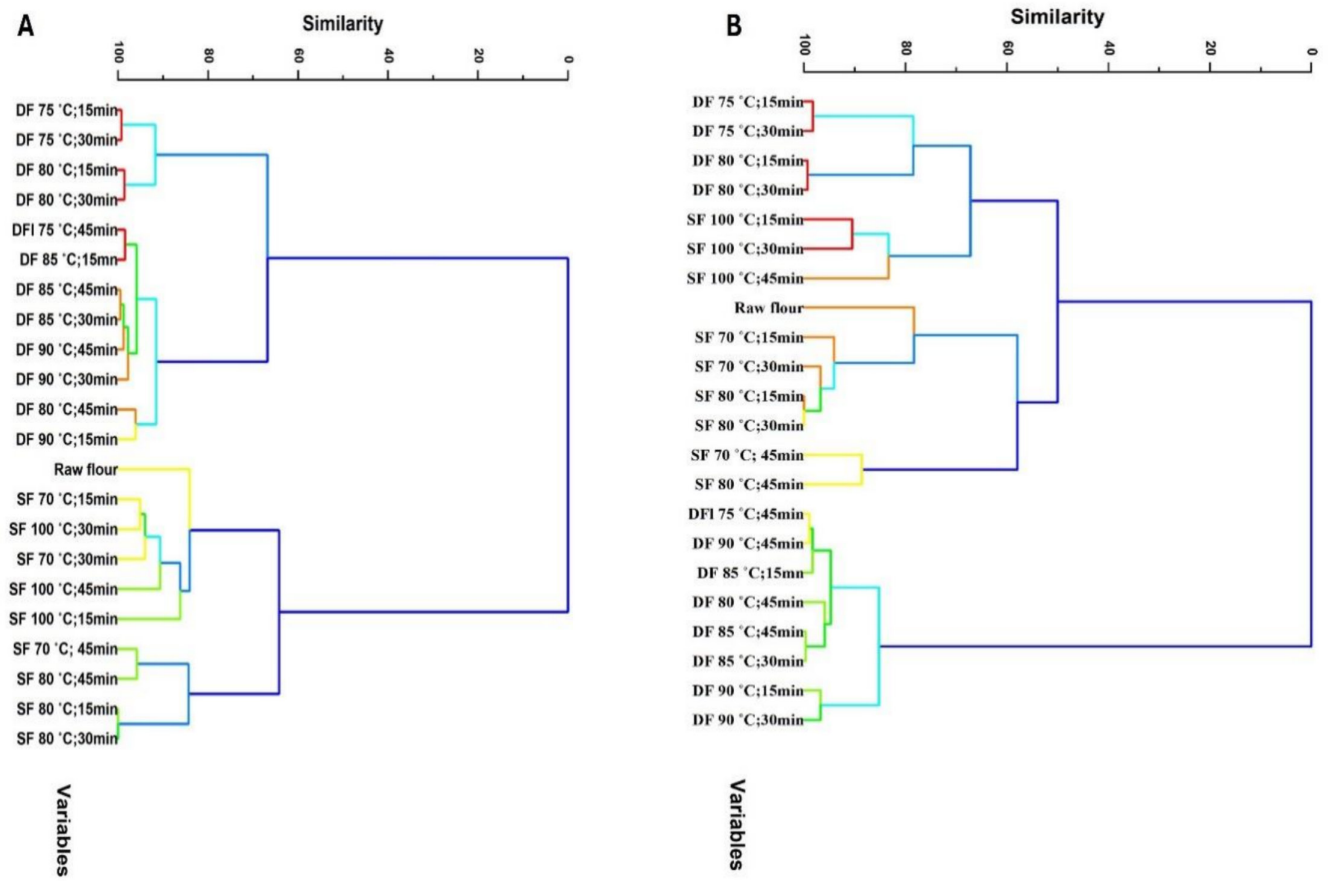

FIGURE 5 | (A,B) Results of sample HCA classification based on FTIR analysis where dendrogram A represent the application of full spectra region, while (B) represent dendrogram from selected protein fingerprint region (1900–1200 cm^{-1}).

