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RESEARCH ARTICLE

Effects of added resulting flours from heat-treated Bambara groundnut seeds on properties of composite Bambara groundnuts–wheat dough and bread

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Abstract

Background: This work determined the effect of compositing wheat flour with the resulting flour (15% and 30%) from heat-treated Bambara seeds on dough rheology and breadmaking properties. Bambara seeds (conditioned 53% moisture) were infrared or microwave heat (1200 W at 130°C) treated alone and in combination. Mixolab, Alveograph, and the creep and recovery test were used to determine the rheological properties of composite dough. A rheofementometer was used to elucidate composite dough behavior during proofing. Bread texture was determined using a texture analyzer and bread characteristics such as loaf volume and size were also determined.

Results: The results showed that the principal component analysis (PCA) explained 67.4% of variations, with Component 1 explaining 34.4% and Component 2 explaining 33%. From the PCA, mixolab parameters, such as WA, protein weakening, and starch behavior parameters (C3–C5), were a better predictor of composite dough behavior than the alveograph and the creep and recovery test. According to the PCA plot, samples composited with 15% Bambara groundnut flour from 53% moisture conditioning and heat treated with a combination of microwave and infrared closely resemble the wheat dough and bread.

Conclusion: PCA showed that composites made with flours from the 53% moisture-conditioned Bambara groundnut seeds and heat-treated using a combination of microwave and infrared were closer to wheat, particularly those composited with 15% Bambara groundnut flour.

Significance: This study provides the nutrient-dense Bambara groundnut flours from heat-treated seeds as a suitable alternative to improve the nutritional quality of composite wheat bread. The study also provides insight into the composite dough's rheological and bread physical properties.

KEYWORDS
Bambara groundnut, bread, composite dough, dough rheology, Mixolab

1 | INTRODUCTION

Bread, particularly white bread, is a staple and convenient food many people consume worldwide. It is energy-dense (about 288.58 kcal/100 g) (Alkurd et al., 2020) rather than nutrient-dense food as it is low in protein (8.6%–11.8%) and amino acid lysine (2.18 mg/g of protein) (Centenaro et al., 2007). The overconsumption of bread can also be related to the development of diet-related noncommunicable diseases, for example, type 2 diabetes (Bautista-Castaño & Serra-Majem, 2012). Bread is mostly made from wheat flour due to the viscoelastic properties of gluten (Maktouf et al., 2016). In sub-Saharan Africa, wheat production is lower than consumption, and there is an overreliance on wheat importation (Silva et al., 2023). The increase in demand for wheat is caused by several factors, such as population growth, urbanization, and economic growth, which contribute to the demand for wheat products such as bread. The Russia–Ukraine war is one example of the disadvantages of overreliance on wheat imports, and it may lead to food insecurity.

Bambara groundnut is an indigenous nutrient-dense legume/pulse in Africa, with its seeds having a nutritional value of ~367–414 kcal/100 mg energy and 16%–25% protein (Boateng et al., 2013). It is an underutilized indigenous legume rich in protein, minerals, and vitamins (Okafor et al., 2014). Bambara groundnut seed is also high in phosphorus, potassium, calcium, and iron minerals. Bambara protein is high in essential amino acids leucine and lysine (Arise et al., 2017; Okpuzor et al., 2010). Heat treatment of Bambara groundnut seed leads to changes in resulting flour characteristics. Heat treatment leads to starch gelatinization and protein–starch aggregation, which leads to low pasting viscosities of their flours and causes changes in functional properties (Mukwevho & Emmambux, 2022).

Wheat flour composited with flour from heat-treated Bambara groundnuts could have desirable changes in the dough's rheological properties, improve bread protein profile, and increase legume utilization. Traditionally, bread is made from wheat flour, and wheat gluten gives bread unique characteristics due to its viscoelastic properties (Maktouf et al., 2016). Wheat dough and bread quality characteristics are mainly influenced by wheat gluten. Adding whole-grain Bambara groundnut flour will also increase the fiber content of composite dough, leading to changes in dough behavior. When replacing wheat flour with non-gluten Bambara groundnut flour, it is expected that the rheological properties of composite dough will be altered, impacting the behavior of composite dough and the features of the bread.

Bread dough rheological measurements are to obtain quantitative data to predict bread performance. The proportion of Bambara groundnut flour to that of the ingredients will also determine the behavior during processing and bread textural quality (Abdualrahman et al., 2012; Erukainure et al., 2016). Developing the optimum formulation of all the ingredients will provide maximum benefits and produce composite bread of good quality.

Bread volume is associated with the viscoelastic properties of gluten and its gas retention capability during dough proofing and baking (Fido et al., 1997). Creep and recovery tests can measure small deformational changes within the linear viscoelastic range (LVR) in polymers when stress is applied and provide compliance. The linear viscoelastic region can be used for testing to understand dough's structural and rheological properties. Heat treatment changes the structural components of raw material, such as heat-treated Bambara groundnut, leading to the different behavior of the material under study. The amount of substitution needs to be appropriate, as it may weaken gluten proteins in wheat flour dough and result in the bread of low volume, and reduced physical but increased protein quality. Changes in starch granules and protein of substituted Bambara groundnut flour will lead to different behavior of the resulting dough.

To understand dough and baking performance, it is important to study the rheological properties of the composite wheat–Bambara groundnut flour dough because the insight gained from such studies will be essential to understanding the bread's quality. Furthermore, when the raw materials have been pretreated, there is an expectation that the resulting dough might exhibit different behavior, which may impact the final product's quality. This study was undertaken to determine the effects of infrared and microwave heat treatment (alone and in combination) of added flour (15% and 30%) from heat-treated Bambara groundnut seeds on wheat-Bambara groundnut dough rheological properties and physical characteristics of the resultant bread. The properties of the treated flours have already been reported in previous research chapters.

2 | MATERIALS AND METHODS

White bread wheat flour was obtained from a local retailer (Pretoria, South Africa). Bambara groundnut seeds were obtained from VKB Agriculture (Pvt) Ltd. The grains were cleaned to remove foreign material, and broken and shriveled seeds before use. Bambara groundnut seeds were soaked (53% moisture levels), and heat treatment (0 and 5 min) of Bambara groundnut seeds was conducted as previously described (Mukwevho & Emmambux, 2022). Bambara groundnut seeds (100 g) were soaked in distilled water for 24 h to reach a 53% moisture level. The resulting flours were stored at 4°C until the time of use. All treatments were done in triplicate. All reagents were of analytical grade.

2.1 | Dough rheology

2.1.1 | Mixing and pasting behavior by Mixolab

Bambara groundnut-wheat composites dough mixing and pasting behavior along with rheological analysis were performed using the Mixolab (Chopin, Tripette et Renaud) according to the standard option "Chopin+" protocol for ICC 173 (ICC Standards, 2011). In brief, a specified amount of flour was calculated using the Chopin+ standard protocol; the amount was then placed on the mixolab bowl and the mixolab program determined the amount of water to be added to the flour. The dough is then subjected to mixing and heating as determined by the software. The measured parameters were as follows: Water absorption capacity (WA), dough development time (DDT), dough stability, consistency at the maximum during dough development (C1), minimum torque of dough when subjected to mechanical and thermal constraints (C2), maximum torque during heating stage (C3), minimum torque reached during cooling to 50°C and also corresponds with the stability of hot starch paste (C4), and torque value corresponding to the final starch paste viscosity after cooling (C5).

