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Ultrasound-treated moringa leaf powder enhances nutritional quality and phytochemical properties of fermented finger millet–Bambara groundnut flour blends

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This study investigated the impact of ultrasonicated *Moringa oleifera* leaf powder (UMOLP) incorporation on the various food properties of fermented finger millet-Bambara groundnut flour (FFM-FBGN). Two groups (A and B) of composite flour were formulated, with the A-group and B-group composite flours having FFM and FBGN as their control samples, respectively. The protein, fibre, and ash contents after the addition of UMOLP to the A-group composite flour ranged from 8.81% to 11.40%, 3.08%–3.80%, and 2.13%–2.75%. In the B-group composite flour, the protein, fibre, and ash contents after the addition of UMOLP ranged from 13.60% to 16.46%, 5.40%–6.30%, and 2.73%–3.64%, respectively. The phytochemicals and antioxidant activity increased significantly as the levels of UMOLP increased in both groups of composite flours. Overall, the B6% composite flour, containing 70% FBGN, 24% FFM, and 6% UMOLP, exhibited superior nutritional quality (protein, fibre, and ash) and health-promoting compounds (total phenolic and flavonoid contents), making it a better option for use in food products to address the issues of malnutrition and non-communicable diseases.

KEYWORDS

composite flour, finger millet, moringa, phytochemicals, starch digestibility

1 Introduction

Finger millet (FM) is an important cereal grain grown by smallholder farmers mostly in eastern Africa and India (Devos et al., 2023). The grain contains higher fibre, mineral, and phytochemical contents than major cereals such as rice, maize, and wheat (Anuratha et al., 2024; Munshi and Dashora, 2024). Bambara groundnut (BGN) is a legume grain belonging to the family *Fabaceae*, *a* subfamily, Faboidea, and the genus Vigna (Ramatsetse et al., 2023; Khan et al., 2023). This grain is underutilised, especially in the food industry, despite its richness in protein (15%–25.5%), fiber (5.2%–6.4%), carbohydrate (49%–64.5%), minerals (2%), and essential amino acids such as lysine and methionine (Esan et al., 2023). This shows that BGN has the potential to address the issue of malnutrition and food insecurity, especially in African countries.

Moringa is a drought-tolerant, resilient tree with exceptional resistance to extreme temperatures (Fidyasari et al., 2024). This plant is said to have many health advantages, including hepatoprotective, anti-inflammatory, antioxidant, and antihypertensive qualities. Additionally, it has been linked to a decrease in hyperglycemia, indicating its antidiabetic property (Aljazzaf et al., 2022; Setyani et al., 2023). A recent study conducted by Leone et al. (2025) revealed that the consumption of 10 g of MOLP daily can positively control blood sugar levels in women suffering from type 2 diabetes. In another study by Amer et al. (2023), the intake of MOLP capsules reduced post-prandial blood glucose levels in diabetic patients. Previous studies have indicated that moringa leaves are rich in important bioactive compounds, such as flavonoids, phenolics, carotenoids, tannins, isothiocyanates, saponins, and vitamins (Hodas et al., 2021; Saleh et al., 2024). Thus, its therapeutic properties are widely recognized (Kumar et al., 2024). According to a recent study by Khalid et al. (2023), Moringa leaf powder is high in protein (26.23%) and contains all essential amino acids (Adewumi et al., 2022). Moringa leaf powder obtained from moringa plants in Dallo Mena and Goro, Ethiopia, was reported to contain fiber contents of 6.29% and 7.55%, respectively (Mengistu and Soboka, 2023). In a study conducted by Masitlha et al. (2024), it was reported that MOLP contains calcium, zinc, iron, sodium, aluminium, chromium, magnesium, manganese, 7.70, 15.50, 30.10, 0.8, 1.7, 0.02, 82.60, and 1.60 mg/100 g, respectively.

Food processing, however, is needed to make all these crops edible, palatable, safe, shelf-stable, and nutritious. Food processing methods include traditional (fermentation, germination, malting, etc.) and novel (ultrasonication, parboiling, etc.) food processing methods. Fermentation is an old food processing method that has always been used to produce nutritious fermented food products in developing countries (Zannou et al., 2022). Ultrasonication is one of the rapidly developing food processing methods to reduce processing time, improve quality, and ensure food safety (Majid et al., 2015). This method is based on the cavitation phenomenon, which causes the production, expansion, and collapse of gas bubbles, resulting in diverse chemical and mechanical consequences (Mudau et al., 2024). These effects improve nutritional and functional qualities by disturbing cellular and macromolecular structures, consequently enhancing the release and bioavailability of nutrients and bioactive compounds, and protein solubility. In this study, fermentation and ultrasonication were employed because they have been proven in our previous studies to enhance the functionality and nutritional compositions of FM and BGN (Mudau et al., 2024; Mudau and Adebo, 2025). Hence, fermented FM and BGN (FFM and FBGN) flours and ultrasonicated *Moringa oleifera* leaf powder (UMOLP) are being used in the formulation of multigrain flour, also known as composite flour (CF).

Composite flour (CF) technology, as applied in this study, could be defined as a technique of blending non-wheat flour with other cereal grain flours and legume flour to create high-quality food products while utilizing local raw materials cost-effectively (Chandra et al., 2015). Cereals and legumes are important parts of the human diet and nutrition, and their combinations have been used to make different products such as bread (Cacak-Pietrzak et al., 2023a; Cacak-Pietrzak et al., 2023b), biscuits (Pokharel et al., 2023; Arogundade et al., 2023), and crackers (Dizlek, 2023; Chatziharalambous et al., 2023). Sometimes cereals or legumes are combined with phytochemical-rich plants such as *M. oleifera* leaf powder (MOLP).

These combinations, prepared by mixing cereals and legumes or plants such as *M. oleifera* leaf powder in proper ratios, are aimed at providing high-quality products with the required amount of essential amino acids, minerals, protein, etc., to the consumer. The hypothesis of this study is that composite flours made from FFM, FBGN, and UMOLP will have higher nutritional content and functional qualities with the potential to address the issue of malnutrition and non-communicable diseases than single-flour controls. Hence, this study aims to develop nutritious composite flours from FFM-FBGN supplemented with UMOLP and evaluate their functional, nutritional, and phytochemical properties.

2 Materials and methods

2.1 Raw materials and chemicals

Raw materials (FM and BGN) used in this study were purchased from Sai wholesaler, Newtown, Johannesburg, South Africa. A pack (100 g) of *M. oleifera* leaf powder (MOLP) was procured from Clicks, while analytical-grade chemicals were procured from Merck Chemicals (PTY) Ltd., Germiston, South Africa.

2.2 Sample preparation

The grains (FM and BGN) were washed with distilled water to eliminate impurities and also to ensure purity in the final product. The washed grains were then spread on a tray covered with aluminium foil and dried at a controlled temperature (40 °C) for 24 h in an oven dryer. After drying, a platinum dry miller (KJ-1250, Castelfranco Veneto, Italy) was used to grind the grains into flours, which were then sieved using a 500 μm mesh sieve to ensure uniform particle size. The resulting flour was used for the fermentation process.

2.2.1 Fermentation and ultrasonication

The fermented flours were prepared through a controlled fermentation process following a method used by Kewuyemi and Adebo (2024). About 100 g of each flour (BGN and FM) was mixed with 0.40 g of the starter culture (*Lactococcus lactis* subsp. *Lactis,* CHN-22, CHR Hansen, Denmark) and sterilised distilled water in separate sterilised bottles. The fermentation process was allowed to run for 2 days (48 h) at 35 °C in an incubator. After fermentation, the samples were spread onto a tray, frozen, and subjected to the freeze-drying process for 24 h. After freeze-drying, the samples were milled again and kept in a ziplock bag in the refrigerator (4 °C) until further analysis. Regarding the ultrasound-treated MOLP, it was obtained using a slightly modified procedure followed by Mudau and Adebo (2025). About 30 g of MOLP was combined with 120 mL of distilled water in a 200 mL beaker. The beaker was held and placed into a 500 mL beaker filled with crushed ice that was on a stand within the sound enclosure. A titanium probe was placed 20 mm above the bottom of the sample-filled beaker, and the treatment began and ran for 15 min. After the ultrasound treatment, the mixture was then spread onto a tray and freeze-dried for 24 h. Following freeze-drying, the samples were kept in a ziplock bag in the refrigerator (4 °C) prior to further investigation.

TABLE 1 The blending ratio of composite flours made from finger millet, Bambara groundnut, and ultrasonicated *Moringa oleifera* leaf powder.