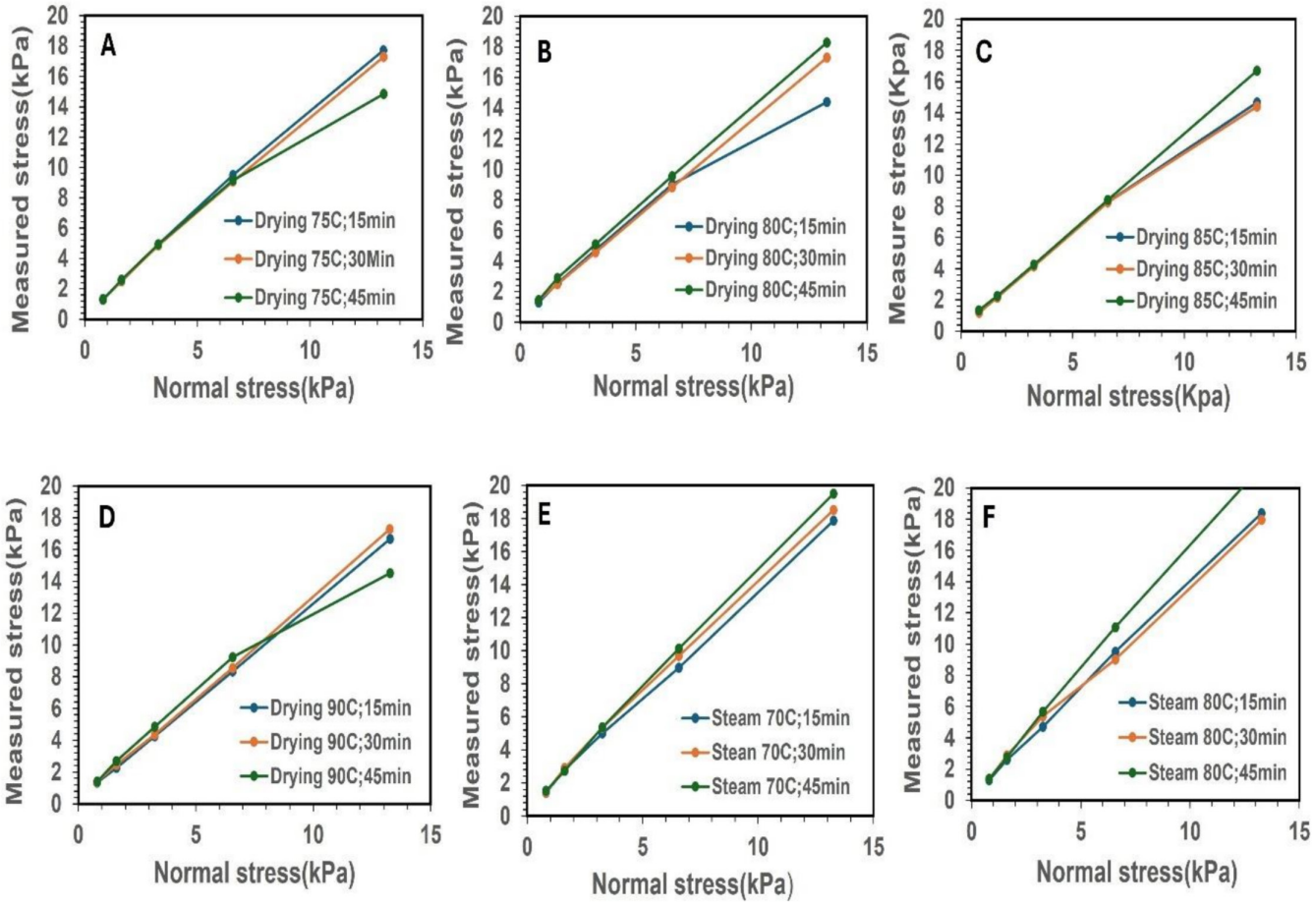

FIGURE 6 | Flow function curves showing measured stress as a function of normal applied stress major principal consolidating stress for dry and steam-treated faba beans.

minimal impact of temperature and short duration on structural modification of protein fingerprint regions. FTIR analysis combined with HCA can enable samples to be compared and differentiated in terms of their similarities in relation to treatment conditions. Owing to its simplicity, rapidity, and non-invasive nature, this approach proves to be informative in monitoring the structural changes occurring during seed processing and storage.

