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Physicochemical, functional, rheological, and thermal properties of underutilized kodo and little millet flours

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Abstract:
Millets are rich sources of nutrients that exhibit excellent functional and health benefits. This study aimed to investigate the engineering and physical properties of kodo and little millet kernels, as well as the physicochemical, nutritional, functional, rheological, and thermal properties of their flours, with refined wheat flour used as a control.

The physicochemical and functional properties of Kodo and Little millet flours were systematically investigated using standard protocols, including rheological assessment of pasting behavior and color determination via a Chroma meter.

According to our results, kodo millet kernel exhibited significantly ($p < 0.05$) higher geometric mean diameter, thousand kernel weight, and sphericity, whereas little millet kernel showed higher length, porosity, and angle of repose. Refined wheat flour had significantly higher protein content, whereas kodo millet flour had higher fiber and carbohydrate contents. Kodo flour also exhibited higher swelling and solubility indices, while little millet showed superior water absorption, oil absorption, bulk density, and foaming capacity. Little millet had higher protein, fat, and mineral contents, whereas kodo millet exhibited higher fiber and carbohydrate contents. Furthermore, kodo millet flour had higher peak, trough, breakdown, setback, and final viscosities, as well as higher pasting temperature and peak time compared to little millet. The rheological properties such as peak torque, water absorption, stability, softening, and mixing tolerance index were determined to be higher in kodo millet flour as compared to little millet flour.

All the millets under study exhibited high nutritional and functional attributes. The underutilized minor millets could be considered for development of functional food for a sustainable approach with maintained human health and minimizing nutritional security. Moreover, the underutilized millet and their nutritional bioavailability and accessibility should be further investigated in future.

Keywords: Millets, crops, nutri-cereals, functional food products, food quality, FTIR, viscosity

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INTRODUCTION

The last few decades have seen a growing interest in plant-based functional foods due to their nutritional and health benefits. Plants are excellent sources of macro- and micronutrients. They fulfil the body's basic requirements and help eliminate several types of diseases. Nowadays, the global population has increased exponentially. It reached 7 billion after 2010 and is expected to reach 9 billion by the year 2045 [1]. This makes food security a major challenge, creating a need to sustain the food resources and use underutilized crops as an alternative to staple foods such as cereals.

Millets, also known as nutri-cereals, are important crops due to their nutritional, functional, and biological properties. There are two categories of millets, major (sorghum, finger, proso, foxtail, pearl) and minor (fonio, Job's tear, guinea, barnyard, brown top, kodo, and little) ones. In recent years, underutilized millets such as kodo and little millets have been reported to be good nutritional ingredients to develop value-added functional foods. Kodo (*Paspalum scrobiculatum* L.) and little (*Panicum sumatrense* Roth) millets contain macro- and micronutrients, including proteins, vitamins, minerals, antioxidants, and dietary fibers. They are easy to digest, gluten-free, and have low glycaemic indices [2].

The consumption of kodo and little millets is key to promoting health, strengthening the immune defense system, and retarding the risk of several types of diseases such as diabetes, cardiovascular diseases, cancer, inflammation, gastrointestinal problems, and anemia. These effects are due to the abundance of minor nutrients such as phenolic compounds, vitamin B_6, niacin, folic acid, minerals (calcium, iron, potassium, magnesium, and zinc), amino acids (cysteine, methionine, and lysine), polyunsaturated fatty acids, tannins, and flavonoids [3–6].

These minor millets can be used in various food applications to develop gluten-free, value-added functional food products with improved textural properties, higher consumer acceptability, and nutritional profile. Neelam *et al.* [7] and Sharma *et al.* [8] have reported an excellent nutritional composition of kodo and little millets, which makes them highly suitable for value-added foods [7, 8]. However, very few studies are available on the physicochemical, functional, rheological, and thermal characterization of these underutilized millets. Therefore, we aimed to evaluate the nutritional, physicochemical, rheological, thermal, and functional properties of kodo and little millets (kernels and flours).

STUDY OBJECTS AND METHODS

Materials and chemicals. Kodo (JK-48) and little (JK-8) millets were provided by the Krishi Vigyan Kendra, Dindori, Madhya Pradesh, India. The chemicals, reagents, and standards were of analytical grade and procured from Sigma Aldrich Inc. and SRL Chemicals, India.

Experimental methodology. Figure 1 shows the experimental methodology for the process and the investigation of physicochemical, nutritional, functional, rheological, and thermal properties of kodo and little millet flours, as well as the engineering and physical properties of their kernels.

Pre-processing of millets. The pre-processing of the millets involved winnowing, de-husking, polishing, and milling into flours. The flours were sieved through 100 mesh size (149 μ) followed by packing, sealing, and storage in airtight high-density polyethene zip-lock bags for further analysis.