Samples	Finger millet (%)	Bambara groundnut (%)	UMOLP (%)
Control A	100	0	0
A0%	70	30	0
A2%	70	28	2
A4%	70	26	4
A6%	70	24	6
Control B	0	100	0
B0%	30	70	0
B2%	28	70	2
B4%	26	70	4
B6%	24	70	6

Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP). A2% = (70% FFM, 28% FBGN, 2% UMOLP). A4% = (70% FFM, 26% FBGN, 4% UMOLP). A6% = (70% FFM, 24% FBGN, 6% UMOLP). Control B = (100% FBGN), B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP). B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM, fermented finger millet flour; FBGN, fermented Bambara groundnut flour; UMOLP, ultrasonicated *Moringa oleifera* leaf powder.

2.3 Formulation of composite flours made from finger millet, Bambara groundnut, and ultrasonicated *Moringa oleifera* leaf powder

In this study, two groups (A and B) of composite flour were formulated, each having its own flour as a base (control), as shown in Table 1. In the A-group composite flours, fermented finger millet flour (FFM) was used as control A, and the blended flours consisted of 70% FFM and 30% fermented Bambara groundnut flour (FBGN), which was substituted with ultrasonicated *M. oleifera* leaf powder (UMOLP) at 2%,4%, and 6% levels of substitution. In the B-group composite flour, FBGN was used as a control B, and the blended flour was made of 70% FBGN and 30% FFM, which was substituted by UMOLP at 2%,4%, and 6% levels of substitution.

2.4 Functional properties

2.4.1 Oil/water absorption capacity

The oil and water absorption capacities (OAC and WAC) of the composite samples were measured using a procedure followed by Mahlanza et al. (2025). Approximately 1 g of flour was placed in a pre-weighed centrifuge tube and combined with 10 mL of vegetable oil or water. The mixture was completely vortexed and allowed to stand at room temperature for 30 min. The samples were then centrifuged at 3000 rpm for 25 min using an Eppendorf 5702 R (Sigma Aldrich, Johannesburg, South Africa). The supernatant (unabsorbed oil or water) was carefully decanted, and the sediment-filled tube was reweighed. The oil and water absorption capacity was then determined using the following formula:

$$Oil\ absorption\ capacity\ (g/g) = \frac{w3 - w2}{w1}$$

$$Water\ absoption\ capacity\ (g/g) = \frac{w3 - w2}{w1}$$

where: W1 = weight of the sample; W2 = weight of the centrifuge tube without sample; W3 = weight of the centrifuge tube with sample.

2.4.2 Bulk density

The bulk density of the composite samples was determined using the method described by Mudau et al. (2022). First, 10 g of the composite flours was weighed and transferred to a 25 mL measuring cylinder. The cylinder was gently tapped on the table many times until the sample settled and the volume stayed constant. The BD was estimated by dividing the sample's weight by its final volume.

2.4.3 Swelling capacity (SC)

To determine the swelling capacity of the composite samples, 10 mL of flour was added to a 100 mL measuring cylinder. Distilled water was then added until the total volume was 50 mL. To ensure thorough mixing, the top of the cylinder was tightly wrapped in foil and shaken many times. After 2 min, it was shaken again to ensure that everything was thoroughly combined. The mixture was then allowed to sit for 30 min so that the flour could settle. After settling, the ultimate volume of the inflated mixture was determined (Adebiyi et al., 2016).

2.5 Thermo-pasting properties

The same procedure detailed in our previous study (Mudau and Adebo, 2025) was applied to determine thermal and pasting properties of composite samples using the DSC 3 STAR^e System (CH-8606, Mettler Toledo, Greifensee, Switzerland) and a Rheometer (Anton Paar MCR 72, Ostfildern, Austria), respectively.

2.6 Starch fractions determinations

The rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) were determined using the slightly modified version of the method described by Rocchetti et al. (2020). After 20 and 120 min of incubation, the amount of glucose released was measured spectrophotometrically (Accuris SmartReader 96, model: MR9600, Jersey City, United States) using a D-Glucose assay kit, and the RDS and SDS were computed taking this into account. The resistant starch (RS) was measured using a K-RSTAR assay kit. The total starch content was estimated by adding non-resistant starch and RS, as per the instructions provided on the K-RSTAR assay kit.

2.7 Proximate composition

2.7.1 Moisture

The moisture content of the samples was analysed using the AOAC (2006) method 934.01.

2.7.2 Ash

The ash content of the composite flour samples was determined using the AOAC (2006) method 923.03.

2.7.3 Crude fat

The fat content of the samples was analysed using the AOAC (2006) method 920.39.

2.7.4 Crude fibre

The crude fibre content of the samples was determined using the AOAC (2006) method 990.03.

2.7.5 Crude protein

The protein content of the samples was analysed using the AOAC (2006) method 978.10.

2.7.6 Carbohydrate

The carbohydrate content of the samples was determined using the variation method (AOAC, 2006).

2.8 Phytochemicals and antioxidant activity

2.8.1 Extraction

The composite samples were extracted according to the procedure described by Arouna et al. (2020). In a 50 mL centrifuge tube, approximately 0.25 g of each flour sample was combined with 5 mL of methanolic acid solution (prepared by adding 1% HCl to 80% methanol). The tubes were agitated in an ultrasonic bath (AU 220, Argo Lab, Carpi, Italy) for a duration of 2 h. They were then centrifuged for 10 min at 4000 rpm using an Eppendorf 5702 R (Sigma Aldrich, Johannesburg, South Africa). The clear liquid (supernatant) was then transferred to 15 mL centrifuge tubes and used for further investigation.

2.8.2 Phytochemicals of composite flours

Composite samples' total phenolic content (TPC) was determined using a procedure outlined by Mahlanza et al. (2025). About 50 µL of Folin-Ciocalteu phenol reagent and 50 µL of 7.5% sodium carbonate were added to a 96-well microplate containing about 10 µL of the extract. The microplate wells wrapped with aluminium foil were then allowed to incubate for 30 min in the dark. Using an Accuris™ SmartReaderTM 96 (model: MR9600, Jersey City, United States), the combination in the microplate was read at 750 nm, and the absorbance readings were noted. Based on the gallic acid standard curve (0–0.2 mg/mL), the TPC values were expressed as a milligram of gallic acid equivalent per gram of the sample (mg GAE/g). The samples' total flavonoid content (TFC) was also examined using a technique proposed by Mahlanza et al. (2025). The extract was put into 96-microplate wells in an amount of approximately 10 µL. Then, 100 µL of 2% sodium hydroxide, 30 µL of 2.5% sodium nitrite, and 30 µL of 1.25% aluminium chloride were added. The entire solution and quercetin standard curve (0–2.0 mg/mL) were read at 450 nm using an Accuris™ SmartReaderTM 96 (model: MR9600, Jersey City, United States) (iMark; Bio-Rad Laboratories, Johannesburg, South Africa). Using the quercetin standard curve, the TFC was calculated and reported as milligrams of quercetin equivalent per gram of sample (mg QE/g).

2.8.3 Antioxidant activity of composite flours

In accordance with Sadh et al. (2017), the ABTS radical scavenging assay was used to assess the antioxidant capacity of the composite samples. Approximately 7.6 mM ABTS (19 mg in 5 mL), 2.6 mM potassium persulfate (3.5 mg in 5 mL), and an extra 5 mL of distilled water were mixed to create the ABTS stock solution. The $ABTS^+$ radical cation was produced by allowing this combination to react for 16 h at room temperature in the dark. For the assay, 200 µL of the working ABTS solution was mixed with 20 µL of the sample extract in a microplate well, and the mixture was left to incubate at room temperature for 1 minute. Using the Accuris™ SmartReaderTM 96 (model: MR9600, Jersey City, United States), the absorbance was measured at 734 nm against the blank. The following formula was used to get the percentage inhibition of ABTS:

$$\%\ \text{inhibition} = \left[(A - As)/A \right] \times 100$$

where: A = blank absorbance; A_s = extract absorbance.

2.9 Statistical analysis

Data collected from analyses conducted on the composite flours were analysed using IBM SPSS Statistics (New York, United States) version 27, and the results were presented as mean values ± standard deviation (SD). One-way analysis of variance (ANOVA) was used to determine significant differences among the mean values, and mean separation was performed using the Duncan multiple range test with a 95% confidence level ($P < 0.05$).

3 Results and discussion

3.1 Functional properties

The functional properties of moringa-enriched composite flours are shown in Table 2. Functional properties are those characteristics that indicate whether the flour is suitable for a specific purpose (Verem et al., 2021). In this study, the functional properties evaluated include bulk density (BD), water/oil absorption capacity (WAC/OAC), and swelling capacity (SC). In terms of BD, the replacement of 30% FFM with FBGN (A0%) and that of 30% FBGN with FFM (B0%) significantly decreased the BD of the composite flours. The BD further decreased as the UMOLP levels of

TABLE 2 Functional properties of moringa-enriched composite flours.

