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Rheological characterization of composite wheat flours enriched with protein-rich plant sources for nutritional enhancement

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ORIGINAL ARTICLE

Abstract

In low- and middle-income nations, the prevalence of protein–energy malnutrition (PEM) is increasingly posing critical nutritional issue, especially among children and women. The incorporation of protein-rich legumes in wheat flour is a promising approach to address this issue. Keeping this in view, the current study is an attempt to enhance nutritional composition of wheat flour by substituting with protein sources, such as legumes. Composite blends are prepared by substituting wheat flour with red lentils, kidney beans, soybeans, chickpeas, and maize flour at levels ranging from 5% to 20%, while moringa are substituted from 1% to 4%, and tested through amylograph, farinograph, and alveograph analyses. Amylograph results showed peak viscosities ranging from 989 to 1,099 Brabender unit (BU), with the lowest viscosity breakdown observed in 10% red lentil (222 BU) and 10% soybean (358 BU) blends, indicating improved thermal stability. Farinograph analysis revealed increased water absorption, with chickpea- and soybean-enriched flours, reaching up to 66.4% and achieving farinograph quality numbers (FQN) as high as 125 at 15% substitution. Alveograph results demonstrated that 10–15% chickpea and soybean blends maintained high dough tenacity (P = 114–117 mm) and extensibility (L = 51–62 mm), with baking strength values (W) of up to 221 × 10^{-4} J. In contrast, maize flour at 20% substitution significantly reduced extensibility (L = 24.91 mm) and baking strength (W = 112.27 × 10^{-4} J), and increased dough tenacity–extensibility (P/L) ratio to 3.86, indicating poor dough performance. The findings confirmed that 10–15% legume flour incorporation optimally enhanced both rheological and functional qualities, offering a promising way to develop nutritionally enriched and technologically stable bakery formulations.

Keywords: baking strength; Brabender; composite flour; extensibility; rheology

Introduction

Protein–energy malnutrition (PEM) continues to be a pressing nutritional issue in low- and middle-income countries. In Pakistan, PEM contributes significantly to morbidity among children and women, where 58% of the population experiences food insecurity (Government of Pakistan and UNICEF, 2011). Although wheat contributes about 60% of daily protein and caloric intake in the Pakistani diet, it is deficient in essential amino acids, such as lysine and tryptophan, limiting its protein quality (Batool *et al.*, 2015; Loro *et al.*, 2023).

The development of composite flour by incorporating legumes and other protein-rich plant ingredients into wheat flour is increasingly recognized as a strategy to enhance protein content and improve nutritional quality (Olaoye *et al.*, 2006). Legumes, such as red lentils, kidney beans, soybeans, and chickpeas, are rich in lysine and can complement the amino acid profile of wheat, while moringa leaves contribute not only protein but also high levels of micronutrients such as calcium, magnesium, and iron (Alexander and Eli, 2025; Gogoi *et al.*, 2023).

Several studies have demonstrated the nutritional and functional values of legumes when incorporated into composite flours. Red lentil flour has consistently shown high protein content, typically ranging from 23% to 25%, along with notable antioxidant capacity. Its inclusion in wheat flour enhances the texture and structure of baked products, particularly when used in moderate proportions (Atudorei *et al.*, 2022; Bae *et al.*, 2016). Soybean flour, containing up to 36% protein, significantly contributes to the protein efficiency ratio of composite flours and improves dough stability, making it a favorable ingredient for nutritional enhancement (Ndife *et al.*, 2011). Chickpeas and kidney beans, with protein levels between 21% and 28%, also are discovered to enhance dough strength and increase water absorption, improving the functional properties of flour blends if used appropriately (Chompoorat *et al.*, 2018; Gadallah *et al.*, 2017). In addition, moringa leaf powder, which boasts protein content by 26–28%, is rich in essential micronutrients, such as calcium, magnesium, and iron. Its inclusion not only supports improved protein content but also adds considerable bioavailable mineral value to the composite flour, contributing to its therapeutic potential in malnutrition interventions (Khan *et al.*, 2022).

While these sources of protein offer nutritional benefits, their incorporation may alter rheological properties, affecting baking quality. Understanding dough behavior using tools, such as amylograph (gelatinization and pasting), farinograph (water absorption and dough development), and alveograph (elasticity and extensibility), is essential for optimizing formulations. Rheological testing provides insight into flour functionality, structural integrity during mixing, and baking suitability (Noorfarahzilah *et al.*, 2014).

Previous research suggested that legume substitution by up to 10–20% generally improves dough handling and protein content without significantly compromising structure or taste (Chandra *et al.*, 2014; Kohajdová *et al.*, 2013). However, higher levels may reduce gluten strength and elasticity, leading to less desirable bread volume and texture unless compensated with processing techniques or gluten supplements.

This study evaluates the rheological profiles of wheat-based composite flours formulated with red lentils, soybeans, kidney beans, chickpeas, and moringa at different substitution levels. The aim is to identify flour blends that offer a balance between nutritional enhancement and desirable rheological behavior, ultimately contributing to the formulation of affordable functional foods for populations vulnerable to PEM.

Materials and Methods

Procurement and preparation of raw materials

Commercial wheat flour (Seher-2006 variety, harvested in 2024) was purchased from a local supplier in Karachi, Pakistan, and served as the control. Additional ingredients, such as red lentils (Masoor variety, harvested in 2024), soybeans (*Glycine max*, locally sourced hybrid, 2024 harvest), kidney beans (Rajma variety, 2024 harvest), chickpeas (Kabuli type, harvested in 2023), moringa leaves (*Moringa oleifera*, collected in late 2023), and maize (*Zea mays*, yellow dent variety, 2023 harvest), were procured from Imtiaz Super Market, Karachi, Pakistan. All raw materials were manually cleaned to remove dust and extraneous matter. Legumes were dehulled where necessary, followed by milling into fine flour using a laboratory hammer mill. The flour was then passed through a 60-mesh sieve to achieve uniform particle size. Moringa leaves were shade-dried before grinding in order to retain their nutritional and bioactive compounds.

Composite flour formulation

The composite flours were formulated by blending wheat flour with each legume (red lentils, soybeans, kidney beans, chickpeas, maize, etc.) at substitution levels of 5%, 10%, 15%, and 20%, while moringa leaf powder was substituted at 1%, 2%, 3%, and 4%. Each formulation was prepared separately to assess the effect of each ingredient on dough behavior. The flour blends were stored in air-tight, moisture-resistant containers at ambient room temperature prior to rheological testing.