Engineering and physical properties of millet kernels. The physical properties of the millet kernels (width, thickness, geometric mean diameter, thousand kernel weight, bulk density, true density, porosity, angle of response, and sphericity) were determined according to the methodology reported by Ramashia *et al.* [9] and Lara *et al.* [10]. The analyses for each parameter were carried out in triplicate.

Color analysis. The color profiles of the millet flours were determined using a hand-held Chroma meter (Hunter Lab D25 LT, USA) in terms of L^* (+ lightness/ – darkness), a^* (+ red/– green), b^* (+ yellow/– blue), and color difference (ΔE). The color differences were calculated using the Eq. (1) [11].

$$\Delta E^*ab = \sqrt{\left(L^*\ 2 \times L^*1\right)^2 + \left(a^*2 - a^*1\right)^2 + \left(b^*2 - b^*1\right)^2} \quad (1)$$

Proximate analysis. The nutritional analysis (moisture, ash, proteins, fat, and crude fiber) of the kodo and little millet flours were determined using the standard

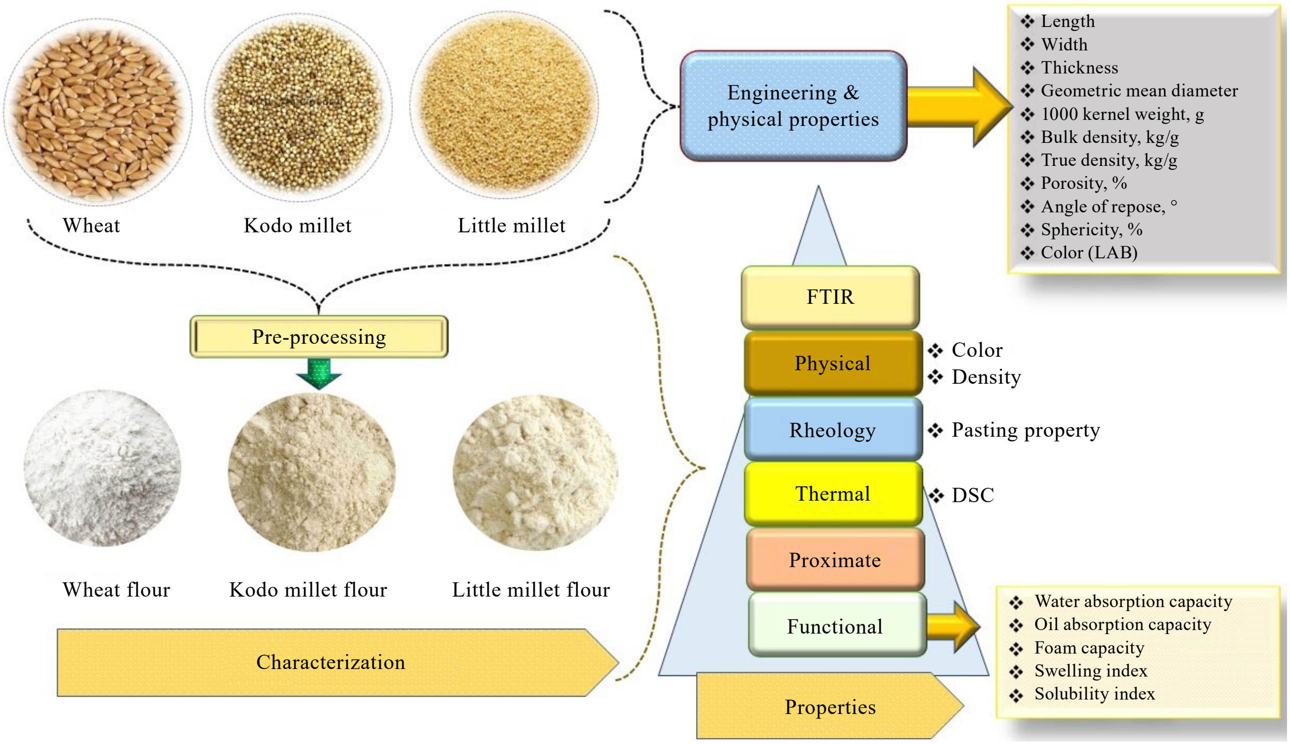


Figure 1 Schematic presentation of experimental method and process

protocols of AOAC followed by Thiex [12]. Total carbohydrates, %, and energy value, kcal, were calculated using the Eq. (2) and (3). The analyses were carried out in triplicate, and the results were expressed as a percentage for proximate parameters (moisture, protein, fat, crude fiber, ash and carbohydrates) and kcal/100 g for total energy.

$$\text{Total Carbohydrates} = 100 - [\text{Moisture (\%)} + \text{Crude Protein (\%)} + \text{Crude Fat (\%)} + \text{Crude Fiber (\%)} + \text{Ash (\%)}] \quad (2)$$

$$\text{Energy} = 4 \times [\text{Protein (g)} + \text{Carbohydrate (g)}] + 9 \times \text{Crude Fat (g)} \quad (3)$$

Rheological properties. The rheological properties of the doughs made from different millet and refined flours were determined according to the method of Voicu *et al.* [13] using a dough lab instrument. For this, the flour (300 g) was sieved (100 mesh size) and dough was prepared using a dough mixer (PerkinElmer dough LAB 2500) for 10 min. The results were expressed in terms of peak torque, FU, water absorption, %, dough development time, min, stability, min, softening, FU, and mixing tolerance index, FU.