Sample	BD (g/mL)	WAC (g/g)	OAC (g/g)	SC (mL)
Control A	0.60 ± 0.02^{e}	1.95 ± 0.03^{a}	1.92 ± 0.04^{b}	17.10 ± 0.14^{a}
A0%	0.57 ± 0.01^{d}	2.05 ± 0.12^{ab}	1.84 ± 0.58^{a}	19.5 ± 0.10^{b}
A2%	0.54 ± 0.04^{c}	2.11 ± 0.04^{b}	1.85 ± 0.04^{a}	20.5 ± 0.13^{c}
A4%	0.51 ± 0.02^{b}	2.31 ± 0.12^{c}	1.84 ± 0.04^{a}	21.00 ± 0.16^{cd}
A6%	0.48 ± 0.02^{a}	2.38 ± 0.04^{c}	1.83 ± 0.02^{a}	21.90 ± 0.14^{d}
Control B	0.67 ± 0.21^{b}	2.53 ± 0.05^{b}	1.72 ± 0.02^{a}	24.5 ± 0.00^{d}
B0%	0.65 ± 0.62^{ab}	2.33 ± 0.02^{a}	1.78 ± 0.04^{b}	23.00 ± 0.03^{c}
B2%	0.64 ± 0.60^{ab}	2.31 ± 0.18^{a}	1.79 ± 0.12^{b}	22.35 ± 0.13^{ab}
B4%	0.63 ± 0.62^{ab}	2.32 ± 0.09^{a}	1.80 ± 0.04^{c}	21.90 ± 0.11^{a}
B6%	0.62 ± 0.60^{a}	2.32 ± 0.13^{a}	1.82 ± 0.02^{bc}	21.52 ± 0.13^{a}

Mean values within a column with different superscripts mean the values were significantly different ($p \leq 0.05$). Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP). A2% = (70% FFM, 28% FBGN, 2% UMOLP). A4% = (70% FFM, 26% FBGN, 4% UMOLP). A6% = (70% FFM, 24% FBGN, 6% UMOLP). Control B = (100% FBGN), B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP). B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM, fermented finger millet flour; FBGN, fermented Bambara groundnut flour; UMOLP, ultrasonicated *Moringa oleifera* leaf powder; BD = bulk density; WAC/OAC = water/oil absorption capacity; SC = swelling capacity.

supplementation increased in two groups (A and B) of composite flours. In the A-group composite flours, the BD ranged from 0.48 to 0.60 g/mL, with A6% having higher lower BD as compared to other composite flours and the control sample. In B-group composite flours, the BD ranged from 0.62 to 0.67 g/mL, with B6% having a lower BD as compared to the B-composite flours and the control. MOLP is rich in ash, protein, and fibre, all of which are known to have low densities compared to denser carbohydrates found in starches of cereals and legumes. So, the partial replacement of starchy flours with UMOLP could be the reason for the decrease of BD observed in UMOLP-containing composite flours. According to Padhi and Dwivedi (2022), BD is a critical component for the food industry in determining the requirements of packaging and material handling of food products.

The lower BD observed in the composite flours supplemented with UMOLP could be good for making weaning foods for babies with reduced bulk density (Mudau et al., 2022). The WAC of A-group flours increased significantly after the replacement of 30% FFM with FBGN (A0%) and further increased with the addition of UMOLP, with A6% having higher WAC as compared to the control sample and other composite flours. This could be due to FBGN and UMOLP added in the A-group composite flours having more hydrophilic groups to bind water molecules, as also shown in Table 1, that FBGN (control B) had higher WAC as compared to control A, which is FFM. However, in the B-group composite flours, the control sample, which is 100% FBGN, had higher WAC than composite flours, suggesting that BGN flour contained more hydrophilic groups than samples where FFM and UMOLP were added. These results contrast with those of Getachew and Admassu (2022), who observed a significant increase in WAC after the addition of MOLP to cereal-based composite flours.

In terms of the OAC, which is the ability of flour to absorb oil when the product is being processed, the control sample in the A-group composite flours had higher OAC as compared to samples supplemented with UMOLP. In the B-group composite flours, the replacement of 30% FBGN with FFM (B0%) and the addition of UMOLP to the composite flours (B2%, B4%, and B6%) further increased OAC. The increasing trend of OAC observed suggests the FFM and UMOLP added to the composite flours had more hydrophobic proteins with oil-binding properties. According to Mudau et al. (2022) and Chinma et al. (2022), the primary chemical factor influencing OAC is protein and nonpolar amino acid chains, including leucine and alanine, that interact with hydrocarbon lipid chains. Also, Higher OAC, as observed in B6% composite flour, is the required quality in the production of sausages and meat analogs where the retention of fat is desirable (Chandra, 2022). Swelling capacity (SC) is the ability of starch to absorb water, allowing the size of starch granules to swell when the inner structure is exposed to water (Gborie et al., 2022). In this study, the SC of composite flours increased as the addition of UMOLP increased in A-group composite flours, while in B-group composite flours, the addition of UMOLP decreased the SC of the flours. A similar decrease in the SC of composite flours supplemented with MOLP was also reported by Jude-Ojei et al. (2017). The discrepancies in SC of the composite flours might probably be due to the molecular arrangement changes in the starch granules, as also reported by Chandra (2022).

3.2 Thermal properties

The gelatinization temperatures [onset temperature (T_O), peak temperature (T_P), and conclusion temperature (T_C)] and gelatinization enthalpy (ΔH) of composite flours enriched with UMOLP are shown in Table 3. In terms of the gelatinisation temperatures, the replacement of 30% FFM with FBGN (A0%) and that of 30% FBGN with FFM (B0%) significantly decreased and increased the gelatinisation temperatures, respectively, as compared to their respective control samples. In the A-group composite flours, the T_O, T_P, and T_C ranged from 70.38 °C to

TABLE 3 Thermal properties of moringa-enriched composite flours.

Sample	To (°C)	Tp (°C)	Tc (°C)	ΔH (J/g)
Control A	84.77 ± 1.27^{e}	99.25 ± 0.33^{c}	112.03 ± 1.44^{bc}	845.79 ± 4.44^{c}
A0%	78.20 ± 2.50^{d}	95.63 ± 1.22^{ab}	111.75 ± 1.58^{bc}	832.28 ± 5.45^{bc}
A2%	75.58 ± 2.44^{c}	95.39 ± 1.40^{ab}	109.93 ± 1.35^{b}	790.78 ± 2.34^{b}
A4%	73.32 ± 1.22^{b}	91.65 ± 1.32^{b}	105.43 ± 1.45^{a}	791.52 ± 0.66^{b}
A6%	70.38 ± 1.78^{a}	87.37 ± 0.44^{a}	105. 27 ± 1.12^{a}	750.47 ± 0.64^{a}
Control B	78.15 ± 1.21^{ab}	102.77 ± 2.05^{ab}	116.17 ± 0.45^{d}	497.45 ± 5.56^{d}
B0%	82.38 ± 2.62^{bc}	105.07 ± 2.02^{c}	120.52 ± 1.04^{e}	445.31 ± 6.76^{c}
B2%	80.46 ± 1.60^{bc}	102.35 ± 1.18^{ab}	115.75 ± 1.12^{c}	434.75 ± 4.45^{ab}
B4%	76.93 ± 1.62^{a}	100.32 ± 1.09^{ab}	110.23 ± 2.04^{b}	299.41 ± 5.11^{a}
B6%	75.62 ± 1.60^{a}	98.21 ± 2.13^{a}	105.23 ± 2.02^{a}	252.21 ± 7.13^{a}

Mean values within a column with different superscripts mean the values were significantly different ($p \leq 0.05$). Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP). A2% = (70% FFM, 28% FBGN, 2% UMOLP). A4% = (70% FFM, 26% FBGN, 4% UMOLP). A6% = (70% FFM, 24% FBGN, 6% UMOLP). Control B = (100% FBGN), B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP). B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM, fermented finger millet flour; FBGN, fermented Bambara groundnut flour; UMOLP, ultrasonicated *Moringa oleifera* leaf powder; T_O, onset temperature; T_P, peak temperature; T_C, conclusion temperature; ΔH, gelatinization enthalpy.