Rheological testing

Amylograph analysis

To assess gelatinization behavior and starch pasting properties, a Brabender® Amylograph®-E (Brabender GmbH & Co. KG, Duisburg, Germany)was employed following the AACC method No. 22-10 (Liaquat *et al.,* 2025). Flour samples (12.5% solids, calculated on a dry basis) were dispersed in distilled water to form slurry and loaded into the amylograph bowl. The temperature was increased from 30°C to 95°C at a uniform rate of 1.5°C/min. The torque exerted by the gelatinizing starch was continuously recorded in Brabender units (BU). Rheological transitions, such as the beginning of gelatinization, peak viscosity, stability during holding, and the start of cooling, were recorded for each formulation. These data provided insights into the thermal and viscous response of starch in the presence of added protein flours.

Farinograph analysis

Mixing behavior of the dough was determined using a Brabender farinograph in accordance with the AACC method 54-21.02 (Korus *et al.*, 2023). For each composite flour, a 300-g sample (based on 14% moisture content) was mixed with water to achieve a dough consistency of 500 farinograph units (FU). The following parameters were recorded: water absorption (%), dough development time (DDT), defined as the time required to reach maximum consistency; dough stability; the duration for which the dough maintained peak consistency; and the degree of softening (DoS), defined as decrease in dough resistance 12 min after development. These parameters offered valuable indicators of flour strength, mixing tolerance, and water management.

Alveograph analysis

Dough resistance to deformation and extensibility was evaluated using a Chopin alveograph (Jødal & Larsen, 2021; AACC, 2000). Dough pieces were sheeted and inflated using controlled air pressure until rupture. From the pressure–time curve, the following rheological parameters were measured: tenacity (P); resistance of dough to expansion, extensibility (L); distance stretched before rupture; baking strength (W); area under the curve representing energy needed to inflate dough bubble; and tenacity–extensibility (P/L) ratio, indicating the balance between dough elasticity and extensibility. These properties are crucial for predicting the performance of composite flours in baking applications, such as flatbreads, noodles, and leavened products.

Statistical analysis

All rheological tests were conducted in triplicate. Data were expressed as mean ± standard deviation. One-way Analysis of Variance (ANOVA) was performed using SPSS version 20.0 to identify significant differences among treatments. When significant differences were observed ($p < 0.05$), Tukey's *post hoc* test was applied to determine group-wise variations.

Results

Rheological evaluation

Amylograph

The amylograph analysis revealed considerable differences in the pasting profiles of the composite flours mentioned in Tables 1–6, influenced by the botanical origin and composition of each ingredient. The results for red lentils, red kidney beans, soybeans, chickpeas, moringa leaves, and maize flour, substituted into wheat flour, are summarized. Key rheological parameters measured include torque (BU) and temperature (°C) at various phases of the heating and cooling cycle; beginning of gelatinization; peak viscosity; holding; and cooling. Parameters, such as breakdown and setback, provide further insight into starch stability and gel formation.

The substitution of red lentils into wheat flour (Table 1) significantly altered gelatinization and viscosity behavior. At 5% substitution, the composite showed early gelatinization at 40.3°C with a torque of 28 BU and a peak viscosity of 1,028 BU. As substitution increased to 10–15%, the onset of gelatinization was delayed due to increased protein and fiber content, with a peak viscosity rising to 1,071 BU at 20%. Breakdown peaked at this level, suggesting poor paste stability under thermal stress. In contrast, 10% substitution exhibited the lowest breakdown (222 BU), indicating superior resistance to heat and shear. Cooling torque and setback also declined with increased substitution, implying reduced retrogradation. Overall, red lentils at 10–15% substitution provided a favorable balance of viscosity, stability, and gel strength.

In the case of soybean flour, the rheological performance was notably influenced by substitution level (Table 2). At 5%, peak viscosity reached 1,079 BU at 90.8°C, but the dough experienced a substantial breakdown of 1,825 BU, suggesting structural collapse during heating. A 10% substitution produced the highest holding torque (1,089 BU) and lower breakdown (358 BU), indicating better thermal stability. At 15%, gelatinization was delayed to 70.0°C with consistent viscosity values and a setback of 617 BU. At 20%, although peak viscosity remained strong, the highest setback value (652 BU) was recorded, pointing to firmer gel formation and potential hardness. The data suggest that 10–15% soybean substitution optimally enhances stability and structure without excessive retrogradation.

For moringa leaf powder, lower substitution levels significantly affected viscosity and thermal response (Table 3). At 1%, peak viscosity was 1,091 BU, but breakdown reached 2,758 BU, suggesting paste instability.

Table 1. Amylograph pasting properties of wheat flour replaced with red lentil flour at different levels (5, 10, 15, and 20%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
5%	Beginning of gelatinization	$28±1.09^{h}$	$40.3±1.46^{d}$
	Maximum viscosity	$1,028±3.72^{d}$	$80.5±1.29^{b}$
	Start of holding period	$1,079±2.58^{d}$	$90±2.06^{a,b}$
	Start of cooling period	$889±2.12^{e}$	$89±2.11^{a,b}$
	End of cooling period	$1,345±2.77^{b,c}$	$53.6±2.75^{c}$
	End of final holding period	$1,578±2.56^{b}$	$50.9±1.71^{c,d}$
	Breakdown	$287±1.55^{g}$	–
	Setback	$628±1.76^{e,f}$	–
10%	Beginning of gelatinization	$26±1.28^{h}$	$70±2.08^{b,c}$
	Maximum viscosity	$1,056±1.37^{d}$	$83.6±1.77^{b}$
	Start of holding period	$1,018±3.69^{d}$	$89.4±1.36^{a,b}$
	Start of cooling period	$689±2.66^{e,f}$	$90.6±1.89^{a,b}$
	End of cooling period	$1,269±3.51^{c}$	$55.6±2.11^{c}$
	End of final holding period	$1,358±2.82^{b,c}$	$50.8±1.56^{c,d}$
	Breakdown	$222±1.42^{g}$	–
	Setback	$518±2.76^{f}$	–
15%	Beginning of gelatinization	$19±0.47^{h}$	$61.8±2.49^{c}$
	Maximum viscosity	$1,066±3.81^{d}$	$89.6±1.15^{a,b}$
	Start of holding period	$1,046±2.58^{d}$	$97±2.77^{a}$
	Start of cooling period	$889±1.42^{e}$	$95.6±2.52^{a}$
	End of cooling period	$1,336±2.51^{b,c}$	$56.4±2.63^{c}$
	End of final holding period	$1,589±1.47^{b}$	$49±1.48^{c,d}$
	Breakdown	$265±3.82^{g}$	–
	Setback	$512±2.76^{f}$	–
20%	Beginning of gelatinization	$20±1.45^{h}$	$59.8±1.66^{c}$
	Maximum viscosity	$1,071±2.27^{d}$	$89.6±2.82^{a,b}$
	Start of holding period	$1,040±2.41^{d}$	$81±2.55^{b}$
	Start of cooling period	$620±2.83^{e,f}$	$83±2.91^{b}$
	End of cooling period	$1,221±1.29^{c}$	$53.6±1.28^{c}$
	End of final holding period	$1,448±1.55^{b}$	$59.8±1.37^{c}$
	Breakdown	$2,569±2.51^{a}$	–
	Setback	$420±2.88^{f,g}$	–

Means with different superscript letters vary significantly at $p < 0.05$.