Pasting properties. The pasting properties of different flour samples were investigated by the method described by Bashir *et al.* [14] using an MCR 52 rheometer (Anton Paar, Austria). The viscosity profiles of the flour samples were studied by using flour suspensions (11%, w/w; 16 g total weight). The suspensions were equilibrated for 1 min at 50°C and then heated at the rate of 6°C/min to 95°C. The suspensions were held at 95°C for 5 min, then cooled to 50°C at the rate of 6°C/min, and finally held at 50°C for 2 min. Initially, the samples were stirred at 960 rpm for 5 s and then kept at 160 rpm throughout the experiment. The profile was depicted by viscosity, mPa·s, with respect to time, min, and graphs.

Functional properties of millet flours. *Swelling and solubility indices.* The swelling and solubility indices at varying temperatures (60, 70, 80, and 90°C) were determined by the method of Wani *et al.* [11] with slight modifications. For this, 2.5 g of the flour samples were dispersed in 30 mL of distilled water for swelling and in 10 mL of distilled water for dissolution in pre-weighed centrifuge tubes. The suspensions were vortexed for 1 min and then heated in a water bath at the above temperatures for 30 min with periodic vortex every 5 min. After that, the samples were cooled to room temperature and centrifuged at 4,500 rpm for 15 min. The supernatants were decanted in pre-weighed moisture dishes and dried at 110°C. The swelling power was calculated as the percent weight gained by the flour, whereas its swelling solubility was expressed as a percentage of dried solids in the supernatant.

Water and oil absorption capacities. The water and oil absorption capacities of the millet flours were determined by the method of Wani *et al.* [11] with slight modifications. About 0.5 g of a sample was mixed with 6 mL of water and oil in pre-weighed centrifuge tubes. The samples were vortexed for 1 min, and the tubes were kept in a vertical position for 30 min, after which they were centrifuged at 3,000 rpm for 15 min. The supernatant layers were decanted and the gain in weight of the flour was expressed as grams of water and oil absorbed in g/mL flour.

Foaming properties. The foaming capacity of the millet flour samples was determined according to the method described by Maninder *et al.* [15] with slight modifications. The samples (1.5 g) were mixed with 50 mL of distilled water and homogenized at 960 rpm for 3 min using a tissue homogenizer (Cole Palmer Servodyne, Model 50000-25). The mixture was transferred to a graduated cylinder and the homogenizer was rinsed with 10 mL of distilled water for pooling the samples. The volume was recorded before and after whipping. The foaming capacity was calculated using the Eq. (4), and the results were expressed as the percent increase in volume upon whipping. The analysis was carried out in triplicate.

$$\text{Foaming capacity} = \frac{V_2 - V_1}{V_1} \quad (4)$$

where V_1 is the initial volume, mL; V_2 is the increase in volume after homogenization, mL.

Thermal properties. The thermal properties of the millet flours were determined using a differential scanning calorimeter (NETZSCH DSC 200 F3 Maia, Netzsch-Geratebau GmbH, Germany) according to the method of Liu *et al.* [16] with slight modifications. The temperature range for the DSC analysis of the flour samples was 25 to 150°C with heating rate of 5.0 K/min and flow rate applied of 20 mL/min.

Functional group analysis (FTIR). The functional groups of different millet flours were analyzed by a Fourier transform infrared (FTIR) spectrophotometer (Agilent Cary 630 FTIR spectrometer, USA) at a range of 4000–600 cm^{-1} at room temperature with 32 scans and resolution of 4 cm^{-1}. The IR spectra were recorded in % transmission and IR correlation charts were used to identify the functional groups.

Statistical analysis. The analyses of the parameters were performed in triplicate and expressed as mean ± standard deviation. One-way ANOVA was used to analyze the data through SPSS software (20.0). The Duncan multiple range test with $p < 0.05$ significance level was applied to determine the significant variation between the values.

RESULTS AND DISCUSSION

Physical and engineering properties of millet kernels. The physical properties of agricultural produce not only aid in designing processing machinery (seed hoppers, screen perforators, cleaning or grading types of equipment) and storage facilities but also indicate its quality and purity [17]. The physical and engineering properties of the millet kernels are presented in Table 1.