84.77 °C, 87.37 °C–99.25 °C, and 105.27 °C–112.03 °C, respectively, with A6% having a lower T_O, T_P, and T_C *as* compared to the control sample. In the B-group composite flours, the T_O, T_P, and T_C ranged from 75.62 °C to 82.38 °C, 98.21 °C–105.07 °C, and 105.23 °C–120.52 °C, respectively, with B6% having a lower T_O, T_P, and T_C as compared to the control sample. It is important to note that all UMOLP-enriched composite flours, especially A6% and B6%, exhibited low gelatinization temperatures, probably because MOLP is known for having low starch content and higher dietary fiber levels as compared to cereals and legumes. According to Fidyasari et al. (2024), dietary fiber hinders starch gelatinization by water absorption capacity, making the fiber more accessible to absorb water. The low values of gelatinization temperatures in the composite flours represent the existence of abundant amylopectin chains, whereas higher values noticed in control A and B0% indicate lesser values of shorter amylopectin chains (Theophilus et al., 2021). According to a study conducted by Fidyasari et al. (2024), MOLP contained more amylopectin than amylose, which explained the decrease in gelatinization temperatures of moringa-enriched composite flours.

Flours with lower gelatinisation temperatures indicate a better capacity to hydrate and gelatinize than those with higher gelatinisation temperatures (Theophilus et al., 2021). Furthermore, flours with low gelatinization temperatures, as observed in this study, have also been reported to have good cooking quality (Mudau and Adebo, 2025). In terms of the ΔH of the composite flours, the replacement of 30% FFM with FBGN (A0%) and that of 30% FBGN with FFM (B0%) significantly decreased the ΔH, as compared to their respective control samples. The addition of UMOLP further decreased the ΔH value in both sets of the composite flours as compared to the control samples. This suggests that in both sets of flours, it required less energy to disrupt starch granule bonds, which could be due to the dilution effect (replacement of starchy food such as FFM and FBGN with UMOLP).

3.3 Pasting properties

The pasting viscosities of FFM-FBGN supplemented with UMOLP are presented in Figures 1A,B. Regarding the peak viscosity (PV) of both sets of composite flour, there was a significant increase in PV after the replacement of 30% FFM with FBGN (A0%), and that of 30% FBGN with FFM (B0%) significantly ($p \leq 0.05$) increased. However, after the addition of UMOLP, the PV of the composite flours started to decrease, which could be due to the dilution effect: replacing a portion of the primary flour (FFM-FBGN) with UMOLP. The increase of PV in A0% and B0% may be the result of the flour's higher starch content compared to the other samples, respectively. Additionally, this indicates that A0% and B0% have a higher thickening power than the other composite flours. The breakdown viscosity (BV) of the flours ranged from 1298 to 1851 cP and 492 to 983.5 cP, respectively, with A0% and B0% having higher BV than other samples. The BV measures how quickly the starch granules that are swollen can be disintegrated (Braşoveanu and Nemţanu, 2020). This means the lower BV observed in all samples containing UMOLP had a reduction in terms of the breaking rate of starch granules. It could be because MOLP has less starch content; hence, the lower BV was observed in samples enriched with MOLP. Additionally, it also implies that the starch content in composite flours with lower BV, such as those with UMOLP, can stabilize under temperate conditions.

Setback viscosity (SV) shows the retrogradation ability of starch, and it varied from 208.10 to 1391 cP and 290.9 to 775.1 cP in the A -and B-group composite flours, respectively. The higher SV was observed in A0% and B0%, while a lower SV was observed in control A (208.10 cP) and control B (290.90 cP). Composite flours, such as those of A0% and B0%, with increased SV, suggest that the amylose of the flours is highly likely to retrograde and form a gel, especially when the chains of amylose rearrange themselves as reported by Farasara et al. (2014). Since the composite flours enriched UMOLP

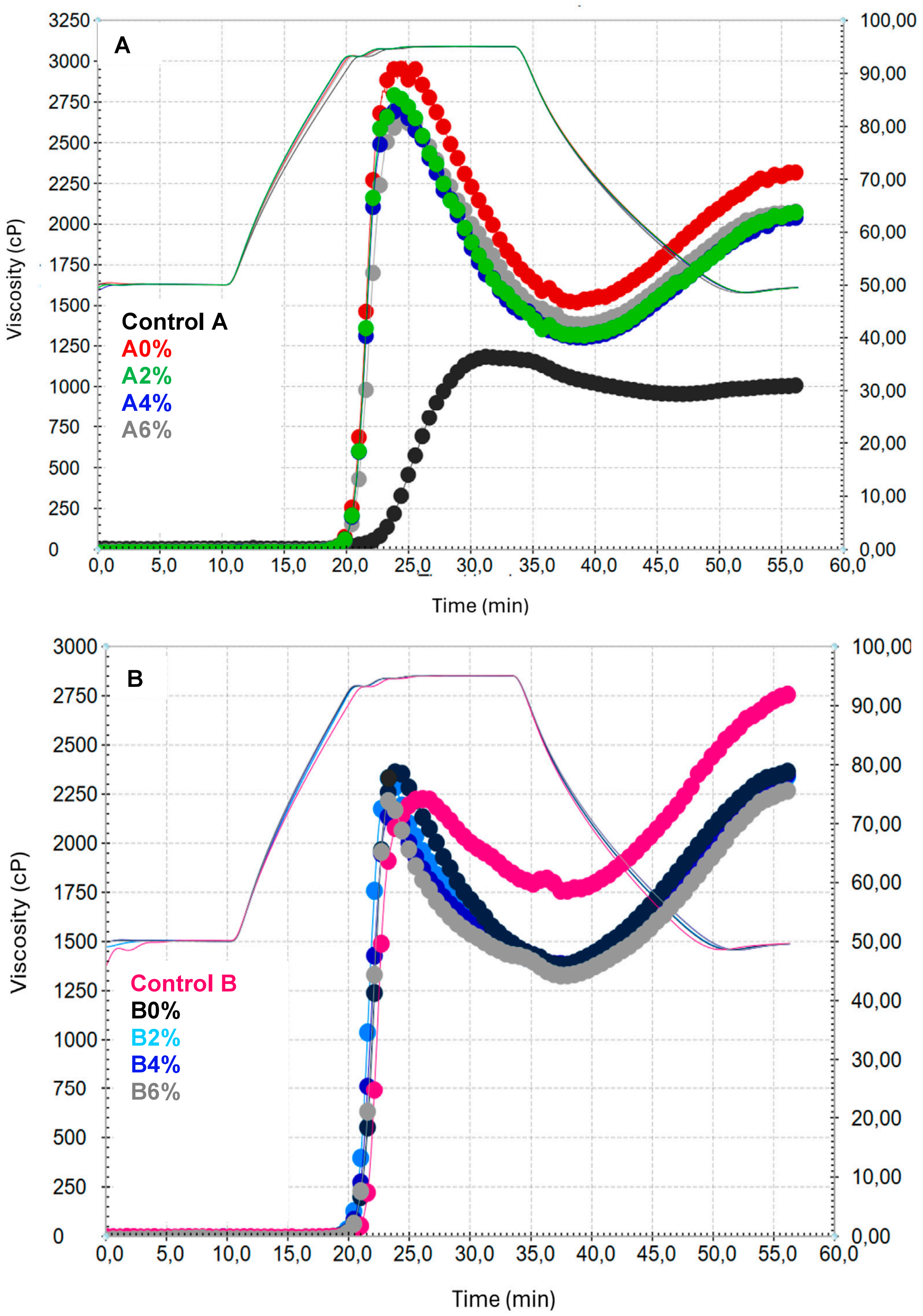

FIGURE 1
(A,B) Pasting curve of fermented finger millet-Bambara groundnut flours supplemented with *Moringa oleifera* leaf powder. key: Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP); A2% = (70% FFM, 28% FBGN, 2% UMOLP); A4% = (70% FFM, 26% FBGN, 4% UMOLP); A6% = (70% FFM, 24% FBGN, 6% UMOLP); Control B = (100% FBGN); B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP); B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM = fermented finger millet flour; FBGN = fermented Bambara groundnut flour; UMOLP = ultrasonicated *Moringa oleifera* leaf powder.

also had higher SV as compared to their respective control samples, it means that the flours have more ability to retrograde. Previous studies indicated that flours with higher SV can come in handy when preparing noodles and jelly foods (Mudau et al., 2022; Mudau and Adebo, 2025).

The final viscosity (FV) of the A- and B-group composite flours ranged from 975.70 to 1667 cP and 1353 to 1945 cP, respectively,

TABLE 4 Starch fractions of moringa enriched finger millet- Bambara groundnut flour.