2.1.2 | Alveograph

The Alveograph characteristics of composite dough were determined by the Alveograph device Chopin NG Alveograph at constant hydration following the AACC method 54-30 (1999). Alveograph parameters such as P-Tenacity, L-Extensibility, P/L ratio, G-Index of Swelling, and W for Baking Strength were automatically recorded by using Chopin Alveolink-NG software.

2.1.3 | Rheofermentometry

A Chopin Rheofermentometer (F3 Rheofermentometer Chopin) was used to detect the gas-release kinetics of dough during fermentation. The dough was prepared according to the CHOPIN protocol. The dough (315 g) was placed in the fermentation chamber and then covered with the optical sensor. The testing chamber was hermetically closed and a 2 kg weight constraint was applied; then, measurements were taken at 35°C for 180 min.

2.1.4 | Creep recovery test

For the creep and recovery tests, a 3 g dough was loaded onto a rheometer (Physica MCR101 model, Anton Paar GmbH) with a temperature control system and the parallel plate was lowered to a 2.0 mm gap. After resting, dynamic oscillatory frequency sweep at constant strain within the LVR (Sun et al., 2020; Yovchev et al., 2017). The dough samples were then subjected to stress ($\tau = 100$ Pa) for 150 s, which lay within the LVR. In the recovery phase, the stress was suddenly removed, and the sample was allowed for 180 s to recover the elastic (instantaneous and retarded) part of the deformation. The data from creep and recovery tests were modeled to the four- and three-parameter Burger's models, respectively (Lazaridou et al., 2007; Pérez-Quirce et al., 2017; Ronda et al., 2013). Concerning the calculated parameters, J_0 is the instantaneous compliance, J_1 is the retarded elastic or viscoelastic compliance, λ_1 is the retardation time, and η_0 is the steady viscosity (estimated from the creep step).

2.2 | Sodium dodecyl sulfate (SDS) sedimentation test

A procedure by Axford et al. (1979) was followed to determine the SDS sedimentation volume.

2.3 | Soluble and insoluble fiber analysis

The fiber was extracted enzymatically by the AOAC enzymatic–gravimetric method of Prosky et al. (2020). The dry sample was homogenized with 40 mL MES/TRIS (pH 8.2) solution and 50 μL α-amylase solution was added. Then, heating with a 95°C water bath was carried out. Afterward, the reactants were cooled at room temperature and washed with distilled water, adding protease solution in a 60°C water bath. It was mixed with 5 mL of 0.56 N HCl solution and adjusted at pH 4.0. After that, 200 μL of amyloglucosidase solution was added and stirred at a 60°C hot plate. To determine the insoluble fiber, the digestate was filtered using a glass filter with 1 g celite, and the filtrate was washed with 78% ethanol, 95% ethanol, and acetone. After overnight, the residue in the glass filter was weighed for the soluble fiber.

2.4 | Bread baking and analysis

2.4.1 | Preparation of bread samples

The bread formula for bread preparation follows the method by ICC official method (ICC 131) with some modifications: flour (200 g), margarine (10 g), sugar (8 g), salt (2 g), yeast (5 g), and water (100 mL for wheat bread and 110 mL for the composite bread). The ingredients were mixed for 15 min using a commercial mixer, and water was added based on the mixolab WA capacity calculation for flour. Fermentation was carried out in a 35°C fermentation cabinet for a total of 90 min at 80% relative humidity. The dough was rested for 10 min before kneading. The dough was baked in a preheated oven at 200°C for 25 min. Bread samples from 100% wheat flour served as control. Three batches each were produced for all bread samples. The analyses were carried out 1 h after bread preparation.

2.4.2 | Bread textural analysis

The bread was sliced manually, and crumb texture analysis was carried out in two slices (1.25 cm thickness each) from the center of the loaves. Texture profile analysis (TPA) was performed using an EZ Test (Shimadzu) texture analyzer equipped with a stainless-steel cylinder probe (P/20, 20 mm diameter). The pretest and posttest speeds were 5, 2.5, and 5 mm s^{-1}, respectively. The compression used was 40%, with a trigger force of 0.20 N, and the time between compression cycles was 5 s.

2.4.3 | Physical characteristics of bread loaves

The modified rapeseed displacement method was used to measure bread volume, with millet seed replacing rapeseed. Millet was used in place of rapeseed AACC method 10–05.01 (AACC, 2000). Loaf volume and weight data were used to calculate the bread-specific volume (Hallén et al., 2004). Loaf weight will be measured by a scale and volume-to-mass ratio was used to calculate the volume of loaves (Vouris et al., 2018).

2.5 | Statistical analysis

The statistical design was a 2 × 2 × 3 factorial design with two levels of flour replacement of 15% and 30%, moisture conditioning of 53%, and added flours from Bambara groundnut seeds that were heat-treated for 5 min using infrared, microwave treatment alone or in combination. Statistical analysis was performed using SPSS 28.0 statistical software for IBM (SPSS, Inc.). Multifactor analysis of variance was performed on the data, and means were compared at $p \leq .05$ using Fisher's least significant difference. The Student's t test was then used to analyze any significant differences in raw untreated Bambara groundnut and wheat flour. Principal component analysis (PCA) of the expression data was used to analyze for any correlation of experimental variables. The Origin software (Origin Pro 2011, Origin Lab Corp.) was used to perform nonlinear regression analyses.

3 | RESULTS AND DISCUSSION

3.1 | Dough rheology

3.1.1 | Mixolab

The addition of untreated Bambara groundnut flour to wheat flour increased the DDT and stability during the mixolab test (Figure 1). The addition of Bambara groundnut flour from heat-treated seeds significantly ($p < .05$) increased WA and DDT, and these increased with increasing Bambara groundnut flour addition from 15% to 30% when compared with the addition of flours from seeds that were not heat treated (Table 1 and Figure 1). The C2 (protein weakening during mixing and heating) value decreased with the addition of Bambara groundnut flour at both replacement levels (15% and 30%), suggesting protein weakening except for the microwave and combined heat-treated samples at 53% moisture level, where the torque increased. This suggests that these two treatments (the microwave and combined heat-treated samples at 53% moisture) have strengthened the composite dough protein network.