Table 1 Physical properties of wheat and millet kernels

Dimensions	Wheat kernels	Kodo kernels	Little millet kernels
Length, mm	6.11 ± 0.23[a]	3.03 ± 0.19[c]	3.26 ± 0.15[b]
Width, mm	3.09 ± 0.05[a]	2.39 ± 0.08[b]	1.83 ± 0.06[c]
Thickness, mm	2.74 ± 0.70[a]	1.67 ± 0.07[b]	1.15 ± 0.03[c]
Geometric mean diameter	4.06 ± 0.09[a]	2.29 ± 0.05[b]	1.90 ± 0.04[c]
1000 kernel weight, g	43.13 ± 0.86[a]	5.74 ± 0.12[b]	3.18 ± 0.03[c]
Bulk density, kg/m^3	789.66 ± 2.12[a]	758.85 ± 0.98[b]	496.63 ± 1.02[c]
True density, kg/m^3	1,263.00 ± 1.89[a]	1,103.00 ± 0.20[c]	1,027.00 ± 0.02[b]
Porosity, %	37.39 ± 6.42[b]	29.01 ± 0.11[c]	51.74 ± 0.01[a]
Angle of repose, °	21.52 ± 0.28[c]	25.95 ± 0.11[b]	35.30 ± 0.02[a]
Sphericity, %	61.94 ± 0.34[b]	76.00 ± 0.04[a]	58.40 ± 0.022[c]

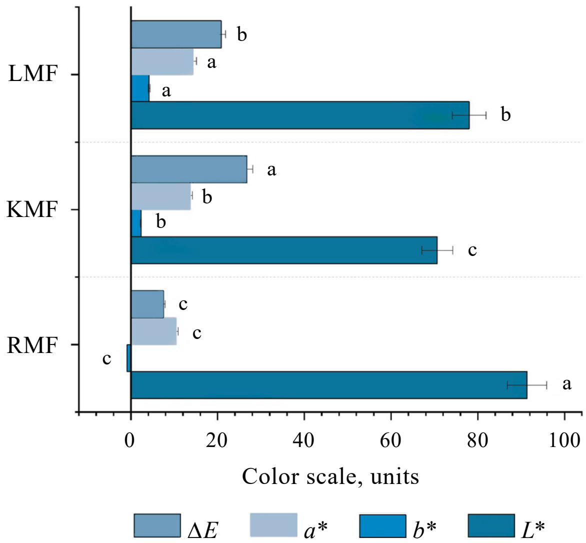
Mean ± standard deviation (n = 5)

Superscripts [a, b, c] indicate the significant difference ($p > 0.05$) row-wise

The kodo and little millet kernels showed wide variation in length (3.03 and 3.27 mm), width (2.40 and 1.83 mm), thickness (1.67 and 1.16 mm) and geometric mean diameter (2.29 and 1.90 mm). The wheat kernels were bigger in size, with physical dimensions (length, width, thickness) of 6.11, 3.09, and 2.74 mm, respectively.

The geometric mean diameter of the kernels is an important parameter for their processing (de-husking and polishing) and for selecting rollers/cylinders for the pre-processing steps. It is also a vital parameter for the terminal velocity and drag coefficient [18]. Amongst the kernels, wheat kernels (4.06 mm) had the highest mean diameter, compared to the kodo and little millet kernels (2.29 and 1.90 mm, respectively). The highest value for 1,000 kernel weight was shown by wheat (43.13 g) and the lowest by little millet (3.18 g). The bulk (758.85 kg/m^3) and true density (1,103 kg/m^3) of the kodo kernels were significantly ($p < 0.05$) higher than those of the little millet kernels (496.63 and 1,027.00 kg/m^3, respectively). The porosity (39.01–51.74%), angle of repose (21.52–35.30°) and sphericity (58.4–76.0%) varied for all the three grains. The little millet exhibited the maximal value of porosity and angle of repose with the lowest sphericity due to their oval form and higher void ratio to the apparent kernel volume. These results are in good agreement with the previous findings reported by Balasubramanian & Viswanathan [19] and Kiber *et al.* [20].

Color analysis. The color properties of wheat and millet flours are presented in Fig. 2. The refined wheat flour showed a significantly ($p < 0.05$) higher value of L^* (91.3) and lower values of a^* (–0.8) and b^* (10.3), with minimal color differences ΔE (7.4), compared to the kodo and little millet flours. The kodo and little millet flours had L^* values of 70.6 and 78.0, a^* values of 2.3 and 4.2, b^* values of 13.6 and 14.2, and ΔE of 26.7 and 20.8, respectively. These differences are due to higher contents of anthocyanins and fiber in millet flours [21]. Our results are consistent with the previous studies of Goswami *et al.* [22] and Prasadi & Joye [23]. The authors attributed the color differences (ΔE) in kodo, little millet, and refined flours to a high fiber content. Another contributor to color difference could be the aleurone layer in millet kernels containing phenolic acids and insoluble and soluble fibers [24].



a, b, c indicate the significant difference ($p > 0.05$)

Figure 2 Color analysis of refined (RWF), kodo (KMF), and little millet (LMF) flours