Sample	RDS	SDS	TDS	RS
Control A	57.47 ± 0.20^{e}	12.66 ± 0.32^{a}	70.12 ± 0.44^{d}	4.23 ± 0.31^{d}
A0%	48.54 ± 0.11^{d}	14.03 ± 0.22^{b}	62.56 ± 0.58^{b}	3.71 ± 0.11^{bc}
A2%	46.72 ± 0.44^{c}	16.36 ± 0.40^{c}	63.08 ± 0.35^{c}	3.70 ± 0.22^{bc}
A4%	45.53 ± 0.22^{b}	16.62 ± 0.13^{c}	62.10 ± 0.45^{b}	3.53 ± 0.11^{b}
A6%	44.45 ± 0.22^{a}	16.89 ± 0.04^{c}	61.30 ± 0.02^{a}	3.32 ± 0.44^{a}
Control B	43.74 ± 0.21^{d}	13.61 ± 0.05^{b}	57.35 ± 0.45^{b}	3.81 ± 0.21^{e}
B0%	44.36 ± 0.62^{d}	11.27 ± 0.18^{a}	55.60 ± 0.04^{a}	3.72 ± 0.60^{d}
B2%	42.43 ± 0.60^{c}	15.78 ± 0.18^{c}	58.21 ± 0.12^{c}	3.59 ± 0.60^{c}
B4%	39.64 ± 0.62^{b}	18.12 ± 0.02^{d}	57.74 ± 0.04^{b}	3.29 ± 0.62^{b}
B6%	37.65 ± 0.60^{a}	19.36 ± 0.13^{de}	57.00 ± 0.02^{b}	3.04 ± 0.62^{a}

Mean values within a column with different superscripts mean the values were significantly different ($p \leq 0.05$). Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP). A2% = (70% FFM, 28% FBGN, 2% UMOLP). A4% = (70% FFM, 26% FBGN, 4% UMOLP). A6% = (70% FFM, 24% FBGN, 6% UMOLP). Control B = (100% FBGN), B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP). B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM, fermented finger millet flour; FBGN, fermented Bambara groundnut flour; UMOLP, ultrasonicated *Moringa oleifera* leaf powder; RDS, rapidly digestible starch; SDS, slowly digestible starch; TDS, total digestible starch; RS, resistant starch.

with B0% (1667 cP) and control B (1945 cP) having higher SV than other samples. In the A-group composite flours, samples containing UMOLP (A2%, A4%, and A6%) also had higher FV compared to their control sample. Higher SV observed in these samples suggests the ability to form a viscous paste compared to control A. It has been reported that FV represents the ability of flour to form a viscous paste (Nazni and Devi, 2016).

Concerning the peak time (pt) of the A- and B-group composite flour, control A and control B had significantly higher pt values of 31.1 and 26.2 min, as compared to other samples. The replacement of 30% FFM with FBGN (A0%), and that of 30% FBGN with FFM (B0%) reduced the pt values of the composite flours. Further reduction of pt values was also observed as the levels of UMOLP supplementation increased. This means less time was required to disintegrate the starch granules in the control samples than in the UMOLP-containing composite flours. As for the peak temperature (PT) of the composite flours, there was no significant difference ($p \leq 0.05$) noted.

3.4 *In vitro* starch digestibility of moringa-enriched finger millet-Bambara groundnut flour

The nutritional starch fraction contents of FFM-FBGN supplemented with UMOLP are reported in Table 4. In the A-group composite flour, the replacement of 30% FFM with FBGN (A0%) decreased and increased the levels of rapidly digestible starch (RDS) and slowly (SDS), respectively. A similar trend was also observed as the levels of UMOLP increased in the A-group composite flour, with A6% having a lower RDS and higher SDS levels than other samples. In the B-group composite flour, the substitution of 30% FBGN with FFM (B0%) significantly ($p \leq 0.05$) reduced the SDS while having no significant impact on the RDS. However, the addition of UMOLP in the B-group composite flour significantly ($p \leq 0.05$) decreased and increased the levels of RDS and SDS, respectively. B6% had lower and higher levels of RDS and SDS, respectively, than other samples.

According to Rocchetti et al. (2020), the RDS fraction causes a quick increase in blood glucose levels in humans, whereas the SDS fraction, which has delayed digesting capabilities, can give a prolonged release of glucose over time. This implies that the consumption of foods made from composite flours such as A6% and B6% with lower levels of RDS and higher levels of SDS can have several beneficial health implications, such as managing blood sugar levels and reducing the risk of insulin resistance. Furthermore, diets high in SDS have been associated with better metabolic profiles, notably enhanced lipid levels, and reduced risk factors for cardiovascular illnesses (Goux et al., 2020; Chisbert et al., 2024).

The mechanism by which UMOLP addition lowered the nutritional starch fraction amounts of composite flours might be attributed to a number of factors, including MOLP's nutrient and phenolic composition. MOLP is high in dietary fibre and protein (Fidyasari et al., 2024; Masitlha et al., 2024). The addition of fibre can change the dietary matrix, possibly encapsulating starch granules and reducing their accessibility to digestion enzymes (Rovalino-Córdova et al., 2019). Similarly, proteins may interact with starch, forming complexes that reduce the rate of starch hydrolysis (Yang et al., 2019). These interactions can lead to a decrease in RDS and an increase in SDS, promoting a more gradual release of glucose during digestion, as reported by Rocchetti et al. (2020). Moringa leaves also contain several phenolic compounds, including flavonoids and phenolic acids (Hamdy, 2024). These bioactive compounds are also known to inhibit starch-digesting enzymes such as α-amylase and α-glucosidase (Li et al., 2022). By inhibiting these enzymes, the breakdown of starch into glucose is slowed, contributing to a reduction in RDS and an enhancement of SDS content in the food product (Gómez-Maqueo et al., 2023).

Resistant starch (RS) is described as a specific fraction of starch not digested in the human small intestine but fermented in the large

TABLE 5 Some proximate compositions of moringa-enriched composite flours.

Sample	Moisture (%)	Protein (%)	Fibre (%)	Ash (%)
Control A	6.58 ± 0.15^{b}	7.40 ± 0.16^{a}	2.71 ± 0.21^{a}	1.66 ± 0.03^{a}
A0%	5.92 ± 0.23^{a}	8.81 ± 0.14^{b}	3.08 ± 0.20^{b}	2.13 ± 0.11^{b}
A2%	5.91 ± 0.16^{a}	9.76 ± 0.12^{c}	3.25 ± 0.16^{c}	2.33 ± 0.04^{c}
A4%	6.01 ± 0.32^{a}	10.58 ± 0.24^{d}	3.43 ± 0.14^{d}	2.44 ± 0.32^{d}
A6%	6.05 ± 0.33^{a}	11.40 ± 0.20^{e}	3.80 ± 0.15^{e}	2.75 ± 0.14^{e}
Control B	7.13 ± 0.10^{b}	21.24 ± 0.11^{e}	5.65 ± 0.27^{ab}	3.01 ± 0.03^{b}
B0%	5.81 ± 0.12^{a}	13.60 ± 0.23^{a}	5.40 ± 0.10^{a}	2.73 ± 0.04^{a}
B2%	5.91 ± 0.24^{a}	14.25 ± 0.24^{b}	5.59 ± 0.12^{ab}	2.83 ± 0.04^{a}
B4%	5.75 ± 0.23^{a}	15.15 ± 0.23^{c}	5.70 ± 0.16^{ab}	3.03 ± 0.10^{b}
B6%	5.80 ± 0.15^{a}	16.46 ± 0.23^{d}	6.30 ± 0.22^{c}	3.64 ± 0.02^{c}

Mean values within a column with different superscripts mean the values were significantly different ($p \leq 0.05$). Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP). A2% = (70% FFM, 28% FBGN, 2% UMOLP). A4% = (70% FFM, 26% FBGN, 4% UMOLP). A6% = (70% FFM, 24% FBGN, 6% UMOLP). Control B = (100% FBGN), B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP). B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM, fermented finger millet flour; FBGN, fermented Bambara groundnut flour; UMOLP, ultrasonicated *Moringa oleifera* leaf powder.

intestine with a number of claimed physiological effects (Oyeyinka et al., 2021; Bojarczuk et al., 2022; Guo et al., 2022). The RS content of the FFM-FBGN decreased with an increasing level of UMOLP addition, with the lowest value recorded in A6% (3.32%) and B6% (3.04%). The decrease in the RS of the composite flour with the addition of moringa could be due to the dilution effect: replacing a portion of the primary flour (FFM-FBGN) with UMOLP might have decreased the overall starch content in the composite flour. Since RS is a fraction of the total starch, its absolute amount may decrease due to this dilution. Similar observations where the addition of MOLP decreased the overall RS were also made in a study conducted by Rocchetti et al. (2020). It is worth noting that, while the RS content decreased in this study, the addition of UMOLP increased SDS, which is advantageous for glucose management since it allows for a slow release of glucose into the bloodstream during digestion.