At 2%, breakdown reduced drastically (245 BU) and setback remained moderate (522 BU). At 3%, setback increased to 613 BU, with manageable breakdown (322 BU), indicating optimal textural integrity. At 4%, setback peaked at 724 BU, with strong holding and cooling torque, implying a firm and stable final product. Moringa substitution at 2–3% offered the best thermal and structural profile for composite flour applications.

Nonetheless, maize substitution influenced pasting behavior in a consistent and thermally responsive manner (Table 4). At 5%, the flour achieved moderate peak viscosity (989 BU) but exhibited high breakdown (2,569 BU), denoting low stability. At 10%, peak viscosity increased to 1,086 BU, with much lower breakdown (335 BU) and a setback of 489 BU, indicating good thermal resistance and final gel structure. The 15% level maintained low breakdown (331 BU) and a higher setback (563 BU). At 20%, while breakdown remained acceptable (375 BU), the highest setback (724 BU) was recorded, suggesting a firmer gel more suited to dense product applications. Thus, 10–15% maize substitution appears optimal for achieving balanced paste stability and texture.

Table 2. Amylograph pasting properties of wheat flour replaced with soybean flour at different levels (5, 10, 15, and 20%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
5%	Beginning of gelatinization	22±1.62^{f}	60.3±1.27^{c}
	Maximum viscosity	1,079±2.75^{c,d}	90.8±2.11^{a,b}
	Start of holding period	1,063±2.18^{c,d}	97±1.58^{a}
	Start of cooling period	512±2.71^{d,e}	91±1.37^{a,b}
	End of cooling period	1,289±2.32^{c}	56.6±1.29^{c}
	End of final holding period	1,369±1.67^{b,c}	49.8±1.50^{c,d}
	Breakdown	1,825±1.43^{a}	–
	Setback	480±1.89^{d,e}	–
10%	Beginning of gelatinization	19±0.38^{f}	61.2±2.18^{c}
	Maximum viscosity	1,059±1.27^{c,d}	85.6±2.76^{b}
	Start of holding period	1,089±3.61^{c,d}	91±1.39^{a,b}
	Start of cooling period	842±2.53^{d}	95.6±1.23^{a}
	End of cooling period	1,356±2.89^{b,c}	42.5±2.76^{d}
	End of final holding period	1,526±2.02^{b}	48±1.62^{c,d}
	Breakdown	358±1.61^{e}	–
	Setback	489±1.75^{e}	–
15%	Beginning of gelatinization	23±0.07^{f}	70±2.92^{b,c}
	Maximum viscosity	1,089±2.49^{c,d}	83.6±2.45^{b}
	Start of holding period	1,011±2.13^{c,d}	89.4±2.13^{a,b}
	Start of cooling period	895±1.76^{d}	90.6±1.78^{a,b}
	End of cooling period	1,256±1.28^{c}	55.6±2.51^{c}
	End of final holding period	1,356±2.09^{b,c}	50.8±1.67^{c,d}
	Breakdown	356±1.61^{e}	–
	Setback	617±2.59^{d,e}	–
20%	Beginning of gelatinization	30±1.72^{f}	40.2±1.39^{d}
	Maximum viscosity	1,087±3.19^{c,d}	81.6±2.77^{b}
	Start of holding period	1,098±1.73^{c,d}	88±2.05^{a,b}
	Start of cooling period	896±2.10^{d}	76±1.53^{b,c}
	End of cooling period	1,356±1.49^{b,c}	52.3±0.71^{c,d}
	End of final holding period	1,520±2.77^{b}	50.1±1.82^{c,d}
	Breakdown	485±1.40^{d,e}	–
	Setback	652±1.16^{d}	–

Means with different superscript letters vary significantly at $p < 0.05$.

Similarly, red kidney bean flour influenced rheological properties depending on the substitution level (Table 5). At 5%, peak viscosity reached 1,066 BU, but with a high breakdown of 2,235 BU and low cooling torque (580 BU), reflecting poor structural resilience. Increasing the level to 10% improved both thermal stability and setback (418 BU), with a notably low breakdown (258 BU). Substitution at 15% further reduced breakdown (215 BU) and increased setback to 498 BU. At 20%, gelatinization began earliest (40.3°C), and although viscosity values remained stable, setback peaked at 589 BU, indicating firmer gel formation. Red kidney bean flour performed best at 10–15% levels, combining viscosity retention with desirable retrogradation.

Finally, chickpea and wheat composite flour also demonstrated strong pasting and gelling behavior (Table 6). At 5%, peak viscosity was highest (1,093 BU) but accompanied by excessive breakdown (2,826 BU), indicating weak structural endurance. At 10% substitution, breakdown dropped sharply (324 BU), and setback improved to 622 BU, showing enhanced structural recovery. The 15% level showed similar trends, with further increased setback (633 BU), suggesting formation of firm texture. At 20%,

Table 3. Amylograph pasting properties of wheat flour replaced with moringa leaf powder at different levels (1, 2, 3 and 4%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
1%	Beginning of gelatinization	18±1.51[f]	61.4±1.72[c,d]
	Maximum viscosity	1,091±2.43[c]	91.2±2.39[a,b]
	Start of holding period	1,070±2.28[c]	91±2.15[a,b]
	Start of cooling period	720±1.39[d]	93±1.57[a]
	End of cooling period	1,321±1.28[b,c]	55.3±1.38[d]
	End of final holding period	1,445±0.77[b]	49.6±2.04[d,e]
	Breakdown	275±2.50[e,f]	–
	Setback	520±1.47[e]	–
2%	Beginning of gelatinization	18±1.36[f]	60.3±1.48[c,d]
	Maximum viscosity	1,076±1.92[c]	90.5±1.29[a,b]
	Start of holding period	1,056±2.88[c]	96±2.73[a]
	Start of cooling period	777±2.45[d]	97.6±2.37[a]
	End of cooling period	1,225±2.13[c]	53.4±1.19[d]
	End of final holding period	1,456±1.97[b]	50±1.05[d,e]
	Breakdown	245±1.05[e,f]	–
	Setback	522±1.76[e]	–
3%	Beginning of gelatinization	25±0.84[f]	70±2.11[c]
	Maximum viscosity	1,069±1.44[c]	83.6±2.56[b]
	Start of holding period	1,028±2.61[c]	89.4±2.48[a,b]
	Start of cooling period	789±2.84[d]	90.6±1.32[a,b]
	End of cooling period	1,369±1.79[b,c]	55.6±1.74[d]
	End of final holding period	1,457±2.52[b]	50.8±1.81[d,e]
	Breakdown	322±1.83[e,f]	–
	Setback	613±1.71[d,e]	–
4%	Beginning of gelatinization	31±1.05[f]	41.2±0.25[e]
	Maximum viscosity	1,090±3.58[c]	86.9±1.48[b]
	Start of holding period	1,088±3.29[c]	94±2.53[a]
	Start of cooling period	998±2.11[c,d]	90±1.71[a,b]
	End of cooling period	1,448±1.73[b]	51.3±1.36[d,e]
	End of final holding period	1,602±1.28[a]	49±1.15[d,e]
	Breakdown	378±2.46[e,f]	–
	Setback	724±2.19[d]	–