Proximate analysis of flours. The proximate composition of the refined wheat and the respective millet flours is depicted in Table 2. As can be seen, the kodo and little millet flours had a high nutritional index in terms of fat (2.95 and 3.02%), crude fiber (6.9 and 6.5%), and ash content (4.02 and 6.14%), respectively. The protein and energy values showed the opposite trend, with the highest values in refined flour (9.24% and 343.5 kcal), followed by little millet flour (8.71% and 310.58 kcal) and kodo flour (6.28% and 316.59 kcal). On the contrary, the maximal carbohydrate content was observed in refined flour (73.94%), followed by kodo (66.23%) and little millet (62.14%) flours. Interestingly, the moisture content in all the flours (13.4–13.8%) did not show much variation ($p \geq 0.05$). These findings are consistent with those of other studies [25, 26], which reported a similar range in kodo and little flours for moisture

Table 2 Proximate composition of refined and millet flours

Parameters	Refined wheat flour	Kodo flour	Little millet flour
Moisture, %	10.91 ± 1.85	9.47 ± 1.17	11.01 ± 1.24
Protein, %	11.96 ± 1.63	8.21 ± 1.34	8.71 ± 1.22
Fat, %	1.62 ± 0.63	2.95 ± 0.34	3.02 ± 0.19
Fiber, %	2.18 ± 1.91	3.29 ± 1.89	1.62 ± 1.66
Ash, %	0.92 ± 0.88	1.53 ± 0.63	1.89 ± 0.34
Carbohydrate, %	72.41 ± 0.34	74.55 ± 0.64	73.55 ± 0.24
Energy, kcal	343.52 ± 1.57	316.59 ± 1.64	310.58 ± 1.13

Mean ± standard deviation (n = 3)

Table 3 Dough development properties of kodo and little millet flours

Parameters	Refined wheat flour	Kodo millet flour	Little millet flour
Measure pt: Peak torque, FU	985.7	374.0	205.5
Water absorption, %	72.7	56.8	52.6
Dough development time, min	3.0	4.2	8.2
Stability, min	2.2	7.7	1.6
Softening, FU	239.0	148.2	n.d.
Mixing tolerance index, FU	270.2	163.1	–0.1

n.d. – not detected

(12.4–14.0%) and protein (6.20–10.66%). Our findings are also in line with the previous study of Srivastava & Vijayakumar [27]. Similar ranges were also reported by Munshi & Dashora [28] for protein (8.05–12.07%), ash (1.22–1.50%), fiber (1.58–3.32%), and carbohydrates (71.41–73.70%) in refined, kodo, and little millet flours. The values of total energy, fat, crude fiber, and ash in our study were similar to those in previous studies [27, 28].

Rheological properties of millet flours dough. Dough is thick, flexible, and elastic in nature, which is why it can be molded into desired products. Its properties include extensibility, elasticity, resistance to deform (tenacity), and stickiness. The millet and wheat dough development properties are presented in Table 3. The kodo millet flour showed a dough development time of 4.2 min, a softening value of 148.2 FU, and a dough development torque of 374 FU. The little millet flour was unable to show its softening properties due to a higher dough development time. Its mixing tolerance index (MTI) was not recorded either because a run time of over 10 min is needed to observe this parameter in little millet flour. Kodo and little millet flours do not have gluten (as shown by their peak torque and MTI values), so they show no resistance during dough kneading.

The dough analysis also involved the analysis of strength of refined, kodo, and little millet flours. Weak flour is characterized by a short development time, low stability, high softening, and a high MTI. Conversely, strong flour has a long development time, high stability, low softening, and a low MTI. We found that the kodo and little millet flours showed long development time, high stability, low softening, and low MTI values. Therefore, it is recommended to add refined wheat flour to entrap carbon dioxide in baked products.

Pasting properties. The millet flours were analyzed for their pasting properties (Fig. 3), or heat-mediated granular swelling of starch [29]. The pasting parameters not only determine the quality of the product but also correlate with its texture profile and rheological parameters. The peak viscosity shows the swelling of starch before it physically breaks down at a higher temperature, indicating that the product has higher palatability [14]. The leaching of amylose from starch, the formation of amylose-lipid (lysophospholipids and monoacylglycerides) complexes, as well as friction force between swollen granules and ungelatinized granules influence the peak viscosity.

According to Fig. 3, the refined wheat flour sample (1,218 mPa·s) formed a stronger gel than the little (446.5 mPa·s) and kodo (337.1 mPa·s) millet flours owing to the presence of degraded or de-branching starch. Trough viscosity indicates the decrease in pasting viscosity resulting from the disruption of granules. Our results showed that trough viscosity was higher in kodo (1,553 mPa·s) as compared to little (1,056 mPa·s) and refined (1,012 mPa·s) flours. This points towards structural hardness of millet flour, which prevents paste from breaking down during the cooling [30]. Noteworthily, the peak time for the pasting properties of refined wheat (496.4 s) and millet (kodo and little) flours (510 s) varied significantly ($p < 0.05$).