3.5 Proximate compositions of fermented finger millet-Bambara groundnut flours enriched with ultrasonicated *Moringa oleifera* leaf powder

The proximate composition of moringa-enriched composite flours is shown in Table 5. The moisture content in the A- and B-group composite flours ranged from 5.91%–6.58% and 5.75%–7.13%, respectively, with both control samples having higher moisture content than their respective samples. The replacement of 30% FFM with FBGN (A0%), and that of 30% FBGN with FFM (B0%), and the addition of UMOLP to composite flours significantly decreased the moisture content. This means the composite flours with lower moisture content, such as A0% and B%, would be less prone to microbial attack than the control samples.

The protein content of both A-group composite flours increased significantly after the replacement of 30% FFM with FBGN (A0%), and with increasing levels of UMOLP addition. A6% had a higher protein content of 11.40% as compared to 7.40% of the control A. Regarding the B-group composite flour, the dilution of high-protein FBGN flour with the low-protein content of FFM flour in B0% decreased the protein content of the flour; however, after the addition of UMOLP, the protein content began to increase, as observed in B2%, B4%, and B6%. This increase in the protein content of the composite flours could be due to the inclusion of protein-enriched UMOLP. MOLP is known for having higher protein content than FM and BGN flour. Verem et al. (2021) also reported a similar increase in the protein content of composite flours after the addition of MOLP. The crude fibre content of the A- and B-group composite flours increased from 2.71% to 3.18% and from 5.65% to 6.30%, respectively, with A6% and B6% having higher crude fibre content. This could be so because MOLP is an excellent source of fibre as reported by Masitlha et al. (2024). A fiber-rich diet provides several health benefits, including aiding in the prevention or decrease of gastrointestinal disorders and potentially lowering the risk of type 2 diabetes and coronary heart disease (Mudau and Adebo, 2025). The ash level of the composite flour ranged from 1.66% to 2.75% in the A-group and 3.01%–3.64% in the B-group. A6% and B6% exhibited higher ash content than their respective control samples, indicating that moringa leaves are an excellent source of ash. It also implies that composite flours containing UMOLP will be high in mineral content. A similar increase in the ash content of composite flours after the addition of MOLP was also observed by Verem et al. (2021).

3.6 Phytochemicals and antioxidant activity of fermented finger-millet flour supplemented with *Moringa oleifera* leaf powder

The impact of ultrasonicated *Moringa oleifera* leaf powder (UMOLP) addition on the phytochemicals and antioxidant activity of two different groups (A and B) of FFM-FBGN composite flours is shown in Figure 2. The TPC and TFC of the

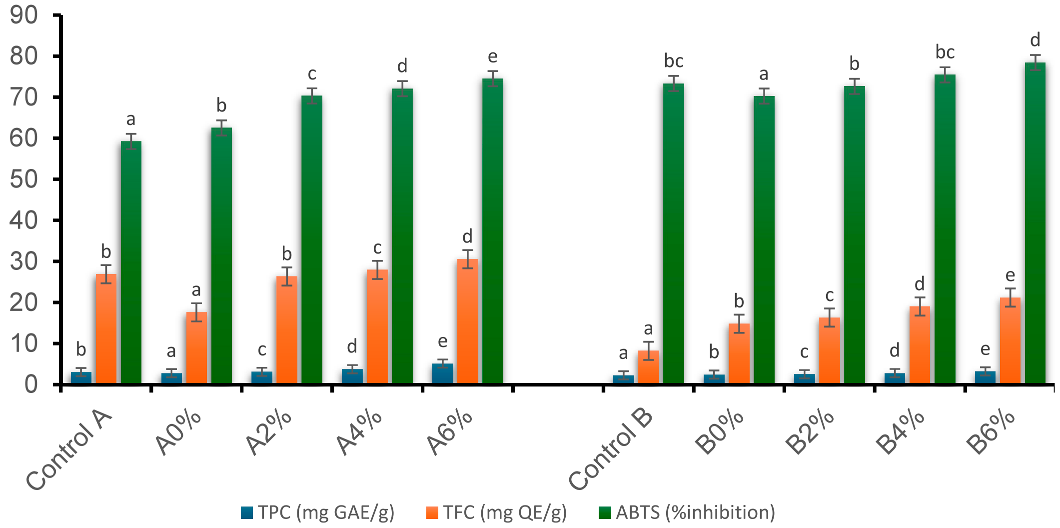

FIGURE 2
Phytochemicals and antioxidant activity of fermented finger millet-Bambara groundnut flours supplemented with ultrasonicated *Moringa oleifera* leaf powder. Different superscripts on top of the error bars mean the mean values were significantly different ($p \leq 0.05$). key: Control A = (100% FFM); A0% = (70% FFM, 30% FBGN, 0% UMOLP); A2% = (70% FFM, 28% FBGN, 2% UMOLP); A4% = (70% FFM, 26% FBGN, 4% UMOLP); A6% = (70% FFM, 24% FBGN, 6% UMOLP); Control B = (100% FBGN); B0% = (70% FBGN, 30% FFM, 0% UMOLP); B2% = (70% FBGN, 30% FFM, 2% UMOLP); B4% = (70% FBGN, 26% FFM, 4% UMOLP); B6% = (70% FBGN, 24% FFM, 6% UMOLP). FFM = fermented finger millet flour; FBGN = fermented Bambara groundnut flour; UMOLP = ultrasonicated *Moringa oleifera* leaf powder. TPC = total phenolic content; TFC = total flavonoid content; ABTS = 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid).

A-group composite flour decreased after the substitution of 30% FFM with FBGN flour (A0%), however, the substitution of FBGN with UMOLP at different levels of supplementation (A2%, A4%, and A6%) increased TPC of the composite, with A6% having higher TPC and TFC as compared to the control A sample.

The TPC and TFC of the composite flour increased in the B-group composite when 30% FBGN was substituted with FFM (B0%). These values were further increased when FFM was substituted with UMOLP at varying UMOLP supplementation levels in B2%, B4%, and B6%, with B6% having TPC and TFC as compared to their respective samples. Regarding the antioxidant activity (ABTS), a significant increment with the addition of UMOLP in the composite flours was also observed, with A6% and B6%, having higher ABTS content as compared to their respective control samples. It should be noted that the increase in the phytochemicals and antioxidant activity of the composite flour could be because MOLP is a rich source of phytochemicals with antioxidants as compared to cereals and legumes. According to a study conducted by Pakade et al. (2013), MOLP has almost twice the amount of TPC and TFC in vegetables such as spinach, cabbage, peas, cauliflower, and broccoli. A similar increase of TPC, TFC, and ABTS as the addition of moringa in wheat flour was also noted in a study by Fapetu et al. (2022).

4 Conclusion

In a bid to enhance the various food quality of the composite flour, most importantly the nutritional quality, *in vitro* starch digestibility, and health-promoting compounds, two sets of composite flours consisting of finger millet and Bambara groundnut as base flours were formulated, each containing 2%,4%, and 6% of UMOLP. In terms of the functional and thermos-pasting properties, the addition of UMOLP decreased the BD and gelatinization temperatures and pasting viscosities of the composite flours. As for the composite flour's starch fractions, adding UMOLP reduced its RDS and RS while boosting its SDS. The addition of UMOLP to both sets of composite flours enhanced their ash, fiber, and protein content. The TPC, TFC, and DPPH increased significantly as the levels of UMOLP increased in both groups of composite flours. Overall, the B6% composite flour, containing 70% FBGN, 24% FFM, and 6% UMOLP, exhibited superior nutritional quality and health-promoting compounds. Future studies should consider developing functional foods using B6% composite flour to address the issue of malnutrition and non-communicable diseases such as cancer, type 2 diabetes, and cardiovascular diseases.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MM: Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. OA: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adebiyi, J. A., Obadina, A. O., Mulaba-Bafubiandi, A. F., Adebo, O. A., and Kayitesi, E. (2016). Effect of fermentation and malting on the microstructure and selected physicochemical properties of pearl millet (*Pennisetum glaucum*) flour and biscuit. *J. Cereal Sci.* 70, 132–139. doi:10.1016/j.jcs.2016.05.026

Adewumi, O. O., Veronica, J., and Jideani, V. A. (2022). Functional properties and amino acid profile of Bambara groundnut and Moringa oleifera leaf protein complex. *Processes* 10, 205. doi:10.3390/pr10020205

Aljazzaf, B., Regeai, S., Elghmasi, S., Alghazir, N., Balgasim, A., Hdud Ismail, I. M., et al. (2022). Evaluation of antidiabetic effect of combined leaf and seed extracts of *Moringa oleifera* (*Moringaceae*) on alloxan-induced diabetes in mice: a biochemical and histological study. *Oxidative Med. Cell. Longev.* 2023, 9136217. doi:10.1155/2023/9136217

Amer, M., Fatima, S. A., Gondal, H. H. U. R., Iqbal, A., Warraich, B. I., Mehmood, A., et al. (2023). Impact of Moringa oleifera on the post-prandial blood glucose level among adults in Rawalpindi, Pakistan. *Int. J. Community Med. Public Health* 10, 3545–3549. doi:10.18203/2394-6040.ijcmph20233083

Anuratha, A., Krishnan, V., Chitra, M., Shibi, S., Tamilzharasi, M., Kamalasundari, S., et al. (2024). Comparative evaluation of nutritional quality attributes of millets in comparison with wheat and rice. *Appl. Ecol. Environ. Res.* 22, 4541–4561. doi:10.15666/aeer/2205_45414561

AOAC (2006). *Official methods of analysis. Proximate analysis, 17th edn.* Gaithersburg, MD: Association of Analytical Communities.