HCA of the ATR-FTIR spectra effectively differentiated faba bean flours based on thermal treatment conditions, confirming distinct molecular modifications. Steam-treated samples, particularly at lower temperatures and shorter durations, exhibited spectral similarities to raw flour, suggesting minimal disruption to native structures. In contrast, dry-heat treatments resulted in clear divergence, especially within the protein fingerprint region, reflecting more pronounced structural rearrangements. These outcomes align with the study's objective to evaluate the structural impact of thermal pretreatment and demonstrate the utility of multivariate FTIR analysis as a rapid, nondestructive tool for monitoring protein conformational changes. The ability to discriminate treatment effects at the molecular level has important implications for tailoring processing strategies to optimize the functionality, stability and application potential of faba bean flours in food formulations.

3.6 | Flowability Measurement

3.6.1 | Flow Function and Bulk Density

Flow properties provide information as to whether a flour will flow smoothly through a process or if issues such as bridging or blocking might occur. The graph in Figure 6 shows the graph of measured stress against normal applied stress. From the plotted data, dry-treated flours exhibited higher shear strength at equivalent consolidating stresses compared to steam-treated flours. In contrast, steam-treated samples showed lower shear stress responses, particularly at milder conditions (e.g., 70°C–80°C, 15–30 min), reflecting improved flow behaviour.

The flowability of both dry and moist-heated faba bean samples was influenced by the normal stress applied. This implies that powders are likely to exhibit varying flow behaviour in different sections of a hopper (Crowley et al. 2014). Results from Figure 6 indicate that differently treated faba bean flours were either free-flowing, easy-flowing or cohesive depending on the stress applied (Chen et al. 2012). Similar behaviour has been reported by Nei (2023) for defatted soybean flours between normal stress range of 2–10 kPa. Additionally, Alonso-Miravalles et al. (2020) reported similar behaviour for different protein-rich pseudocereals flours. The authors suggested that flour properties such as moisture, protein and

fat content affect flow properties as well as materials surface properties (particle morphology and size).

Bulk density versus principal consolidating stress controls volumetric handling, packaging and pressure transmitted during storage (Hazlett et al. 2021). Bulk density of the powders increased with increasing major principal consolidation stress applied (Figure 7). Values of bulk density at lower major principal consolidation stress (2–5 kPa) showed similar behaviour for both dry and steam-treated faba bean flours; however, at high major principal consolidation stress (> 10 kPa), high bulk density was observed in dry-heated samples compared to steam-treated samples. DF samples generally exhibited higher bulk densities, particularly at elevated consolidation stresses compared to SF flours (Figure 7A–D vs. E,F). Lower moisture levels in DF samples promote tighter packing and reduced porosity, allowing particles to reorganize under pressure more efficiently. SF samples showed lower bulk densities overall, consistent with their higher moisture contents and higher degrees of surface hydration. Increased moisture results in swelling of starch and protein matrices, increasing particle volume and reducing packing efficiency.

Previous studies have reported bulk density values of 600–730 kg/m^3 for corn, wheat and soy flours (Fitzpatrick et al. 2004). Such powders have been shown to compress under self-weight during storage, which can affect handling performance (Crowley et al. 2014). However, Alonso-Miravalles et al. (2020) showed that protein-rich pseudocereals had bulk density values between 240–470 kg/m^3. This highlights that while bulk density provides useful information on storage behaviour, its relationship with flowability is not always straightforward and may be influenced by other structural and compositional factors (Suhag et al. 2024). In our study, the higher bulk density of dry-heated flours did not correspond to improved flowability, suggesting that other physical properties could play a contributing role.

3.7 | PCA of Flowability Characteristics With Processing Conditions

The flowability of faba bean flour, a critical parameter for industrial handling, blending and processing applications, was significantly affected by the thermal pretreatment conditions (dry heat, DF and steam heat, SF). The flow properties were quantified using the flow function coefficient (ff_c), which relates the major principal consolidating stress to the unconfined failure strength (Table 3; Figure 6). Particulate flowability can be categorized as nonflowing (ff < 1), very cohesive ($1 < ff_c < 2$), cohesive ($2 < ff_c < 4$), easily flowing ($4 < ff_c < 10$) and freely flowing (ff > 10) (Schulze 2021). All dry treated samples showed ff_c values between 1.77 and 2.91, which indicated that the flours were either cohesive or very cohesive.