The difference between peak viscosity and trough viscosity is known as breakdown viscosity. It determines the degree of disintegration of swollen granules and influences the palatability of the final product. As shown in Fig. 3, the kodo flour sample had higher breakdown viscosity (318 mPa·s) compared to the little millet flour sample (271.3 mPa·s). This may be due to the rupturing and fragmentation of swollen starch in little millet four. Meanwhile, the refined wheat flour sample had maximum breakdown viscosity (485.1 mPa·s) due to its higher starch content.

The final viscosity signifies the capacity of starch to transform into thick paste after heating and cooling. The final viscosity was the highest in refined flour (1,744 mPa·s) and the lowest in little millet flour (1,121 mPa·s). Leached amylose and long-linear amylopectin's re-ordering, or polymerization, is substantially responsible for the setback and final viscosity. Pasting temperature implies a greater propensity for swelling or a lower level of resistance to swelling. Millet flour has higher pasting temperature due to its greater amylose content, phosphorous content, and granules size [11].

The pasting temperature was the highest in little millet flour (75.15°C) followed by kodo (60.97°C) and refined wheat (60.78°C). This demonstrated that millet flours have higher physicochemical values and greater granules size. These characteristics affect their

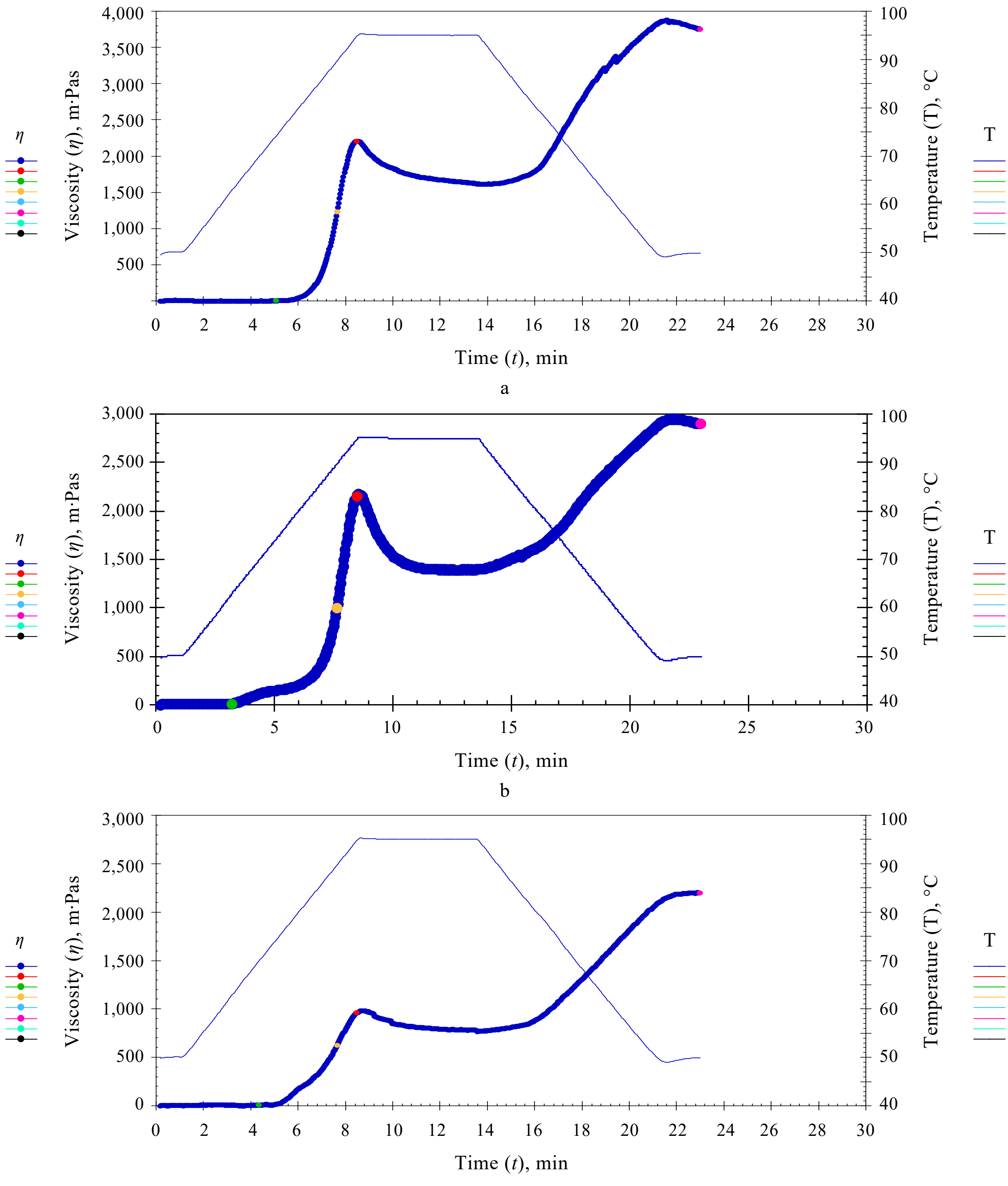


Figure 3 Pasting properties of refined and millet flours: a – refined wheat flour; b – kodo millet flour; and c – little millet flour