Arogundade, T. J., Oluwamukomi, M. O., and Dada, M. A. (2023). Nutritional qualities and antioxidant properties of ginger-flavored biscuits developed from wheat, bambara groundnut, and plantain flour blends. *Food Front.* 4, 407–419. doi:10.1002/fft2.203

Arouna, N., Gabriele, M., and Pucci, L. (2020). The impact of germination on sorghum nutraceutical properties. *Foods* 9, 1218. doi:10.3390/foods9091218

Bojarczuk, A., Skąpska, S., Khaneghah, A. M., and Marszałek, K. (2022). Health benefits of resistant starch: a review of the literature. *J. Functional Foods* 93, 105094. doi:10.1016/j.jff.2022.105094

Braşoveanu, M., and Nemţanu, M. R. (2020). Pasting properties modeling and comparative analysis of starch exposed to ionizing radiation. *Radiat. Phys. Chem.* 168, 108492. doi:10.1016/j.radphyschem.2019.108492

Cacak-Pietrzak, G., Sujka, K., Księżak, J., Bojarszczuk, J., and Dziki, D. (2023a). Sourdough wheat bread enriched with grass pea and lupine seed flour: physicochemical and sensory properties. *Appl. Sci.* 13 (15), 8664. doi:10.3390/app13158664

Cacak-Pietrzak, G., Sujka, K., Księżak, J., Bojarszczuk, J., Ziarno, M., Studnicki, M., et al. (2023b). Assessment of physicochemical properties and quality of the breads made from organically grown wheat and legumes. *Foods* 13 (8), 1244. doi:10.3390/foods13081244

Chandra, D. (2022). Evaluation of physicochemical and functional properties of composite flours blended with different ratios of moringa leaves powder. *Pharma Innovation J.* 11, 2024–2028.

Chandra, S., Singh, S., and Kumari, D. (2015). Evaluation of functional properties of composite flours and sensorial attributes of composite flour biscuits. *J. Food Sci. Technol.* 52, 3681–3688. doi:10.1007/s13197-014-1427-2

Chatziharalambous, D., Kaloteraki, C., Potsaki, P., Papagianni, O., Giannoutsos, K., Koukoumaki, D. I., et al. (2023). Study of the total phenolic content, total antioxidant activity and *in vitro* digestibility of novel wheat crackers enriched with cereal, legume and agricultural by-product flours. *Oxygen* 3, 256–273. doi:10.3390/oxygen3020017

Chinma, C. E., Ibrahim, P. A., Adedeji, O. E., Ezeocha, V. C., Ohuoba, E. U., Kolo, S. I., et al. (2022). Physicochemical properties, *in vitro* digestibility, antioxidant activity and consumer acceptability of biscuits prepared from germinated finger millet and Bambara groundnut flour blends. *Heliyon* 8, e10849. doi:10.1016/j.heliyon.2022.e10849

Chisbert, M., Castell, A. L., Vinoy, S., and Nazare, J. A. (2024). The impact of slowly digestible and resistant starch on glucose homeostasis and insulin resistance. *Curr. Opin. Clin. Nutr. Metabolic Care* 27, 338–343. doi:10.1097/MCO.0000000000001044

Devos, K. M., Qi, P., Bahri, B. A., Gimode, D. M., Jenike, K., Manthi, S. J., et al. (2023). Genome analyses reveal population structure and a purple stigma color gene candidate in finger millet. *Nat. Commun.* 14, 1–15. doi:10.1038/s41467-023-38915-6

Dizlek, H., and Dizlek, H. (2023). Development of novel and functional gluten-free cracker formulas by using diverse cereal, pseudo-cereal and legume flours. *J. Food Saf. Food Quality/Archiv für Lebensmittelhygiene* 74, 18. doi:10.31083/0003-925x-74-18

Esan, V. I., Oke, G. O., and Ogunbode, T. O. (2023). Genetic variation and characterization of Bambara groundnut [*Vigna subterranea* (L.) verdc.] accessions under multi-environments considering yield and yield components performance. *Sci. Rep.* 13, 1–19. doi:10.1038/s41598-023-28794-8

Fapetu, A. P., Karigidi, K. O., Akintimehin, E. S., Olawuwo, T., and Adetuyi, F. O. (2022). Effect of partial substitution of wheat flour with Moringa oleifera leaf powder on physical, nutritional, antioxidant and antidiabetic properties of cookies. *Bull. Natl. Res. Centre* 46, 53. doi:10.1186/s42269-022-00746-8

Farasara, R., Hariyadi, P., Fardiaz, D., and Dewanti-Hariyadi, R. (2014). Pasting properties of white corn flours of Anoman 1 and pulut harapan varieties as affected by fementation process. *Food Nutr. Sci.* 5, 2038. doi:10.4236/fns.2014.521215

Fidyasari, A., Estiasih, T., Wulan, S. N., and Khatib, A. (2024). The physicochemical, functional, and pasting properties of Moringa oleifera leaf powder from different leaf stalk colors. *CyTA-Journal Food* 22, 2402062. doi:10.1080/19476337.2024.2402062

Gborie, S. K., Mugabi, R., and Byaruhanga, Y. (2022). Effect of extrusion on the functional and pasting properties of high-quality cassava flour (HQCF). *J. Food Res.* 11, 1–12. doi:10.5539/jfr.v11n4p1

Getachew, M., and Admassu, H. (2022). Evaluation of functional and rheological properties of the composite flour from oat, wheat and moringa tree leaves. *Cogent Food and Agric.* 8, 2120009. doi:10.1080/23311932.2022.2120009

Gómez-Maqueo, A., Ferreira-Lazarte, A., Amirruddin, N. S., and Lin, A. H. M. (2023). Generating slow digestibility in cooked potatoes by modulating starch accessibility to α-amylase and mucosal α-glucosidase to different levels. *Food Hydrocoll.* 141, 108718. doi:10.1016/j.foodhyd.2023.108718

Goux, A., Breyton, A. E., Meynier, A., Lambert-Porcheron, S., Sothier, M., Van Den Berghe, L., et al. (2020). Design and validation of a diet rich in slowly digestible starch for type 2 diabetic patients for significant improvement in glycemic profile. *Nutrients* 12, 2404. doi:10.3390/nu12082404

Guo, J., Tan, L., and Kong, L. (2022). Multiple levels of health benefits from resistant starch. *J. Agric. Food Res.* 10, 100380. doi:10.1016/j.jafr.2022.100380

Hamdy, N. M. (2024). Exploring the anti-inflammatory potential of the polyphenolic compounds in Moringa oleifera leaf: *in silico* molecular docking. *Egypt. J. Basic Appl. Sci.* 11, 367–385. doi:10.1080/2314808x.2024.2347126

Hodas, F., Zorzenon, M. R. T., and Milani, P. G. (2021). Moringa oleifera potential as a functional food and a natural food additive: a biochemical approach. *An. Acad. Bras. Ciencias* 93, e20210571. doi:10.1590/0001-3765202120210571

Jude-Ojei, B. S., Lola, A., Ajayi, I. O., and Seun, I. (2017). Functional and pasting properties of maize 'ogi'supplemented with fermented moringa seeds. *J. Food Processing Technology* 8, 647. doi:10.4172/2157-7110.1000674

Kewuyemi, Y. O., and Adebo, O. A. (2024). Complementary nutritional and health promoting constituents in germinated and probiotic fermented flours from cowpea, sorghum and orange fleshed sweet potato. *Sci. Rep.* 14, 1987. doi:10.1038/s41598-024-52149-6