Dry-treated faba bean flours (DF) exhibited predominantly cohesive to very cohesive behaviour, with ff_c values ranging from 1.60 to 2.91. Notably, samples treated at 80°C for 15 and 30 min demonstrated the lowest ff_c values (1.605), classifying them as very cohesive, which implies a high likelihood of flow issues

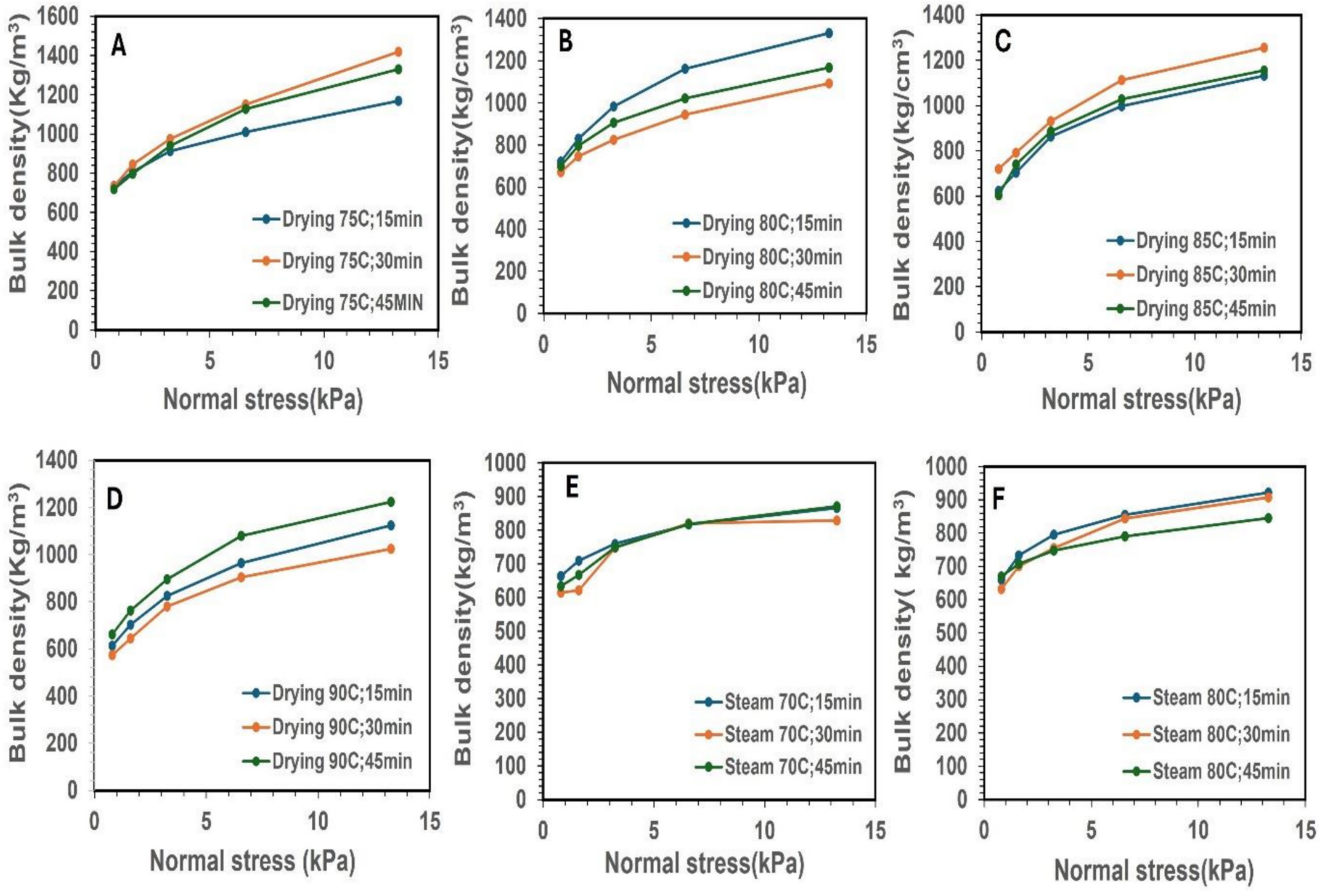

FIGURE 7 | Bulk density as a function of major principal consolidating stress for steam-heated faba bean flours.