Means with different superscript letters vary significantly at $p < 0.05$.

setback reached 724 BU, indicating the firmest gel, but possibly too rigid for soft-texture products. Hence, 10–15% chickpea substitution was ideal for balanced gel strength and stability.

Finally, the botanical origin and substitution level of each composite flour distinctly affected its thermal, structural, and retrogradation behavior. Red lentils, soybeans, and chickpeas performed best at 10–15% inclusion levels, offering a balance between viscosity, stability, and gel strength. Moringa and maize were most effective at 2–3% and 10–15%, respectively. These insights are essential for tailoring functional wheat-based composite flours for specific product formulations in bakery and food processing.

Farinograph

The farinograph analysis revealed noticeable changes in the dough mixing properties of wheat flour when substituted with red lentils, kidney beans, soybeans, chickpeas, moringa leaves, and maize (Table 7). The composite flours exhibited variations in water absorption, DDT,

Table 4. Amylograph pasting properties of wheat flour replaced with maize flour at different levels (5, 10, 15, and 20%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
5%	Beginning of gelatinization	19±1.75^{f}	60.9±1.19^{c}
	Maximum viscosity	989±2.58^{c}	91.2±1.06^{a,b}
	Start of holding period	1,058±2.77^{c}	94±1.64^{a}
	Start of cooling period	691±1.69^{d}	98±1.38^{a}
	End of cooling period	1,256±0.98^{b}	53.6±2.54^{c,d}
	End of final holding period	1,489±2.25^{a,b}	50.6±0.35^{c,d}
	Breakdown	256±3.18^{e}	–
	Setback	590±1.76^{d,e}	–
10%	Beginning of gelatinization	24±1.83^{f}	61.1±2.41^{c}
	Maximum viscosity	1,086±2.71^{c}	91.5±1.37^{a,b}
	Start of holding period	1,067±1.84^{c}	95±1.59^{a}
	Start of cooling period	896±2.41^{c,d}	98.6±1.23^{a}
	End of cooling period	1,456±3.69^{a,b}	50.8±2.94^{c,d}
	End of final holding period	1,554±3.72^{a}	50±2.55^{c,d}
	Breakdown	335±2.38^{e}	–
	Setback	489±3.71^{d,e}	–
15%	Beginning of gelatinization	24±1.32^{f}	69.1±1.48^{b,c}
	Maximum viscosity	1,077±2.69^{c}	82.4±1.37^{b}
	Start of holding period	1,056±2.58^{c}	89.1±2.23^{a,b}
	Start of cooling period	789±2.11^{c,d}	92.6±1.07^{a,b}
	End of cooling period	1,326±1.56^{a,b}	53.4±2.82^{c,d}
	End of final holding period	1,489±1.37^{a,b}	51.8±1.17^{c,d}
	Breakdown	331±1.105^{e}	–
	Setback	563±1.27^{d,e}	–
20%	Beginning of gelatinization	29±2.81^{f}	71.1±1.46^{b,c}
	Maximum viscosity	1,014±3.42^{c}	85.6±1.79^{b}
	Start of holding period	1,075±3.47^{c}	98±2.43^{a}
	Start of cooling period	889±1.69^{c,d}	91±2.62^{a,b}
	End of cooling period	1,356±3.21^{a,b}	53.6±1.45^{c,d}
	End of final holding period	1,508±2.64^{a}	49±1.84^{c}
	Breakdown	375±1.35^{e}	–
	Setback	724±2.46^{c,d}	–

Means with different superscript letters vary significantly at $p < 0.05$.

stability, DoS, and farinograph quality number (FQN), reflecting the influence of each ingredient's biochemical composition on dough rheology.

Substitution with red lentils increased water absorption capacity from 56% at 5% substitution to 63.3% at 20%, attributed to the high water-binding capacity of legume proteins and fibers. DDT values ranged from 7.7 min to 9.5 min, with the highest dough stability of 14.5 min observed at 15% substitution. The FQN improved progressively, reaching 121 at 20% substitution, indicating stronger gluten interaction and dough strength.

Kidney bean substitution followed a similar pattern. Water absorption increased from 52.2% to 66.4%, and DDT reached a maximum of 9.4 min at 15%. Stability values remained relatively stable between 12.1 min and 14.1 minutes. Notably, the dough showed consistent DoS values, and FQN improved from 89 at 5% to 100 at 20%, confirming good structural retention and mixing tolerance. Soybean-substituted flour displayed the highest overall dough strength and stability. At 10% substitution, the dough exhibited a stability of 14.1 min and maintained strong resistance to softening, with a DoS of 9.5 FU. The highest FQN of 125 was recorded at 15%, signifying