During C3 (Figure 2 and Table 1), starch has a greater influence and increased viscosity may be observed through increased torque. However, this increase in torque was lower for heat-treated flours when compared with wheat flour alone and the torque was lower as the level of flour inclusion was increased from 15% to 30% (Figure 2a,b). The addition of flour from heat-treated Bambara groundnut seed to wheat flour increased C4 (represents holding viscosity and amylase activity) compared with wheat alone for most samples except for 30% Bambara groundnut flour addition that was heat-treated seed at 53% moisture by microwave. A study by Erukainure et al. (2016) reported a low amylase activity as the Bambara groundnut replacement was increased in their study and this was attributed to Bambara groundnut starch having the ability to withstand

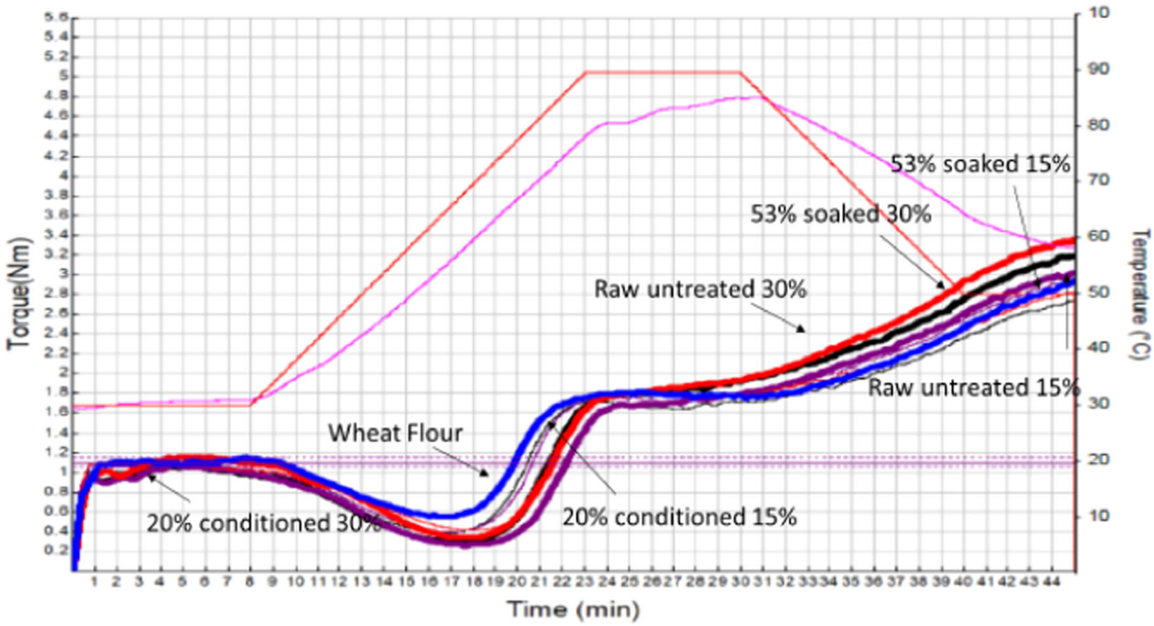

FIGURE 1 Mixolab curves of wheat and wheat-untreated Bambara groundnut composite flours. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Effects of compositing wheat flour with untreated 53% moisture and heat-treated Bambara on the mixolab parameters.

Moisture content	Heat treatment method	Flour replacement	WA (g/100 g)	DDT (min)	Stability (min)	C1 (Nm)	C2 (Nm)	C3 (Nm)	C4 (Nm)	C5 (Nm)
Wheat		0	64.5	7.6[a] (0.3)	9.6[a] (0.1)	1.0[a] (0.0)	0.5[a] (0.0)	1.7[a] (0.0)	1.5[b] (0.0)	2.5[b] (0.0)
Raw untreated		15	55	9.0[d] (0.1)	13.4[c] (0.2)	1.0[a] (0.0)	0.4[b] (0.0)	1.7[a] (0.0)	1.7[d] (0.0)	2.7[c] (0.1)
Raw untreated		30	50	9.1[c] (0.4)	13.0[c] (0.1)	1.1[ab] (0.0)	0.3c (0.0)	1.6b (0.0)	1.9e (0.0)	3.2e (0.1)
53%		15	54.5	9.2[c] (0.3)	12.4[b] (0.2)	1.0[ab] (0.0)	0.3[b] (0.0)	1.7[d] (0.0)	1.6[d] (0.0)	2.7[c] (0.0)
		30	49.3	8.4[ab] (1.4)	12.5[b] (0.0)	1.0[ab] (0.0)	0.2[a] (0.0)	1.6[c] (0.0)	1.9[e] (0.0)	3.2[e] (0.1)
	Infrared	15	57.6	9.4[d] (0.3)	12.7[c] (0.1)	1.1[ab] (0.0)	0.4[a] (0.0)	1.6[c] (0.0)	1.6[d] (0.0)	3.2[e] (0.5)
		30	52.6	9.1[c] (0.0)	12.3[b] (0.0)	1.1[ab] (0.0)	0.3[b] (0.0)	1.4[b] (0.1)	1.6[d] (0.0)	2.8[d] (0.1)
	Microwave	15	63.4	10.1[a] (0.1)	12.8[c] (0.2)	1.1[ab] (0.0)	0.5[d] (0.0)	1.6[a] (0.0)	1.5[c] (0.0)	2.6[c] (0.0)
		30	59.6	9.4[d] (0.2)	13.4[e] (0.2)	1.1[ab] (0.0)	0.5[d] (0.0)	1.4[c] (0.0)	1.1[a] (0.0)	2.1[a] (0.3)
	Combined	15	58.8	10.2[a] (0.1)	13.0[d] (0.1)	1.1[ab] (0.0)	0.5[d] (0.0)	1.6[c] (0.0)	1.6[d] (0.0)	3.0[e] (0.0)
		30	59	9.5[d] (0.2)	13.0[d] (0.1)	1.1[ab] (0.0)	0.5[d] (0.0)	1.4[b] (0.1)	1.4[b] (0.0)	2.5[b] (0.0)

Note: Means of three replicate experiments and SDs. Meaning of phases for wheat flour: C1 is used to calculate flour WA to achieve a given consistency during the constant temperature phase; C2 is an indication of protein weakening as a function of mechanical work and temperature; C3 is an indication of starch paste viscosity; C4 indication of the stability of the paste; C5 indication of starch retrogradation. Mean values in a column with different superscript letters differ significantly ($p < .05$).

Abbreviations: DDT, dough development time; WA, water absorption.

amylase activity better than wheat starch alone. Bambara groundnut flour, being whole grain, contains flavonoids (Harris et al., 2018) and some of the latter are known to bind to α-amylase and lower its activity (Tadesse et al., 2019; Takahama & Hirota, 2018).

Moreover, the heat treatment can inactivate enzymes as proteins were denatured during the microwave and infrared heat treatment. C5 represents retrogradation during cooling and final torque, where gelatinized amylose molecules in the dough begin to recrystallize. The addition of untreated