Khalid, S., Arshad, M., Mahmood, S., Ahmed, W., Siddique, F., Khalid, W., et al. (2023). Nutritional and phytochemical screening of *Moringa oleifera* leaf powder in aqueous and ethanol extract. *Int. J. Food Prop.* 26, 2338–2348. doi:10.1080/10942912.2023.2246685

Khan, M. M. H., Rafii, M. Y., Ramlee, S. I., Jusoh, M., Al Mamun, M., and Kundu, B. C. (2023). Molecular insight into genetic differentiation, population structure and banding pattern analysis of Bambara groundnut (*Vigna subterranea [L.] Verdc.*) linked with inter simple sequence repeats (ISSR). *Mol. Biol. Rep.* 50, 7619–7637. doi:10.1007/s11033-023-08693-x

Kumar, S., Murti, Y., Arora, S., Akram, W., Bhardwaj, H., Gupta, K., et al. (2024). Exploring the therapeutic potential of Moringa oleifera Lam. *Pharmacol. Res. - Mod. Chin. Med.*, 12, 100473, doi:10.1016/j.prmcm.2024.100473

Leone, A., Di Lello, S., Bertoli, S., Ravasenghi, S., De Amicis, R., Menichetti, F., et al. (2025). Moringa oleifera leaf powder enhances glycemic control in Sahrawi women with type 2 diabetes: findings from a 3-month unblinded randomized controlled trial. *PharmaNutrition* 31, 100434. doi:10.1016/j.phanu.2025.100434

Li, X., Bai, Y., Jin, Z., and Svensson, B. (2022). Food-derived non-phenolic α-amylase and α-glucosidase inhibitors for controlling starch digestion rate and guiding diabetes-friendly recipes. *LWT* 153, 112455. doi:10.1016/j.lwt.2021.112455

Mahlanza, Z. P., Bamidele, O. P., Oyeyinka, S. A., Wilkin, J., and Adebo, O. A. (2025). Enhancement of nutritional and functional properties in finger millet (*Eleusine coracana*) and cricket (*Acheta domesticus*) flours through traditional and novel processing methods. *Int. J. Food Sci. Technol.* 60, vvaf056. doi:10.1093/ijfood/vvaf056

Majid, I., Nayik, G. A., and Nanda, V. (2015). Ultrasonication and food technology: a review. *Cogent Food and Agric.* 1, 1071022. doi:10.1080/23311932.2015.1071022

Masitlha, E. P., Seifu, E., and Teketay, D. (2024). Nutritional composition and mineral profile of leaves of Moringa oleifera provenances grown in Gaborone, Botswana. *Food Prod. Process. Nutr.* 6, 3. doi:10.1186/s43014-023-00183-8

Mengistu, B., and Soboka, S. (2023). Nutritional quality analysis of different moringa provenance in bale, Southeast Ethiopia. *Int. J. Agric. Res. Innovation Technol. (IJARIT)* 13, 83–88. doi:10.3329/ijarit.v13i1.68053

Mudau, M., and Adebo, O. A. (2025). Effect of traditional and novel processing technologies on the thermo-pasting, microstructural, nutritional, and antioxidant properties of finger millet and Bambara groundnut flours. *Int. J. Food Sci. Technol.* 60, vvae037. doi:10.1093/ijfood/vvae037

Mudau, M., Ramashia, S. E., and Mashau, M. E. (2022). Mineral content, functional, thermo-pasting, and microstructural properties of spontaneously fermented finger millet flours. *Foods* 11, 2474. doi:10.3390/foods11162474

Mudau, M., Chinma, C. E., Ledbetter, M., Wilkin, J., and Adebo, O. A. (2024). Gas chromatography–mass spectrometry analysis of metabolites in finger millet and Bambara groundnut as affected by traditional and novel food processing. *J. Food Sci.* 89, 6394–6412. doi:10.1111/1750-3841.17337

Munshi, M., and Dashora, K. (2024). "Comparative study of physico-chemical composition, functional, morphological and pasting properties of major and minor millet flours as a gluten free alternative to wheat flour," *Measurement*, 16. 100202. doi:10.1016/j.meafoo.2024.100202

Nazni, P., and Devi, R. S. (2016). Effect of processing on the characteristics changes in barnyard and foxtail millet. *J. Food Process. Technol.* 7, 566. doi:10.4172/2157-7110.1000566

Oyeyinka, S. A., Oyedeji, A. B., Ogundele, O. M., Adebo, O. A., Njobeh, P. B., and Kayitesi, E. (2021). Infrared heating under optimized conditions enhanced thermal and swelling behavior of cowpea starch. *Int. J. Biol. Macromol.* 184, 678–688. doi:10.1016/j.ijbiomac.2021.06.129

Padhi, S., and Dwivedi, M. (2022). Physico-chemical, structural, functional and powder flow properties of unripe green banana flour after the application of refractance window drying. *Future Foods* 5, 100101. doi:10.1016/j.fufo.2021.100101

Pakade, V., Cukrowska, E., and Chimuka, L. (2013). Comparison of antioxidant activity of Moringa oleifera and selected vegetables in South Africa. *South Afr. Journal Science* 109, 1–5. doi:10.1590/sajs.2013/1154

Pokharel, A., Dangal, A., Karki, S., Lamichhane, S., Timsina, P., and Bohara, A. (2023). Study on the effect of different treatments on soy flour, and quality and sensory evaluation of prepared biscuits incorporated with oats and soy flour. *Legume Sci.* 5, e181. doi:10.1002/leg3.181

Ramatsetse, K. E., Ramashia, S. E., and Mashau, M. E. (2023). A review on health benefits, antimicrobial and antioxidant properties of Bambara groundnut (Vigna subterranean). *Int. J. Food Prop.* 26, 91–107. doi:10.1080/10942912.2022.2153864

Rocchetti, G., Rizzi, C., Pasini, G., Lucini, L., Giuberti, G., and Simonato, B. (2020). Effect of *Moringa oleifera* L. leaf powder addition on the phenolic bioaccessibility and on *in vitro* starch digestibility of durum wheat fresh pasta. *Foods* 9, 628. doi:10.3390/foods9050628

Rovalino-Córdova, A. M., Fogliano, V., and Capuano, E. (2019). The effect of cell wall encapsulation on macronutrients digestion: a case study in kidney beans. *Food Chem.* 286, 557–566. doi:10.1016/j.foodchem.2019.02.057

Sadh, P. K., Saharan, P., Duhan, S., and Duhan, J. S. (2017). Bio-enrichment of phenolics and antioxidant activity of combination of Oryza sativa and Lablab purpureus fermented with GRAS filamentous fungi. *Resource-Efficient Technologies* 3, 347–352. doi:10.1016/j.reffit.2017.02.008

Saleh, A., Suleiman, M. M., and Fatihu, M. Y. (2024). Phytochemical analysis of bioactive compounds in ethanol leaf extract of Moringa oleifera [Lam.]. *Sokoto J. Veterinary Sci.* 22, 76–86. doi:10.4314/sokjvs.v22i2.1

Setyani, W., Murwanti, R., Sulaiman, T. N. S., and Hertiani, T. (2023). Flavonoid from Moringa oleifera leaves revisited: a review article on *in vitro*, and *in silico* studies of antidiabetic insulin-resistant activity. *J. Adv. Pharm. Technol. Res.* 14, 283–288. doi:10.4103/JAPTR.JAPTR_290_23

Theophilus, M. I., Nkama, I., and Okafor, I. G. (2021). Comparative studies of the proximate, microscopic and thermal properties of processed maize, wheat, millet, cassava and Bambaranut flours. *J. Diabetes Cholesterol Metab.* 6, 140. doi:10.31080/ASNH.2023.07.1186

Verem, T. B., Dooshima, I. B., Ojoutu, E. M., Owolabi, O. O., and Onigbajumo, A. (2021). Proximate, chemical and functional properties of wheat, soy and moringa leaf composite flours. *Agric. Sci.* 12, 18–38. doi:10.4236/as.2021.121003

Yang, C., Zhong, F., Goff, H. D., and Li, Y. (2019). Study on starch-protein interactions and their effects on physicochemical and digestible properties of the blends. *Food Chemistry* 280, 51–58. doi:10.1016/j.foodchem.2018.12.028

Zannou, O., Agossou, D. J., Miassi, Y., Agani, O. B., Aisso, M. D., Chabi, I. B., et al. (2022). Traditional fermented foods and beverages: indigenous practices of food processing in Benin republic. *Int. J. Gastron. Food Sci.* 27, 100450. doi:10.1016/j.ijgfs.2021.100450