Table 5. Amylograph pasting properties of wheat flour replaced with red kidney bean flour at different levels (5, 10, 15, and 20%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
5%	Beginning of gelatinization	18±0.07^{f}	59.8±1.91^{b}
	Maximum viscosity	1,066±0.57^{b,c}	89.6±2.64^{a}
	Start of holding period	1,039±1.48^{b,c}	81±1.82^{a,b}
	Start of cooling period	580±1.23^{d}	83±1.51^{a,b}
	End of cooling period	1,165±1.81^{b}	53.6±0.09^{c}
	End of final holding period	1,325±2.66^{a,b}	59.8±1.73^{b}
	Breakdown	223±2.73^{e,f}	–
	Setback	360±2.19^{e}	–
10%	Beginning of gelatinization	15±1.16^{f}	61.8±1.52^{b}
	Maximum viscosity	1,001±2.59^{c}	89.6±2.75^{a}
	Start of holding period	1,069±2.91^{b,c}	97±2.89^{a}
	Start of cooling period	996±2.76^{c}	95.6±2.11^{a}
	End of cooling period	1,456±3.12^{a}	56.4±1.74^{b,c}
	End of final holding period	1,458±3.09^{a}	49±1.28^{c}
	Breakdown	258±1.57^{e,f}	–
	Setback	418±1.49^{d,e}	-
15%	Beginning of gelatinization	21±1.16^{f}	50±1.59^{c}
	Maximum viscosity	1,038±0.73^{b,c}	83.6±2.28^{a,b}
	Start of holding period	1,011±0.52^{b,c}	89.4±2.16^{a}
	Start of cooling period	589±1.64^{d}	91.6±1.75^{a}
	End of cooling period	1,126±2.88^{b}	54.6±0.05^{c}
	End of final holding period	1,268±2.09^{a,b}	50.8±0.17^{c}
	Breakdown	215±1.73^{e,f}	-
	Setback	498±1.51^{d,e}	-
20%	Beginning of gelatinization	30±1.69^{f}	40.3±1.64^{d}
	Maximum viscosity	1,038±2.92^{b,c}	79.5±1.89^{a,b}
	Start of holding period	1,069±3.51^{b,c}	83±1.37^{a,b}
	Start of cooling period	850±3.07^{c,d}	91±2.09^{a}
	End of cooling period	1,265±2.83^{a,b}	53.6±1.74^{c}
	End of final holding period	1,485±2.56^{a}	50.1±1.37^{c}
	Breakdown	258±1.74^{e,f}	-
	Setback	589±1.38^{d}	-

Means with different superscript letters vary significantly at $p < 0.05$.

excellent dough-handling properties. Although a decline in stability and FQN was observed at 20%, the dough still performed well compared to other composites.

Chickpea flour also enhanced dough characteristics effectively. Water absorption increased with higher substitution, reaching 65.4% at 20%. DDT increased to 9.9 min at 15%, and stability peaked at 15.5 min at 20% substitution. The dough maintained good resistance to softening, with DoS values ranging between 6.9 FU and 9.1 FU. The FQN peaked at 125 for 15%, demonstrating superior dough strength and extensibility, ideal for baking applications. Moringa leaf powder, even at low substitution levels, markedly affected farinograph behavior. At 1% substitution, the flour demonstrated the highest consistency (620 FU) and water absorption of 65.5%. DDT and stability peaked at 3% substitution with values of 9.7 min and 15.1 min, respectively. However, FQN values changed, ranging from 0 to 129, potentially because of moringa's fiber, tannins, and bioactive compounds interfering with development of gluten network.

In contrast, maize flour substitution significantly weakened dough strength. Water absorption remained low

Table 6. Amylograph pasting properties of wheat flour replaced with chickpea flour at different levels (5, 10, 15, and 20%), covering measurements of torque related to dough rheology and pasting temperature (mean values ± standard deviation).

Treatments	Parameters	Torque (BU)	Temperature (°C)
5%	Beginning of gelatinization	21±0.06^{f}	60.9±2.01^{b,c}
	Maximum viscosity	1,093±3.76^{c}	91.2±2.53^{a,b}
	Start of holding period	1,080±2.81^{c}	92±1.75^{a,b}
	Start of cooling period	780±2.55^{c,d}	93±1.38^{a,b}
	End of cooling period	1,421±3.39^{a,b}	55.3±1.47^{c}
	End of final holding period	1,545±3.08^{a}	50.6±0.26^{c,d}
	Breakdown	282±1.41^{e,f}	–
	Setback	620±2.72^{d,e}	–
10%	Beginning of gelatinization	22±0.03^{f}	61.1±1.15^{b,c}
	Maximum viscosity	1,099±2.74^{c}	90.5±2.48^{a,b}
	Start of holding period	1,067±1.89^{c}	95±2.21^{a}
	Start of cooling period	888±1.28^{c,d}	99.5±2.89^{a}
	End of cooling period	1,335±3.72^{b}	52.6±1.44^{c}
	End of final holding period	1,554±3.16^{a}	50±1.27^{c,d}
	Breakdown	324±2.54^{e}	–
	Setback	622±4.22^{d,e}	–
15%	Beginning of gelatinization	27±0.56^{f}	69.1±2.69^{b,c}
	Maximum viscosity	1,088±3.71^{c}	82.4±1.34^{b}
	Start of holding period	1,064±3.89^{c}	89.4±1.71^{a,b}
	Start of cooling period	889±2.41^{c,d}	91.5±1.64^{a,b}
	End of cooling period	1,432±2.63^{a,b}	55.6±2.17^{c}
	End of final holding period	1,598±2.59^{a}	51.8±2.63^{c,d}
	Breakdown	328±2.17^{e}	–
	Setback	633±2.52^{d,e}	–
20%	Beginning of gelatinization	31±0.38^{f}	72.1±2.09^{b,c}
	Maximum viscosity	1,090±0.69^{c}	88.6±1.75^{a,b}
	Start of holding period	1,088±2.74^{c}	96±2.28^{a}
	Start of cooling period	998±2.61^{c,d}	92±1.55^{a,b}
	End of cooling period	1,448±3.88^{a,b}	53.6±0.43^{c}
	End of final holding period	1,602±2.18^{a}	48±0.69^{d}
	Breakdown	378±2.79^{e}	–
	Setback	724±4.61^{d}	–

Means with different superscript letters vary significantly at $p < 0.05$.

(59–60.1%), and DDT values dropped drastically to as low as 1.8 min. Dough stability declined from 10.5 min to 6.3 min, while DoS increased sharply, indicating substantial weakening of gluten network. The FQN dropped to 44 at 20% substitution, reflecting poor baking quality. Maize flour, owing to its lack of gluten-forming proteins, is better suited in limited ratios or when paired with stronger flours.

These findings suggest that 10–15% substitution of legumes, such as soybean, chickpea, and red lentils, results in optimal farinograph performance, balancing water absorption, dough strength, and stability. Moringa may be advantageous at 2–3% for functional enhancements, while maize flour must be used conservatively to avoid compromising dough integrity.

Alveograph

Alveograph analysis was conducted to evaluate gas-retention capacity, dough tenacity, extensibility, baking

Table 7. Farinograph attributes for wheat flour blends replaced with red lentils, kidney beans, soybeans, chickpeas, moringa leaves, and maize flour, showing effects on dough consistency, water absorption, dough development time (DDT), stability, degree of softening (DOS) recoded in International Association for Cereal Science and Technology (ICC) and farinograph quality number (FQN) (mean values ± standard deviation).