TABLE 3 | Data on flow properties obtained from shear cell testing; major consolidation stress (kPa), unconfined yield loss, flow index flow classification and cohesion (kPa).

Sample	Moisture content (%)	Major principal consolidating stress (kpa)	Unconfined failure strength (kPa)	ff_c	Cohesion (kPa)
DF75°C; 15 min	9.53 ± 0.11^{gh}	4.83	1.728	2.80 ± 0.04^{de}	0.61 ± 0.01^{bcde}
DF75°C; 30 min	9.48 ± 0.02^{gh}	4.85	1.859	2.61 ± 0.00^{def}	0.67 ± 0.00^{bcde}
DF75°C; 45 min	9.33 ± 0.20^{h}	4.83	1.7595	2.75 ± 0.13^{de}	0.62 ± 0.04^{bcde}
DF80°C; 15 min	9.35 ± 0.11^{h}	4.56	2.839	1.61 ± 0.00^{g}	1.06 ± 0.00^{a}
DF80°C; 30 min	9.18 ± 0.24^{hi}	4.56	2.839	1.61 ± 0.00^{g}	1.06 ± 0.00^{a}
DF80°C; 45 min	8.4 ± 0.06^{ij}	5.09	2.877	1.77 ± 0.03^{fg}	0.99 ± 0.03^{a}
DF85°C; 15 min	7.77 ± 0.10^{jk}	4.29	1.567	2.74 ± 0.11^{de}	0.59 ± 0.01^{cde}
DF85°C; 30 min	7.53 ± 0.10^{jk}	4.25	1.529	2.78 ± 0.13^{de}	0.58 ± 0.02^{cde}
DF85°C; 45 min	7.33 ± 0.38^{k}	4.28	1.466	2.92 ± 0.01^{cde}	0.55 ± 0.00^{cde}
DF90°C; 15 min	7.84 ± 0.15^{jk}	4.94	2.569	2.04 ± 0.54^{def}	0.88 ± 0.30^{ab}
DF90°C; 30 min	7.84 ± 0.15^{jk}	4.49	1.943	2.56 ± 0.10^{def}	0.71 ± 0.08^{bcd}
DF90°C; 45 min	7.01 ± 0.21^{k}	4.85	2.347	2.07 ± 0^{efg}	0.83 ± 0.00^{abc}
SF70°C; 15 min	11.57 ± 0.33^{cde}	4.98	1.189	4.24 ± 0.63^{a}	0.40 ± 0.05^{e}
SF70°C; 30 min	12.48 ± 0.43^{bc}	5.37	1.785	3.01 ± 0.20^{bcd}	0.59 ± 0.01^{cde}
SF70°C;45 min	15.59 ± 0.69^{a}	5.19	1.512	3.47 ± 0.24^{abcd}	0.51 ± 0.10^{de}
SF80°C;15 min	11.54 ± 0.41^{de}	4.71	1.268	3.72 ± 0.13^{abc}	0.44 ± 0.01^{de}
SF80°C; 30 min	12.72 ± 0.63^{b}	5.79	1.768	3.28 ± 0.05^{bcd}	0.56 ± 0.06^{cde}
SF80°C; 45 min	14.88 ± 0.25^{a}	6.34	1.661	3.92 ± 0.72^{ab}	0.43 ± 0.09^{de}
SF100°C;15 min	10.73 ± 0.27^{ef}	5.79	1.768	3.28 ± 0.05^{bcd}	0.56 ± 0.06^{cde}
SF100°C; 30 min	11.48 ± 0.03^{de}	6.34	1.661	3.93 ± 0.70^{ab}	0.43 ± 0.09^{de}
SF100°C; 45 min	12.08 ± 0.06^{bcd}	5.27	1.615	3.27 ± 0.15^{bcd}	0.52 ± 0.02^{de}