Table 4 Physical and functional properties of wheat and millet flours

Properties	Refined flour	Kodo flour	Little millet flour
Water absorption capacity, %	151.00 ± 1.16[a]	74.93 ± 2.86[b, c]	76.83 ± 3.38[b]
Oil absorption capacity, %	169.97 ± 3.38[a]	74.74 ± 3.00[c]	84.36 ± 3.27[b]
Bulk density, g/mL	0.57 ± 0.23[a, b]	0.55 ± 0.79[a, b, c]	0.70 ± 0.41[a]
Foaming capacity, %	13.02 ± 0.56[a]	8.01 ± 0.11[a, b]	8.24 ± 0.05[a, b]
Swelling index, g/g	0.42 ± 0.01[c]	0.54 ± 0.03[a]	0.47 ± 0.01[b]
Water solubility index, g/100 g	13.36 ± 0.55[a, b]	14.15 ± 1.27[b]	12.11 ± 0.36[c]

Means ± standard deviation (n = 3)

Superscripts [a, b, c] indicate significant difference ($p < 0.05$) between the values gelling capacity or retrogradation ability, which can be defined as a setback value. Setback viscosity determines the gelling capacity and retrogradation of flours and reflects the firmness of the final product in cooking. The highest setback values were recorded in kodo (–1,235 mPa·s), while the lowest were found in little millet (–784.3 mPa·s), contributing to higher water absorption and firm texture during cooking.

Physical and functional properties of millet flours. ***Density.*** Bulk density varies with the moisture content and particle size of the flour. Higher bulk density, which is common in composite flours, is preferred for food preparation as it helps in reducing the viscosity of the paste [31, 32]. The highest bulk density was exhibited by little millet flour (0.70 g/mL) followed by refined wheat flour (0.57 g/mL) and kodo millet flour (0.55 g/mL) (Table 4).

Water solubility and swelling. A significant amount of interaction on the starch chains between the amorphous and crystalline areas was demonstrated by the swelling ability and solubility of starch granules. The crystalline structure of starch relaxes as a result of heating in excess water, and the amylose and amylopectin groups form hydrogen bonds with water molecules. As a result, the granules swelling power and solubility rise (Table 4). The water solubility index measures the soluble solids dissolved in water after drying. This index was the highest in kodo millet flour (14.15 g/100 g) and the lowest in little millet flour (12.11 g/100 g). The swelling index may be defined as the swelling of flour after treatment with water. It was the highest in kodo (0.54 g/g) and the lowest in refined wheat flour (0.42 g/g). The lower swelling capacity and starch solubility may be due to structural disruption within the starch granules [33].

Water and oil absorption capacity. Water absorption capacity affects the physical, functional, and sensory characteristics of the food product. In our study, water absorption capacity showed slight variation between kodo and little millet flours (74.93 and 76.83 mL/100 g, respectively) but was significantly ($p < 0.05$) higher in refined flour (151.00 mL/100 g), as shown in Table 4. Water absorption capacity is affected by a high content of polar amino acids, the surface distribution of hydrophilic amino acids, the conformational characteristics of proteins, and their interactions with water. It is also influenced by the type of carbohydrates, higher solubility, the leaching of amylose, and the loss of structural crystallinity of starch in the flour [31]. Higher oil absorption capacity potentiates the protein's physical tendency to bind fat via capillary action. Oil absorption shows how non-covalent bonds, hydrophobic and electrostatic interactions, as well as hydrogen bonding have an effect on an amino acid profile, while covalent bonds, protein conformation and lipid-protein moiety interactions facilitate oil entrapment within the protein matrix thereby improving hydrophobicity, flavor, palatability, and shelf stability. Additionally, the interfacial film developed by proteins sustains air bubbles and reduces coalescence, contributing to foaming capacity and stability [34]. Conversely, refined flour showed the highest oil absorption capacity (169.97 g/100 g) probably due to the gelatinization of starch resulting in lipophilicity. Furthermore, gluten in wheat has higher affinity for oil [35].

Foaming capacity. Foaming capacity can be defined as the amount of interfacial area generated during the operation [31]. In our study, the foaming capacity varied from 8.00 to 13.02% for different flours. The highest value was exhibited by refined wheat flour (13.02%), followed by little (8.24%) and kodo (8.01%) millet flours (Table 4). The highest foaming capacity in refined wheat flour might be due to its higher protein content resulting in the increased formation of larger air bubbles.