Treatments	Consistency (FU)	Water absorption (%)	DDT (min)	Stability (min)	DOS (10 min)	DOS (ICC)	FQN
95% wheat flour+5% red lentils	480±3.67^{b,c}	56±1.27^{b}	7.8±0.02^{b,c}	11.4±0.05^{c}	9±0.02^{d}	51±1.78^{b}	88±2.07^{b,c}
90% wheat flour+10% red lentils	520±2.59^{a,b}	61±0.05^{a,b}	7.7±0.05^{b,c}	13.1±1.27^{b}	5±0.09^{e}	52±2.09^{b}	90±1.79^{b,c}
85% wheat flour+15% red lentils	523±3.28^{a,b}	62.2±0.62^{a,b}	9.5±1.16^{a,b}	14.5±1.89^{a,b}	8±0.05^{d,e}	45±1.38^{c}	100±1.37^{b}
80% wheat flour+20% red lentils	410±1.82^{c}	63.3±1.83^{a}	8.4±0.03^{b}	12.2±1.15^{b,c}	9±0.01^{d}	25±0.74^{d}	121±2.05^{a}
95% wheat flour+5% kidney beans	510±3.92^{b}	52.2±1.49^{b}	8.4±0.09^{b}	12.1±0.03^{b,c}	9.1±0.63^{d}	50±2.11^{b}	89±1.45^{b,c}
90% wheat flour+10% kidney beans	599±3.11^{a}	62.4±2.01^{a,b}	7.4±0.56^{b,c}	14.1±0.17^{a,b}	9.4±0.92^{d}	56±1.97^{b}	90±1.72^{b,c}
85% wheat flour+15% kidney beans	550±2.67^{a,b}	66.1±1.63^{a}	9.4±0.31^{a,b}	12.1±0.49^{b,c}	9.5±0.11^{d}	45±1.36^{c}	95±1.31^{b}
80% wheat flour+20% kidney beans	511±2.25^{b}	66.4±1.26^{a}	8.8±0.72^{b}	12.5±0.57^{b,c}	6.8±0.38^{e}	78±1.89^{a,b}	100±1.59^{b}
95% wheat flour+5% soybean	550±3.81^{a,b}	56±1.48^{b}	8.1±0.97^{b,c}	13.1±0.08^{b}	9.2±1.17^{d}	90±2.38^{a}	100±1.83^{b}
90% wheat flour+10% soybean	510±2.73^{b}	60±2.08^{a,b}	8.5±0.64^{b}	14.1±0.02^{a,b}	9.5±0.29^{d}	88±2.17^{a}	101±1.76^{b}
85% wheat flour+15% soybean	420±3.28^{c}	62.2±1.28^{a,b}	9.5±0.59^{a,b}	12.1±0.09^{b,c}	9.8±1.56^{d}	49±1.64^{b,c}	125±1.15^{a}
80% wheat flour+20% soybean	350±1.69^{d}	65.1±2.71^{a}	9.8±1.24^{a,b}	13.5±1.04^{b}	6.9±1.83^{e}	75±1.31^{a,b}	85±0.64^{c}
95% wheat flour+5% chickpeas	510±2.66^{b}	62.2±2.73^{a,b}	8.8±0.38^{b}	11.1±2.34^{c}	9.1±0.04^{d}	95±3.07^{a}	101±2.74^{b}
90% wheat flour+10% chickpeas	490±1.91^{b,c}	65.1±1.17^{a}	8.9±0.21^{b}	12.1±1.67^{b,c}	8.8±1.47^{d,e}	89±2.23^{a}	99±2.18^{b}
85% wheat flour+15% chickpeas	520±3.38^{b}	66.4±0.03^{a}	9.9±0.56^{a,b}	14.1±1.29^{a,b}	6.9±1.28^{e}	59±1.76^{b}	125±1.79^{a}
80% wheat flour+20% chickpeas	480±1.74^{b,c}	65.4±0.66^{a}	8.8±0.73^{b}	15.5±1.17^{a}	8.1±0.57^{d,e}	81±1.97^{a,b}	90±1.42^{b,c}
99% wheat flour+1% moring leaves	620±2.13^{a}	65.5±1.42^{a}	10.5±1.71^{a}	12.4±1.17^{b,c}	9.5±0.08^{d}	85±1.26^{a,b}	2±0.04^{f}
98% wheat flour+2% moring leaves	550±2.89^{a,b}	64.2±1.36^{a}	11.1±0.33^{a}	13.1±0.03^{b}	8.5±0.47^{d,e}	65±1.67^{b}	22±0.28^{e}
97% wheat flour+3% moring leaves	520±2.07^{b}	62.5±0.32^{a,b}	9.7±0.06^{a,b}	15.1±1.59^{a}	6.6±0.71^{e}	58±1.79^{b}	129±1.59^{a}
96% wheat flour+4% moring leaves	490±3.71^{b,c}	62.1±1.17^{a,b}	8.4±0.01^{b}	14.8±1.82^{a,b}	8.2±1.29^{d,e}	85±1.16^{a,b}	100±1.34^{b}
95% wheat flour+5% maize flour	440±2.81^{c}	59±1.88^{a,b}	2.3±0.38^{c}	10.5±1.72^{c}	18±1.84^{c}	46±0.08^{b,c}	116±1.49^{a,b}
90% wheat flour+10% maize flour	449±1.64^{c}	59.1±1.12^{a,b}	1.9±0.55^{d}	7.6±0.38^{d}	45±1.67^{a,b}	76±0.53^{a,b}	71±1.27^{c,d}
85% wheat flour+15% maize flour	470±3.37^{b,c}	59.4±1.54^{a,b}	1.8±0.83^{d}	8.3±0.07^{c,d}	38±1.38^{b}	62±0.71^{b}	80±0.43^{c}
80% wheat flour+20% maize flour	510±3.18^{b}	60.1±0.48^{a,b}	2±0.77^{c}	6.3±1.89^{d}	50±0.79^{a}	89±0.16^{a}	44±0.91^{d}

Means with different superscript letters vary significantly at $p < 0.05$.

strength, and dough tenacity–extensibility ratio, which reflects a balance between dough resistance and extensibility. The values obtained for composite flours with red lentils, kidney beans, soybeans, chickpeas, moringa leaves, and maize flour substitutions provided insights into how each ingredient affected dough deformation and baking performance (Table 8).

Red lentil substitution led to a gradual decrease in both tenacity and extensibility. As substitution increased from 5% to 20%, tenacity (P) decreased from 99.27 mm to 79.42 mm, and extensibility (L) from 55.33 mm to 51.36 mm. Consequently, baking strength (W) dropped from 202.58×10^{-4} J to 165.83×10^{-4} J. However, the P/L ratio remained relatively stable, fluctuating between 1.59 and 1.79, indicating balanced dough resistance and extensibility up to 15% substitution, with a slight loss of elasticity beyond that point. Incorporating red kidney beans resulted in higher dough tenacity (117.52–120.47 mm) and gradually reduced extensibility (61.83–43.49 mm). The P/L ratio increased significantly, peaking at 2.77 for 20% substitution, indicating a stiffer dough with less extensibility. Baking strength decreased from 269.41 $\times 10^{-4}$ J to 201.82 $\times 10^{-4}$ J, suggesting that while the dough retained gas well, it became too rigid with higher kidney bean content, possibly affecting loaf volume and softness of crumb.