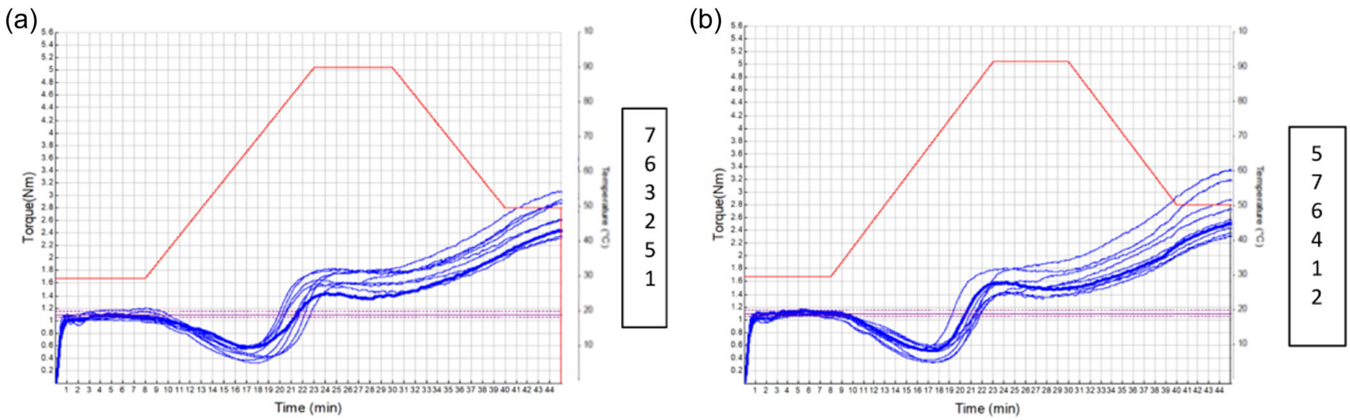

FIGURE 2 (a, b) Mixolab curves of wheat and wheat-untreated and heat-treated Bambara composite flours. (a) 53% moisture conditioning 15% Bambara flour addition; (b) 53% moisture conditioning 30% Bambara flour addition. The samples are labeled in order of appearance from top to bottom: 1, Wheat; 2, raw untreated; 3, 20% conditioned; 4, 53% conditioned; 5, infrared; 6, microwave; 7, combined. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Effects of compositing wheat flour with untreated; 53% moisture and heat-treated Bambara on the Alveograph dough rheological properties of the composite dough.

Moisture content	Heat treatment method	Flour replacement	(P, mm H_2O)	(L, mm)	(P/L)	(W, $J \times 10^{-4}$)
Wheat		0	86.6^{efh} (20.1)	91.3^{c} (6.2)	0.78^{cd} (0.3)	195.2^{a} (21.1)
Raw untreated		15	73.7^{de} (18.8)	69.6^{a} (7.3)	2.1^{d} (0.5)	70.0^{ef} (6.6)
Raw untreated		30	49.6^{b} (6.4)	55.9^{a} (6.8)	0.9^{f} (0.2)	91.0^{c} (10.0)
53%		15	69.6^{c} (6.2)	63.1^{c} (6.2)	1.8^{de} (0.3)	80.1^{d} (6.4)
		30	43.8^{b} (5.8)	53.2^{c} (14.5)	1.4^{e} (0.1)	48.4^{fh} (7.5)
	Infrared	15	87.4^{h} (8.9)	22.1^{e} (3.1)	4.0^{a} (1.2)	86.7^{b} (14.7)
		30	72.2^{de} (7.8)	22.3^{e} (2.2)	3.2^{c} (1.1)	61.4^{h} (10.7)
	Microwave	15	51.4^{bc} (4.7)	22.7^{e} (1.4)	2.2^{d} (0.4)	79.2^{h} (4.7)
		30	61.4^{cd} (5.2)	20.5^{e} (1.5)	2.9^{c} (0.9)	47.8^{fh} (5.0)
	Combined	15	75.7^{ed} (7.4)	25.1^{de} (1.4)	3.0^{bc} (0.5)	76.8^{ef} (6.3)
		30	61.8^{cd} (5.1)	20.3^{e} (1.3)	3.1b^{c} (0.4)	48.5^{fh} (4.9)

Note: Means of three replicate experiments and SDs. Mean values in a column with different superscript letters differ significantly ($p < .05$).
Abbreviations: L, extensibility; P, tenacity; P/L, curve configuration ratio; W, deformation energy.

Bambara groundnut flour significantly reduced the toque for C5 at 30% flour addition more than for the 15%.

3.1.2 | Alveograph

The addition of Bambara groundnut flour (untreated and heat-treated) to wheat flour significantly ($p < .05$) reduced the dough extensibility (L), while tenacity (P) improved with a 15% addition of heat-treated Bambara groundnut flour (Table 2 and Figure 3). Atudorei, Stroe, et al. (2021) reported reduced dough extensibility by adding germinated bean flour. Dough extensibility is associated with a well-developed gluten network, and the inclusion of Bambara groundnut flour caused the dilution effect of the gluten. The Bambara groundnut fiber may also have increased competition for available water. Both reasons are later discussed in further detail.

The deformation energy (W) of the composite Bambara groundnut-wheat dough increased with 15% flour replacement but significantly decreased when Bambara groundnut flour compositing increased to 30%, possibly due to the dilution effect of the dough. Atudorei, Atudorei, et al. (2021) reported a decrease in W value with the inclusion of germinated bean flour. Cappelli et al. (2020) study replaced wheat with 5 10% and 15% chickpea flour and reported a decrease in W value as the percentage of substitution increased. The

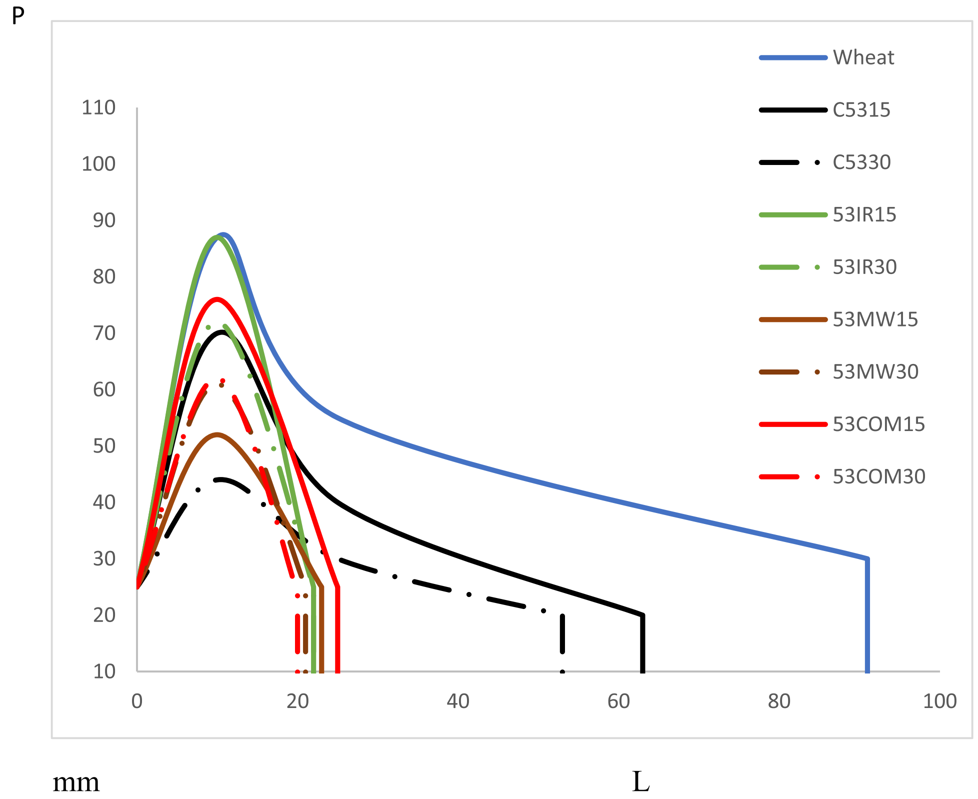

FIGURE 3 Effects of compositing wheat flour with untreated; 53% moisture and heat-treated Bambara on the Alveograph dough rheological properties of the composite dough; RUT15, raw seeds and 15% replacement; RUT30, raw seeds and 30% replacement; C5315, 53% moisture and 15% replacement; C5330, 53% moisture and 30% replacement; 53IR15, infrared and 15% replacement; 53IR30, infrared and 30% replacement; 53MW15, microwave and 15% replacement; 53MW30, microwave infrared and 30% replacement; 53COM15, combined and 15% replacement; 53COM30, combined and 15% replacement. [Color figure can be viewed at wileyonlinelibrary.com]

alveogram of composite flours with 15% added flour fraction from infrared heat-treated seeds seemed the closest to wheat reference among composite samples.