such as arching during handling. This reduced flowability corresponds with an observed increase in cohesion values (> 1.0 kPa), indicating stronger interparticle forces. Interestingly, treatments at 75°C and 85°C produced slightly higher ff_c values (~2.6–2.9), indicating relatively improved flow within the cohesive range. Flow function (ff_c) values differed significantly among the thermally processed flours, and these variations must be interpreted in light of the statistically different moisture contents (Table 3). DF samples exhibited low-moisture levels (7.01–9.53) and correspondingly low ff_c values (1.60–2.91), categorizing them as cohesive to very cohesive. The driest samples (e.g., DF90°C; 45 min, 7.01%) were among the most cohesive. This demonstrates that moisture depletion is a major factor increasing flow resistance, enhancing interparticle friction and diminishing powder mobility.

In contrast, steam-heated (SF) samples displayed higher and significantly different moisture contents (10.73%–15.59%) and correspondingly higher ff_c values (3.01–4.24). Even though moisture typically increases cohesiveness due to capillary forces, in this case, the higher moisture levels likely plasticized particle surfaces, reducing frictional resistance. SF 70°C, 15 min demonstrated the best flow characteristics ($ff_c = 4.24$), classifying it as easy flowing. This improved flow may be attributed to moisture retention. At higher steam temperatures (80°C–100°C), ff_c values remained in the 3.2–3.9 range, still within the cohesive to borderline easy-flowing classification. Despite the increased processing intensity, these values remained higher than those observed in dry-heated samples, suggesting that the presence of steam mitigates the negative effects of thermal exposure. These differences in flowability might be attributed to different factors such as moisture content, particle size and particle morphology. According to Amagliani et al. (2016), high-moisture content greatly influences cohesiveness, which may be the case with steam-treated samples. Fitzpatrick et al. (2004) in their previous studies also described corn flour as cohesive as well as soy and wheat flours.

From an industrial standpoint, powders with lower ff_c values (e.g., DF80°C–90°C samples) are more prone to arching and ratholing in hoppers, require larger discharge angles and may feed inconsistently into mixers and extruders. Conversely, steam-treated flours with higher ff_c values (e.g., SF70°C; 15 min) are more suitable for automated dosing, pneumatic transfer and

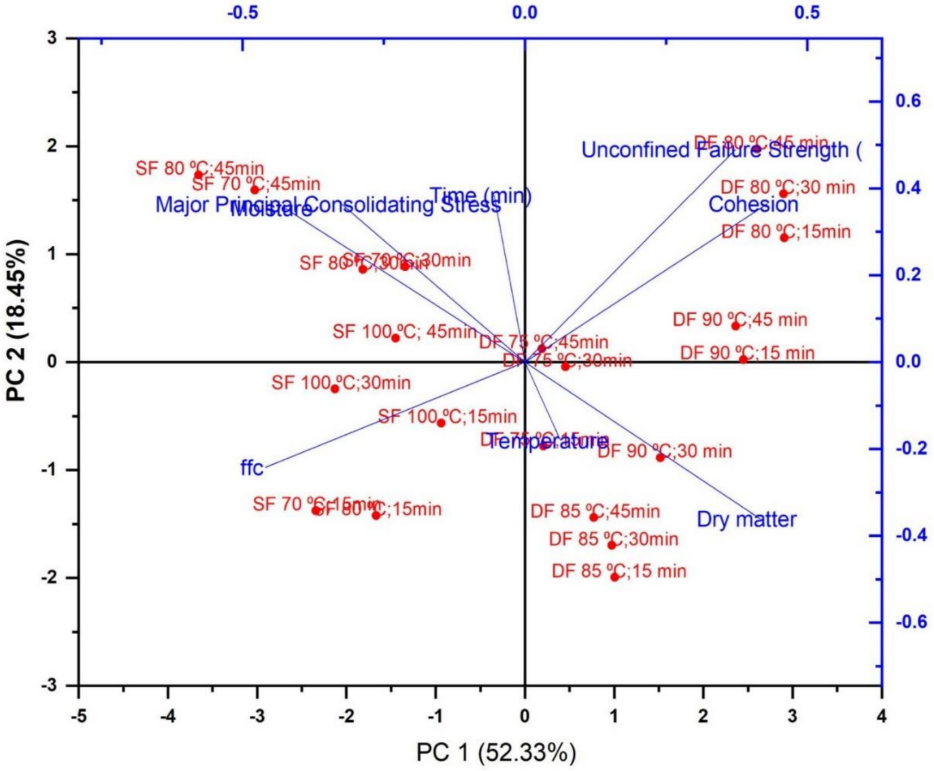

FIGURE 8 | Principal component analysis of flowability characteristics and processing conditions.

uniform feeder operation. The stronger cohesiveness of fine DF flours may still be advantageous in specific applications requiring rapid hydration, such as instant batters or high-solids doughs, but at the cost of more challenging handling (Siliveru et al. 2017).