Soybean substitution maintained a relatively consistent balance between tenacity and extensibility across treatments. Tenacity ranged from 111.73 mm to 116.82 mm, and extensibility declined from 62.72 mm at 5% to 44.37 mm at 20%. Despite this, baking strength remained satisfactory, ranging from 192.34 $\times 10^{-4}$ J to 221.38 $\times 10^{-4}$ J. The P/L ratio increased with substitution, from 1.83 to 2.51, implying increasing stiffness but with retention of adequate

Table 8. Alveograph parameters for wheat flour blends replaced with red lentils, kidney beans, soybeans, chickpeas, moringa leaves, and maize flour, showing the effects on dough elasticity (P) and flexibility (L), index of swelling (G), and area under curve (W) (mean values ± standard deviation).

Treatments	P (mm)	L (mm)	G (mm)	W (10−4 J)	P/L
95% wheat flour+5% red lentils	99.27±1.87^{b,c}	55.33±1.18^{b}	15.67±1.72^{a,b}	202.58±4.09^{b,c}	1.79±0.16^{b}
90% wheat flour+10% red lentils	92.46±2.78^{c}	53.89±0.57^{b,c}	13.71±1.39^{b}	179.67±1.73^{c,d}	1.72±1.53^{b,c}
85% wheat flour+15% red lentils	83.51±2.18^{c,d}	52.48±1.49^{b,c}	12.38±0.05^{b}	172.38±1.48^{c,d}	1.59±0.08^{b,c}
80% wheat flour+20% red lentils	79.42±2.94^{c,d}	51.36±1.32^{b,c}	10.59±0.41^{b,c}	165.83±2.36^{d}	1.54±0.18^{c}
95% wheat flour+5% kidney beans	117.52±3.05^{a}	61.83±1.29^{b}	17.69±1.33^{a,b}	269.41±4.37^{a,b}	1.90±0.03^{b}
90% wheat flour+10% kidney beans	115.73±2.56^{a,b}	54.48±2.05^{b}	16.38±1.78^{a,b}	224.68±2.56^{b}	2.12±0.02^{b}
85% wheat flour+15% kidney beans	118.92±2.69^{a}	50.63±1.74^{b,c}	15.52±2.04^{a,b}	211.47±2.93^{b,c}	2.34±0.09^{a,b}
80% wheat flour+20% kidney beans	120.47±1.39^{a}	43.49±0.73^{c}	14.81±1.37^{b}	201.82±1.42^{b,c}	2.77±0.48^{a,b}
95% wheat flour+5% soybean	114.79±1.48^{a,b}	62.72±1.58^{b}	16.36±0.02^{a,b}	221.38±3.92^{b}	1.83±0.97^{b,c}
90% wheat flour+10% soybean	116.82±1.37^{a,b}	57.38±1.27^{b}	15.27±0.51^{a,b}	210.67±2.67^{b,c}	2.03±0.56^{b}
85% wheat flour+15% soybean	113.61±2.41^{a,b}	51.89±1.62^{b,c}	15.78±1.97^{a,b}	202.57±1.39^{b,c}	2.19±0.31^{b}
80% wheat flour+20% soybean	111.73±0.06^{b}	44.37±1.33^{c}	14.39±1.32^{b}	192.34±1.42^{c}	2.52±0.62^{a,b}
95% wheat flour+5% chickpeas	111.76±1.37^{b}	59.22±1.77^{b}	14.62±1.69^{b}	206.71±3.67^{b,c}	1.89±0.11^{b}
90% wheat flour+10% chickpeas	107.43±2.59^{b}	52.83±1.83^{b,c}	13.78±1.85^{b}	185.56±2.75^{c,d}	2.03±1.67^{b}
85% wheat flour+15% chickpeas	104.71±1.12^{b,c}	45.37±0.68^{c}	11.89±0.04^{b,c}	169.59±2.01^{d}	2.31±0.72^{a,b}
80% wheat flour+20% chickpeas	101.23±2.83^{b,c}	37.42±3.04^{c,d}	10.27±1.27^{b,c}	151.67±1.69^{d}	2.71±0.34^{a,b}
99% wheat flour+1% moring leaves	91.67±0.47^{c}	78.83±2.58^{a}	17.69±1.73^{a,b}	256.48±3.72^{a,b}	1.16±0.04^{c}
98% wheat flour+2% moring leaves	89.32±1.06^{c}	81.25±1.42^{a}	18.36±1.82^{a,b}	249.13±2.34^{a,b}	1.09±0.16^{c}
97% wheat flour+3% moring leaves	81.59±1.62^{c,d}	82.68±3.11^{a}	21.47±0.61^{a}	237.27±1.89^{b}	0.98±0.59^{d}
96% wheat flour+4% moring leaves	74.71±1.73^{d}	81.89±1.51^{a}	20.27±1.48^{a}	228.83±1.27^{b}	0.91±1.37^{d}
95% wheat flour+5% maize flour	109.58±2.88^{b}	42.58±0.52^{c}	10.39±1.44^{b,c}	147.79±2.66^{d,e}	2.57±a1.48^{b}
90% wheat flour+10% maize flour	107.61±2.16^{b}	37.29±0.97^{c,d}	9.58±1.29^{b,c}	133.62±1.48^{d,e}	2.88±0.73^{a,b}
85% wheat flour+15% maize flour	102.83±2.84bc	31.79±1.19cd	7.31±1.36c	125.68±2.72e	3.23±1.04a
80% wheat flour+20% maize flour	96.32±1.42^{c}	24.91±1.48^{d}	8.53±0.07^{c}	112.27±1.53^{e}	3.86±1.15^{a}

Means with different superscript letters vary significantly at $p < 0.05$.

extensibility, making up to 15% soybean a suitable option for elastic doughs. Chickpea flour substitution followed a similar pattern. With increasing levels, tenacity dropped slightly from 111.76 mm to 101.23 mm, and extensibility decreased substantially from 59.22 mm to 37.42 mm. The P/L ratio increased from 1.88 at 5% to 2.70 at 20%, indicating progressively firmer, less extensible dough. However, baking strength remained between 151.67 × 10^{-4} J and 206.71 × 10^{-4} J, suggesting that chickpea blends could still produce strong doughs but may require gluten reinforcement for highly extensible applications.