3.1.3 | Rheofermentometer

As expected, in general, Bambara groundnut flour addition to wheat flour significantly ($p > .05$) decreased rheofermentometer values in terms of Maximum dough height and Maximum height of gaseous production, with the increase in flour replacement level (15% and 30%) (Supporting Information S1: Table S1). The gas retention progressively decreased with the increase in flour replacement from 15% to 30%. The lowest reduction was in the infrared heat-treated samples at 15% and 30% replacement levels. Dough height (Hm) decreased with the increasing proportion of Bambara groundnut flour inclusion for the flours from 53% moisture level. However, the 15% replacement increased while the 30% replacement decreased, indicating the gluten dilution effect of the dough. The time of maximum gas formation (T'1) increased with the inclusion of heat-treated Bambara groundnut flours, especially in flour at 30% replacement.

The peak time of CO_2 production (T′1) ($p > .05$) increased for all treatments compared to wheat dough alone. Among the composite samples, peak CO_2 production (T′1) decreased for dough composited with 53% moisture-conditioned Bambara groundnut flour. This may indicate that adding Bambara groundnut flour decreased the movement of gas through the dough. However, this may also result from the low rate and amount of fermentation. The Tx value representing the time gas starts to escape from the dough showed a significant increase with the addition of Bambara groundnut flour ($p < .05$), suggesting that the composite dough retains less gas than wheat dough. Bojňanská et al. (2021) used a Rheofermentometer to study the fermentation behavior of composite dough of legumes and wheat. They indicated that the addition of legume flour resulted in a reduced capacity to hold and maintain the highest gas volume in the composite dough. However, this was related to the level of replacement.

3.1.4 | Creep and recovery

The results from the creep and recovery of the composite dough were fitted to the Burges model (Supporting Information S1: Table S2). The doughs showed acceptable viscoelastic creep behavior, and the Burgers model fitted well ($r^2 > 0.99$). Bambara groundnut addition significantly ($p < .05$) decreased the instantaneous shear compliance (J_0) dough compliance compared with wheat flour dough (Figure 4). Struck et al. (2018) found similar results when they replaced wheat with dried black currant pomace flour. The decrease has been associated with reduced dough elasticity as composite dough becomes rigid (Chompoorat et al., 2013). The addition of Bambara groundnut flour at 15% led to a significant reduction in composite dough elastic compliance (J_1) and this was further reduced with Bambara groundnut addition at 30%. Untreated and treated Bambara groundnut addition caused a reduction in elasticity.

The zero-shear viscosity (η_0) was significantly reduced with Bambara groundnut (treated and untreated) and increased with increasing flour replacement (15%–30%) ($p > .05$) and was higher for flours from 53% moisture-conditioned seeds. Adding Bambara groundnut flour may further support the reduction in zero shear viscosity. The retardation time (λ) increased with the addition of Bambara groundnut flour and seemed to increase more when heat-treated and untreated samples were added. Instantaneous compliance significantly decreased with increased Bambara groundnut flour addition when flours from 53% moisture conditioning were added. Adding treated and untreated Bambara groundnut flour reduced Jr_0 (elastic compliance during recovery). The addition of Bambara groundnuts also led to a reduction in the Jr_1 viscoelastic compliance. A similar reduction trend existed between composite dough's creep and recovery compliance (Figure 4). During the recovery phase, there was a decrease in compliance with the increase in the addition of Bambara groundnut flour. The instantaneous shear compliance, retard elastic compliance had a behavior similar to the creep phase, i.e., it behaved the same way as in the creep phase. Similar results were observed by Struck et al. (2018). There was a decrease in recovery with an increase in Bambara groundnut flour addition from 15% to

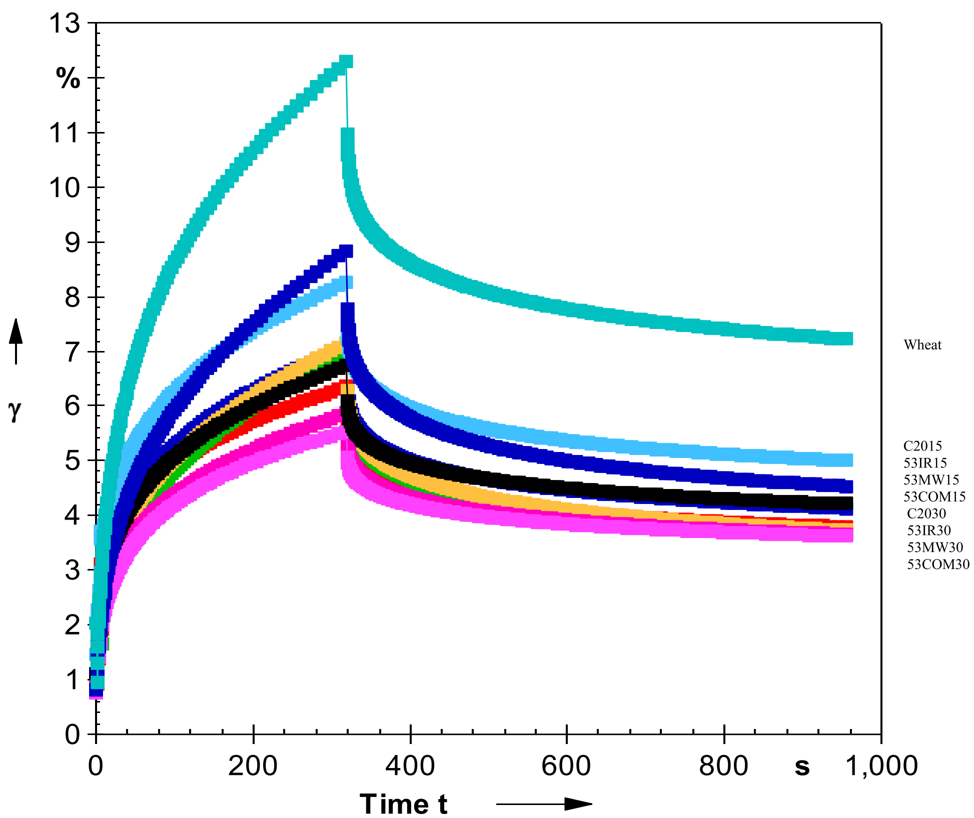

FIGURE 4 Effects of compositing wheat flour with untreated; 53% moisture and heat-treated Bambara on the creep and recovery dough rheological properties of the composite dough. RUT15, raw seeds and 15% replacement; RUT30, raw seeds and 30% replacement; C5315, 53% moisture and 15% replacement; C5330, 53% moisture and 30% replacement; 53IR15, infrared and 15% replacement; 53IR30, infrared and 30% replacement; 53MW15, microwave and 15% replacement; 53MW30, microwave infrared and 30% replacement; 53COM15, combined and 15% replacement; 53COM30, combined and 30% replacement. [Color figure can be viewed at wileyonlinelibrary.com]

30%, while untreated flours had a lower recovery than those from seeds that received heat treatment.