To compare the relative differences between process conditions of thermally treated faba bean flours, a PCA was performed. As shown in Figure 8, 70.78% of the total variance was explained by the first two principal components (PC1 and PC2) while 52.33% and 18.45% of the variances were accounted for by PC1 and PC2, respectively. The dry treated faba bean flours were distributed along the positive end of PC1 and PC2, while steam-treated samples were distributed along the negative ends of PC1 and the positive end of PC2. PC1 explained 52.33% of the variation and was primarily associated with unconfined failure stress and cohesiveness of flours. However, the second component explains an additional 18.54% of the variation and is mainly driven by major principal consolidation stress, moisture content and duration of treatment.

4 | Conclusion

This study systematically evaluated the influence of dry and steam thermal pretreatments on the physical, structural and flowability properties of faba bean flours to optimize their performance for food processing applications. Moisture content emerged as a significant factor separating DF and SF samples. DF treatments resulted in substantial moisture loss, producing powders with lower ff_c values and higher cohesion. These effects were intensified in samples subjected to longer or higher temperature dry heating. In contrast, SF treatments produced significantly higher moisture contents, leading to improved flowability through enhanced particle plasticization and reduced frictional resistance. Dry-heated samples were classified as cohesive to very cohesive ($ff_c = 1.61–2.91$) with higher cohesion values (> 1.0 kPa), while steam-treated samples, especially those treated at 70°C for 15 min, demonstrated easy-flowing behaviour ($ff_c = 4.24$; cohesion = 0.40 kPa).

FTIR analysis revealed treatment-specific structural changes in both protein and starch domains. Dry heat induced reduced intensity in the amide I and II regions, suggesting protein aggregation and modification of native conformation. Conversely, steam-treated samples exhibited higher intensity in amide I and II bands. PCA further emphasized the role of processing parameters, explaining 70.78% of the total variance and separating samples based on flow and moisture traits. These insights provide a valuable foundation for tailoring pretreatment strategies to optimize faba bean flour performance in various food engineering applications, particularly where flow behaviour, hydration and structural retention are critical.

From an industrial perspective, these findings have meaningful implications. DF flours, being more cohesive and denser, may exhibit challenges during storage, silo discharge, pneumatic conveying or dosing, and may require mechanical assistance or modified hopper angles. Conversely, SF flours demonstrate superior flow characteristics and more uniform mixing behaviour, which can reduce processing energy and improve product consistency. Their higher moisture content and structural preservation may also enhance dough expansion, batter viscosity development and rehydration performance. These insights are relevant for manufacturers of bakery products, extruded snacks, plant-based foods and ingredient blends.

Author Contributions

Abraham Badjona: writing – review and editing, writing – original draft, methodology, investigation, data curation, conceptualization. **Robert Bradshaw:** writing – review and editing, writing – original draft, visualization, supervision, project administration, methodology, conceptualization. **Caroline Millman:** writing – review and editing, supervision, project administration. **Martin Howarth:** writing – review and editing, writing – original draft, supervision, project administration. **Bipro Dubey:** writing – review and editing, writing – original draft, supervision, project administration, methodology, conceptualization.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data generated during the current study are available upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** FTIR spectra of raw and dry-heated faba bean flours. **Figure S2:** FTIR spectra of raw and steam-heated faba bean flours. **Figure S3:** FTIR spectra of raw and dry-heated faba bean flours at 75°C, 80°C, 85°C and 90°C at protein fingerprint region (1900–1200 cm^{-1}). **Figure S4:** FTIR spectra of raw and steam-injected faba bean flours at 70°C, 80°C and 100°C with the protein fingerprint region (1900–1200 cm^{-1}).