Moringa leaf powder had a different impact. As substitution increased from 1% to 4%, extensibility increased (from 78.83 mm to 81.89 mm), while tenacity decreased notably from 91.67 mm to 74.71 mm. Interestingly, the P/L ratio declined from 1.16 to 0.91, indicating highly extensible, weak doughs. Despite the softness, baking strength remained relatively high (228.83–256.48 ×10^{-4} J), suggesting that moringa may contribute to dough extensibility but compromise its ability to retain shape without structural reinforcement. Maize flour significantly reduced dough quality in terms of extensibility and strength. Tenacity declined from 109.58 mm at 5% to 96.32 mm at 20%, while extensibility plummeted from 42.58 mm to 24.91 mm. The P/L ratio increased sharply, reaching 3.87 at 20%, the highest among all samples, highlighting excessively rigid dough with very low elasticity. Meanwhile, baking strength decreased from 147.79 × 10^{-4} J to 112.27 × 10^{-4} J, indicating a weaker dough with poor fermentation tolerance and baking performance. These findings suggest that maize must be best used <10% in formulations requiring extensible dough.

Overall, the alveograph results indicated that legume flours, such as soybean, red lentils, and chickpeas, when used at 10–15% levels, support good gas retention, dough elasticity, and baking strength. Moringa leaf flour provided high extensibility but low dough resistance, while maize flour significantly stiffened the dough and reduced extensibility, affecting its baking potential.

Discussion

The functional performance of wheat flour blends enriched with various plant-based ingredients was evaluated using a combination of amylograph, farinograph, and alveograph analyses.

The rheological behavior of each composite flour was distinctly influenced by the physicochemical properties of the substituted ingredient, particularly its protein, fiber, and starch structure affecting water absorption, gelatinization, dough formation, and extensibility.

Amylograph results demonstrated that legume-based substitutions, particularly red lentils, chickpeas, and soybeans, maintained strong peak viscosities across all levels (typically above 1,050 BU), indicating robust gelatinization behavior and potential for forming thick pastes. These findings are consistent with previous reports showing that pulse starches tend to exhibit high swelling power and peak viscosity because of their large granule size and amylose content (Hoover *et al.*, 2010). Among the tested legumes, chickpeas and red lentils showed earlier gelatinization at low substitution levels, while soybeans exhibited delayed but more thermally stable viscosity profiles. The breakdown values were relatively lower at 10–15% substitution in all legumes, suggesting better thermal stability and stronger starch–protein interactions, which are beneficial for processed food applications, such as baking (Siddiq *et al.*, 2010). Setback values, indicating amylose retrogradation, generally increased with substitution level, most notably in chickpeas and soybeans, signaling firmer gels and possible implications for product shelf life and textural rigidity (Ragaee and Abdel-Aal, 2006).

Farinograph analysis further validated the functional suitability of legume flours. Red lentils, chickpeas, and soybeans improved water absorption and dough stability, particularly at 10–15% substitution. This is in agreement with Rosell *et al.* (2001), who found that legume protein and fiber improve dough strength because of water retention and gluten-like network formation. Soybean flour yielded the highest FQN (=125), confirming its dough-forming potential and high mixing tolerance. Chickpea blends also achieved excellent stability (up to 15.5 min) and strong FQN, indicating well-structured gluten matrices that could withstand mechanical stress. Kidney beans showed moderate improvement, while moringa leaf flour introduced greater variability, potentially because of the presence of polyphenols and dietary fiber, which may interfere with gluten formation (Govender and Siwela, 2020). In contrast, maize flour substitution significantly weakened dough development. Despite marginal improvements in water absorption, maize blends exhibited sharp decline in dough development time and stability, with high softening values and poor FQN, confirming maize's incompatibility in high-gluten baking systems without structural enhancers (Moreira *et al.*, 2015).

Alveograph data provided additional insight into the gas-holding and baking potential of the doughs. Legumes maintained satisfactory tenacity and extensibility values, with soybean and kidney beans showing balanced P/L ratios of around 2.0 at 10–15% substitution, signifying doughs that can stretch without tearing and retain gas, making them ideal for leavened bakery products (Yousaf *et al.*, 2019). Chickpea blends, although increasingly tenacious at higher levels, maintained acceptable baking strength, suitable for flatbreads and high-structure applications. Moringa leaf powder, although highly extensible, demonstrated low tenacity and a declining P/L ratio at higher substitutions, highlighting its limited applicability in standalone bakery products. Maize flour blends had the poorest extensibility and the highest P/L ratios (of up to 3.87), confirming their unsuitability for breadmaking because of stiff and gas-restrictive dough properties, a well-documented issue in cereal–legume composite flours (Miñarro *et al.*, 2012).

Integrating all three rheological tests reveals that 10–15% substitution with legumes, such as red lentils, chickpeas, or soybeans, optimally balances gelatinization properties, dough stability, and baking performance. These flours improve water absorption, maintain thermal resilience during processing, and deliver structurally sound and extensible doughs. Moringa leaf flour, although functional in small quantities, is best used at 2–3% to prevent gluten interference. Maize flour, while nutritionally valuable, requires support from gluten-rich flours or textural enhancers because of its negative impact on extensibility and stability.

These findings aligned with earlier work advocating legume fortification of wheat flour as a method for improving protein content and functional characteristics while sustaining baking quality (Iqbal *et al.*, 2006; Jimenez-Lopez *et al.*, 2020). Overall, legume-based enrichment of wheat flour offers a promising strategy for developing high-protein, functionally rich, and technologically viable flours for diverse baking and food industry applications.

Conclusion

This study comprehensively evaluated the rheological behavior of wheat flour blends substituted with red lentils, kidney beans, soybeans, chickpeas, moringa leaves, and maize flour using amylograph, farinograph, and alveograph analyses. The results demonstrated that the botanical origin and substitution level significantly influenced gelatinization characteristics, dough stability, and baking performance. Legume flours, particularly chickpea, soybean, and red lentils, at substitution levels of 10–15%, provided the most favorable balance between water absorption, thermal stability, and dough extensibility. These blends exhibited enhanced protein content while maintaining or improving functional properties suitable for baking applications. Moringa leaf flour, although beneficial at low levels (2–3%), showed variability in dough behavior and is best applied in controlled ratios. In contrast, maize flour adversely affected dough strength and extensibility, limiting its use in gluten-reliant bakery products unless supplemented with structural enhancers. Overall, the incorporation of protein- and fiber-rich legume flours into wheat flour represents a promising approach for developing nutritionally enhanced bakery products without compromising dough rheology. The future work should explore sensory, nutritional, and shelf-life aspects of these composites to validate their applicability in commercial food formulations.

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Author Contributions

Anum Liaquat carried out all analysis and wrote the research paper, while Drs. Halima Sadia and Safila Naveed performed statistical analysis along with formatting the paper. Dr. Humaira Ashraf supervised and helped in manuscript writing. Dr. Hina Rehman assisted in manuscript preparation and editing.

Conflict of Interest

The authors declared no conflict of interest associated with this study.

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