3.2 | Physical properties of bread

The addition of Bambara groundnut flour decreased the loaf volume of composite bread. Among the composite samples, bread volume was highest in the infrared heat-treated samples, followed by microwave, while the untreated samples had low bread volume. Composite bread made from infrared heat-treated samples of the 53% moisture-conditioned seeds had higher loaf volume than bread from the microwave and combined heat-treated samples.

3.2.1 | TPA

Adding Bambara groundnut flour significantly ($p < .05$) increased the crumb firmness of composite bread. Composite breads formulated using raw untreated flours had the highest crumb firmness (42.6). Dough formulated using heat treatment flours resulted in significantly lower crumb firmness values ($p < .05$) in untreated Bambara groundnut flours. As such, there were no significant differences among the breadcrumb adhesiveness values in this study ($p < .05$).

Flour addition from heat treatment of Bambara groundnut seeds significantly increased ($p < .05$) bread springiness in composite bread compared with flours from untreated seeds. Composite bread made from infrared heat-treated Bambara groundnut flours showed higher springiness, which was better than microwaved bread. Wheat had the highest crumb springiness value (210.7) and the lowest was in the raw untreated flours (40.09). The highest value (178.5) among the composite bread was in the 53% moisture-conditioned combined heat treatment at the 30% replacement level.

3.2.2 | PCA analysis

PCA analysis was performed to study the relationship of the variance between dependent variables of dough and bread analysis data for wheat and its Bambara groundnut composites. The results showed that the PCA explained 67.4% of variations, with Component 1 explaining 34.4% and Component 2 explaining 33%. Furthermore, Components 1 and 3 (Supporting Information S1: Figure S1) explained 42.9% of the variations, whereas Component 3 explained 8.5% of the variations. From the PCA, mixolab parameters, such as WA, protein weakening, and starch behavior parameters (C3–C5), were a better predictor of composite dough behavior than the alveograph and the creep and recovery test. This may be related to mixolab's ability to show the WA of flours, protein weakening, and dough starch behavior. Protein weakening (C2) is associated with the dilution of gluten and perhaps the competition of the available water during dough development and subsequent baking. Composites made with Bambara groundnut flours that did not receive heat treatment clustered far from wheat, while composites with 15% replacement clustered together. According to the PCA plot, samples composited with 15% Bambara groundnut flour from 53% moisture conditioning and heat treated with a combination of microwave and infrared closely resemble the wheat dough and bread. Overall, samples with 15% Bambara groundnut flour addition clustered closer to the wheat sample than those with 30% Bambara groundnut flour added (Figure 5).

Overall, mixolab parameters were a better predictor for bread properties, and flour WA indicated an improvement in the specific volume and firmness of bread. The higher WA is due to low soluble flour solids from heat-treated Bambara groundnut seeds, as evidenced by low solubility indices (nitrogen and water). In a previous study, Bambara groundnut flour showed an increase in WA capacity with an increase in heat treatment and time of treatment (from 0, 5, and 10 min), but there was a reduction in nitrogen and water solubility indices (Mukwevho & Emmambux, 2022).

The addition of Bambara groundnut flour resulted in the dilution effect of wheat gluten. It reduced the composite dough's viscoelastic properties in terms of protein weakening (C2) and starch paste viscosity (C3), Extensibility (L), Maximum dough height (Hm), instantaneous elastic compliance(J_0), zero-shear viscosity (η_0) (Tables 1 and 2; Supporting Information S1: Tables S1, S2, S4; and Figures 1–3). The addition of Bambara groundnut flour negatively affected composite bread's properties compared to reference wheat bread (Supporting Information S1: Table S4 and S5). Wheat proteins can be classified as glutenins with a high amount of disulfide bonds and gliadins, which are monomeric, giving dough viscosity components, while glutenins give the dough elasticity (Jia et al., 2020; Popineau et al., 1994). Bambara groundnut proteins are mainly globulins made up of trimeric vicilin of about 170 and a 385 kDa legumin hexamer and water-soluble albumins (Amonsou et al., 2011; Arise et al., 2017; Diedericks et al., 2019). Bambara groundnut proteins do not possess viscoelastic behavior compared to wheat gluten. Thus, although the addition of Bambara groundnuts caused an increase in protein content in dough and bread, it had a negative impact on the dough's viscoelasticity and bread's quality. This is due to the gluten dilution effect.

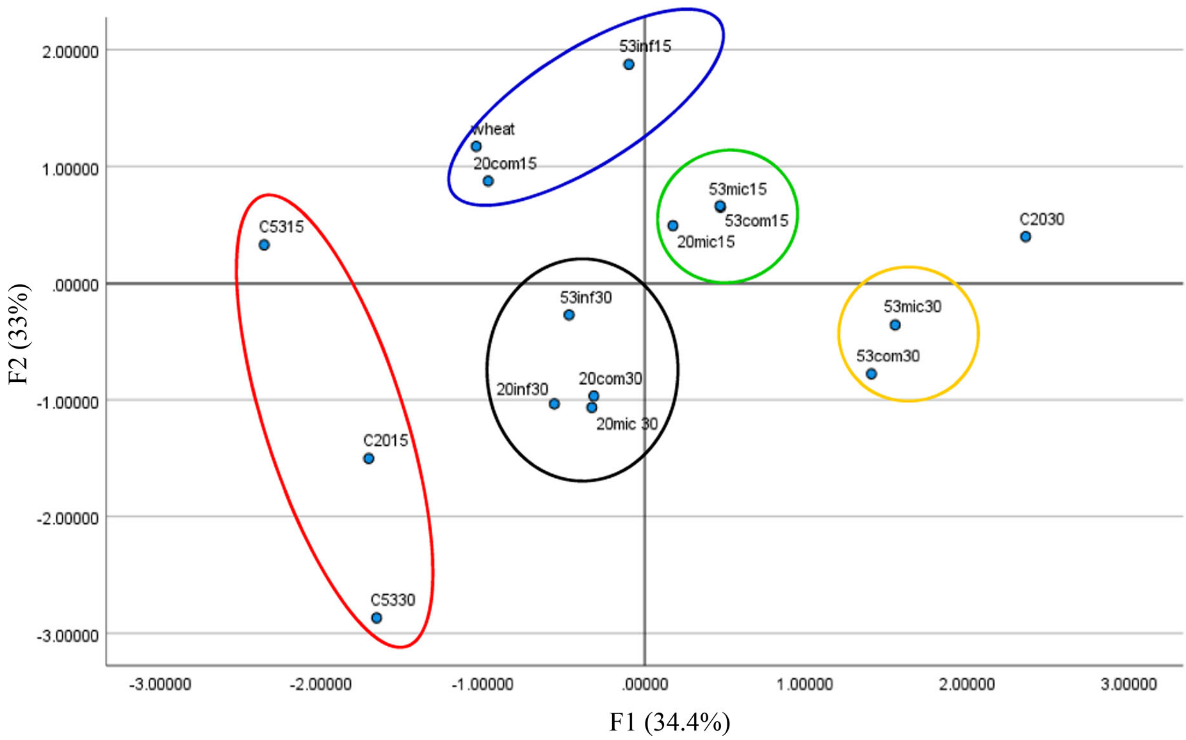

FIGURE 5 Principal component analysis showing important factors: Scores and component loading plot. [Color figure can be viewed at wileyonlinelibrary.com]

As expected, in the SDS sedimentation test, wheat flour had a higher sedimentation value of 54 mL, and the lowest was in the 15% replacement (25 mL) for the flours that did not undergo heat treatment. The gluten dilution effect was 24% with 15% Bambara groundnut flour added, and 52% with 30% Bambara groundnut added, as determined by the SDS sedimentation test (Supporting Information S1: Table S3). There was a significant decrease in sedimentation value as flour replacement was increased from 15% to 30% ($p > .05$). As Bambara groundnut flour inclusion increased, a higher dilution of gluten led to a decrease in the sedimentation value. There was a positive correlation between bread-specific volume and SDS Sedimentation value (Figure 6). The reduction in the specific volume of the bread may be related to the Bambara groundnut protein's lack of viscoelastic ability when compared with wheat gluten.