Thermal properties of flours. The thermal properties of the wheat and millet flours are shown in Table 5. We found that kodo millet flour had significantly higher glass transition than little millet flour. This indicated high crystallinity and amylopectin concentration.

The high degree of crystallinity results in higher resistance to gelatinization, imparting structural stability [11]. Conversely, a reduction in the gelatinization temperature causes a breakdown of glycosidic bonds in starch [36, 37]. In our study, kodo millet flour had a higher transition temperature range denoting the stability of amorphous regions, with the branching chain having a lower degree than little millet flour.

Functional group analysis (FTIR). The functional groups identified using FTIR in different flours are shown in Fig. 4. The results revealed that both millet flours showed similar types of functional groups, with similar stretching and bending vibration. The O-H stretch region was identified in the spectra range of 3000–3600 cm^{-1}, which denoted the presence of hydroxyl groups in the samples. A peak at 800 cm^{-1} and 800 to 1500 cm^{-1} denoted the fingerprint region in the flours. The C-H stretching region in all the samples was found at peaks 2800 and 3000 cm^{-1}. The most frequently used IR spectral range in carbohydrate analysis was the anomeric region at 950 to 750 cm^{-1}. In that region, it was possible to distinguish bands characteristic of the A and B conformers, or pyranoid and furanoid ring vibrations of mono- and polysaccharides. At the right side of the peak, a C-H compound was observed in the millet flours at 2925 cm^{-1}. In the region of 1600–600 cm^{-1}, both millet flours had peaks that indicated the presence of primary amines. These results are in good agreement with the findings of Gull *et al.* [38], who reported similar trends in finger and pearl millet flours.

Table 5 Thermal properties of wheat and millet flours

Samples	Temperature, °C					ΔC_p, J/gK
	Peak	Onset	Inflection	End	Tf	
Refined flour	108.0	97.9	104.4	97.0	49.0	83.61
Kodo flour	98.6	78.2	91.6	72.9	118.2	76.60
Little flour	98.2	106.3	109.3	106.0	32.5	110.71

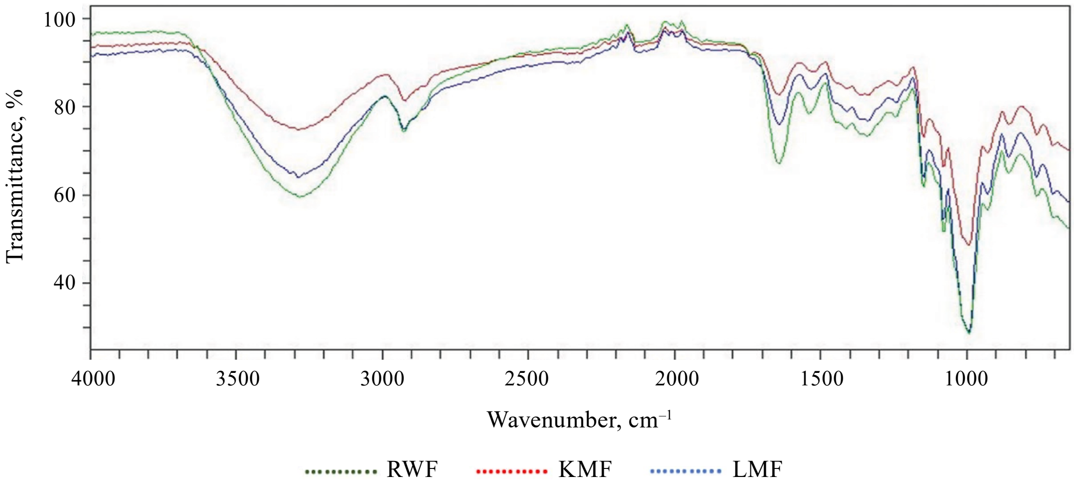


Figure 4 FTIR spectral patterns of different flours (RWF – Refined wheat flour; KMF – Kodo millet flour; and LMF – Little millet flour)

CONCLUSION

In this study, we investigated the physicochemical, nutritional, functional, rheological, and thermal properties of kodo and little millet flours compared to refined wheat flour used as a control. The millet flours exhibited higher nutritional properties than refined wheat flour. Little millet flour had higher protein and mineral contents than kodo and wheat flours, while kodo millet flour had a higher fiber content. Underutilized minor millet can be used to reduce the feeding load of the world's major cereals such as wheat, barley, psyllium, and oats. Future investigations can explore the storage stability of millet-based value-added food products and the *in vitro* and *in-vivo* bioavailability of the nutrients to affirm their regular consumption of these products in the human diet.

CONTRIBUTION

The authors were equally involved in writing the manuscript and are equally responsible for any potential plagiarism.

CONFLICT OF INTEREST

The authors declared no potential conflict of interest regarding the research, authorship, and/or publication of this article.

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