The increase in fibrous material caused by the addition of flours from whole Bambara groundnut seed may also reduce the viscoelastic properties of the composite dough and bread volume. Most of the Bambara groundnut fiber was insoluble dietary fiber (Supporting Information S1: Table S3) and insoluble dietary fibers are known to have detrimental effects on bread quality. This is because dietary fibers may interfere with the development of the gluten network. Dietary fiber can interfere with gas bubble formation by weakening the gluten network and disrupting the starch–protein network, thereby connecting the bubble lamellae (Alkurd et al., 2020). The interactions between dietary fibers and gluten have been reported predominantly through hydrogen bonding, hydrophobic interactions, and physical interaction (competition for water and steric hindrance) (Zhou et al., 2021).

Wang et al. (2002) found that the addition of carob fiber, inulin, and pea fibers decreased dough elasticity mixing tolerance indices, and this reduction was related to the interaction of gluten and fibers. On the other hand, studies on dry heating of cowpea flour reported a decrease in flour-soluble solids as a result of heat treatment (Phillips et al., 1988; Renzetti et al., 2022) and this caused a reduction in flour water binding capacity.

Adding Bambara groundnut flour from heat-treated seeds introduced starch-protein aggregates with exposed hydrophobic sites, reducing their affinity for water. The aggregates seem less detrimental to the developing gluten network in composite dough, because they are possibly less reactive and will have low competition for water as they expose their hydrophobic sites. This agrees with recent findings by Renzetti et al. (2022), who studied the effects of dry heating of cowpea flour for bread application. There were fewer soluble solids, as evidenced by the low solubility of flours because of heat treatment. Reduced soluble material will lead to less interaction with water, and more water is available for

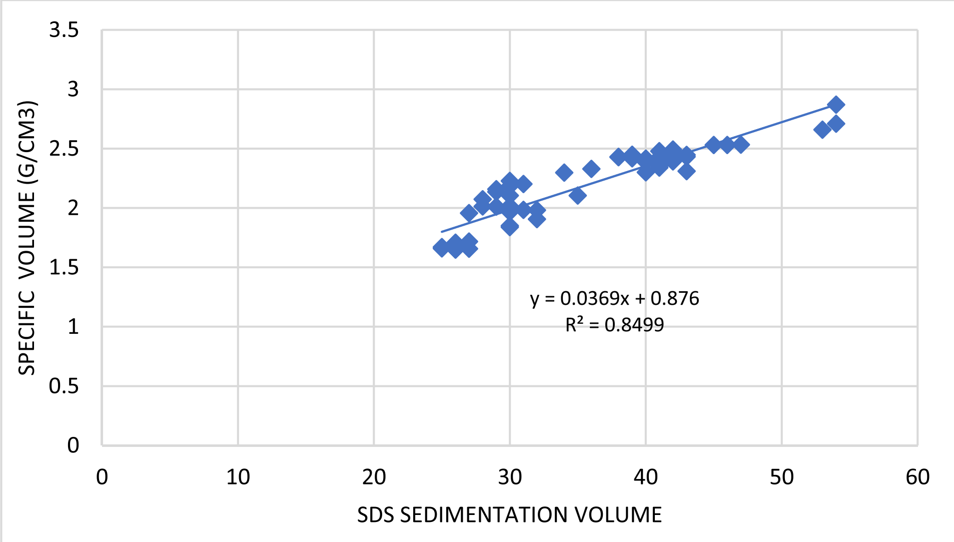

FIGURE 6 Graph illustrating the positive correlation of specific volume and sodium dodecyl sulfate (SDS) sedimentation volume data fitted to a straight line as indicated by their correlation coefficients R^2 values. [Color figure can be viewed at wileyonlinelibrary.com]

the gluten network to form. This may help explain an increase in WA capacity from Mixolab (Table 1) as flours from heat-treated seeds were added to wheat flour.

It has been reported that protein and starch complexes formed as heat treatment stabilize the batter during baking, forming a structure that improves gluten-free bread volume (Marston et al., 2016). Denatured proteins may improve their functionality as they may slowly unfold during subsequent heating (Erdogdu-Arnoczky et al., 1996). Marston et al. (2016) found that heat pretreatment of sorghum flour produced bread with finer and more uniformly sized cell structures, while untreated flour crumb structures collapsed. It was suggested that sorghum starch increased its ability to absorb water due to an increase in the viscosity of the sorghum flour, which increased with an increase in heat treatment time and temperature. In our previous study, microwave, infrared, and a combined microwave/infrared heat treatment increased the WAC of Bambara groundnut flour (Mukwevho & Emmambux, 2022).

4 | CONCLUSIONS

The addition of Bambara groundnut flour to wheat flour results in significant negative changes in dough visco-elastic properties, which subsequently affects bread properties. Mixolab better-predicted dough viscoelastic behavior of composite dough and bread firmness. Composite flour WA significantly affected the composite dough behavior. The composite doughs and bread made with 15% Bambara groundnut flour from heat-treated seeds performed better than those with 30% Bambara groundnut flour added. The results demonstrate that flour from heat treatment of Bambara groundnut seeds can produce dough with acceptable elastic properties and bread of potentially acceptable sensory texture when composited into wheat flour.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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REFERENCES

AACC. (2000). Method 10–05.01 guidelines for measurement of volume by rapeseed displacement, *AACC Approved Methods of Analysis* (pp. 1–4). AACC International.

Abdualrahman, M. A. Y., Ali, A. O., Elkhali, E. A., & Suliema, A. E. (2012). Effect of Bambara groundnut flour (*Vigna subterranea* (L.) Verdc.) supplementation on chemical, physical, nutritional and sensory evaluation of wheat bread. *Pakistan Journal of Biological Sciences*, *15*, 845–849.

Alkurd, R., Takruri, H., Muwalla, M., & Arafat, T. (2020). The nutritional value, energy and nutrient contents and claims of marketed multi-grain breads. *Journal of Food and Nutrition Research*, *8*, 600–605.

Amonsou, E., Taylor, J., & Minnaar, A. (2011). Microstructure of protein bodies in marama bean species. *LWT Food Science and Technology*, *44*, 42–47.

Arise, A. K., Nwachukwu, I. D., Aluko, R. E., & Amonsou, E. O. (2017). Structure, composition and functional properties of storage proteins extracted from Bambara groundnut (*Vigna subterranea*) landraces. *International Journal of Food Science & Technology*, *52*, 1211–1220.

Atudorei, D., Atudorei, O., & Codină, G. G. (2021). Dough rheological properties, microstructure and bread quality of wheat-germinated bean composite flour. *Foods*, *10*, 1542.

Atudorei, D., Stroe, S.-G., & Codină, G. G. (2021). Impact of germination on the microstructural and physicochemical properties of different legume types. *Plants*, *10*, 592.

Axford, D. W. E., Mcdermott, E. E., & Redman, D. G. (1979). Note on the sodium dodecyl sulfate test of breadmaking quality: Comparison with Pelshenke and Zeleny tests. *Cereal Chemistry Journal*, *56*, 582–584.

Bautista-Castaño, I., & Serra-Majem, L. (2012). Relationship between bread consumption, body weight, and abdominal fat distribution: Evidence from epidemiological studies. *Nutrition Reviews*, *70*, 218–233.

Boateng, M., Addo, J., Okyere, H., Adu-Dapaah, H., Berchie, J., & Tetteh, A. (2013). Physicochemical and functional properties of proteinates of two Bambara groundnut (*Vigna subterranean*) landraces. *African Journal of Food Science and Technology*, *4*, 64–70.

Bojňanská, T., Musilová, J., & Vollmannová, A. (2021). Effects of adding legume flours on the rheological and breadmaking properties of dough. *Foods*, *10*, 1087.

Cappelli, A., Oliva, N., Bonaccorsi, G., Lorini, C., & Cini, E. (2020). Assessment of the rheological properties and bread characteristics obtained by innovative protein sources (*Cicer arietinum*, *Acheta domesticus*, *Tenebrio molitor*): Novel food or potential improvers for wheat flour? *LWT*, *118*, 108867.

Centenaro, G. S., Feddern, V., Bonow, E. T., & Salas-Mellado, M. (2007). Enriquecimento de pão com proteínas de pescado. *Ciência e Tecnologia de Alimentos*, *27*, 663–668.

Chompoorat, P., Ambardekar, A., Mulvaney, S., & Rayas-Duarte, P. (2013). Rheological characteristics of gluten after modified by DATEM, ascorbic acid, urea and DTT using creep-recovery test. *Journal of Modern Physics*, *4*, 1–8.

Diedericks, C. F., De Koning, L., Jideani, V. A., Venema, P., & Van Der Linden, E. (2019). Extraction, gelation and microstructure of Bambara groundnut vicilins. *Food Hydrocolloids*, *97*, 105226.

Erdogdu-Arnoczky, N., Czuchajowska, Z., & Pomeranz, Y. (1996). Functionality of whey and casein in fermentation and in breadbaking by fixed and optimized procedures. *Cereal Chemistry*, *73*, 309–316.

Erukainure, O. L., Okafor, J. N., Ogunji, A., Ukazu, H., Okafor, E. N., & Eboagwu, I. L. (2016). Bambara-wheat composite flour: rheological behavior of dough and functionality in bread. *Food Science & Nutrition*, *4*, 852–857.

Fido, R. J., Békés, F., Gras, P. W., & Tatham, A. S. (1997). Effects of α-, β-, γ- and ω-Gliadins on the dough mixing properties of wheat flour. *Journal of Cereal Science*, *26*, 271–277.

Hallén, E., İbanoğlu, S. E., & Ainsworth, P. (2004). Effect of fermented/germinated cowpea flour addition on the rheological and baking properties of wheat flour. *Journal of Food Engineering*, *63*, 177–184.

Harris, T., Jideani, V., & Le Rose-Hill, M. (2018). Flavonoids and tannin composition of Bambara groundnut (*Vigna subterranea*) of Mpumalanga, South Africa. *Heliyon*, *4*, e00833.

Jia, F., Wang, J., Wang, Q., Zhang, X., Di Chen, C., Chen, Y., & Zhang, C. (2020). Effect of extrusion on the polymerization of wheat glutenin and changes in the gluten network. *Journal of Food Science and Technology*, *57*, 3814–3822.

Lazaridou, A., Duta, D., Papageorgiou, M., Belc, N., & Biliaderis, C. G. (2007). Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations. *Journal of Food Engineering*, *79*, 1033–1047.

Maktouf, S., Jeddou, K. B., Moulis, C., Hajji, H., Remaud-Simeon, M., & Ellouz-Ghorbel, R. (2016). Evaluation of dough rheological properties and bread texture of pearl millet-wheat flour mix. *Journal of Food Science and Technology*, *53*, 2061–2066.

Marston, K., Khouryieh, H., & Aramouni, F. (2016). Effect of heat treatment of sorghum flour on the functional properties of gluten-free bread and cake. *LWT Food Science and Technology*, *65*, 637–644.

Mukwevho, P., & Emmambux, M. N. (2022). Effect of infrared and microwave treatments alone and in combination on the functional properties of resulting flours from Bambara groundnut seeds. *LWT*, *153*, 112448.

Okafor, J. N. C., Ani, J. C., & Okafor, G. I. (2014). Effect of processing methods on qualities of Bambara groundnut (*Voandzeia subterranea* (L.) Thouars) flour and their acceptability in extruded snacks. *American Journal of Food Technology*, *9*, 350–359.

Okpuzor, J., Ogbunugafor, H. A., Okafor, U., & Sofidiya, M. O. (2010). Identification of protein types in Bambara nut seeds: perspectives for dietary protein supply in developing countries. *EXCLI Journal*, *9*, 17–28.

Pérez-Quirce, S, Ronda, F, Lazaridou, A, & Biliaderis, C. G. (2017). Effect of microwave radiation pretreatment of rice flour on gluten-free breadmaking and molecular size of β-Glucans in the fortified breads. *Food and Bioprocess Technology*, *10*, 1412–1421.

Phillips, R. D., Chinnan, M. S., Branch, A. L., Miller, J., & Mcwatters, K. H. (1988). Effects of pretreatment on functional and nutritional properties of cowpea meal. *Journal of Food Science*, *53*, 805–809.

Popineau, Y., Bonenfant, S., Cornec, M., & Pezolet, M. (1994). A study by infrared spectroscopy of the conformations of gluten proteins differing in their gliadin and glutenin compositions. *Journal of Cereal Science*, *20*, 15–22.

Prosky, L., Asp, N.-G., Schweizer, T. F., Devries, J. W., & Furda, I. (2020). Determination of insoluble and soluble dietary fiber in foods and food products: Collaborative study. *Journal of AOAC International*, *75*, 360–367.

Renzetti, S., Heetesonne, I., Ngadze, R. T., & Linnemann, A. R. (2022). Dry heating of cowpea flour below biopolymer melting temperatures improves the physical properties of bread made from climate-resilient crops. *Foods*, *11*, 1554.

Ronda, F., Pérez-Quirce, S., Angioloni, A., & Collar, C. (2013). Impact of viscous dietary fibres on the viscoelastic behaviour of gluten-free formulated rice doughs: A fundamental and empirical rheological approach. *Food Hydrocolloids*, *32*, 252–262.

Silva, J. V., Jaleta, M., Tesfaye, K., Abeyo, B., Devkota, M., Frija, A., Habarurema, I., Tembo, B., Bahri, H., Mosad, A., Blasch, G.,

Sonder, K., Snapp, S., & Baudron, F. (2023). Pathways to wheat self-sufficiency in Africa. *Global Food Security*, *37*, 100684.
Struck, S., Straube, D., Zahn, S., & Rohm, H. (2018). Interaction of wheat macromolecules and berry pomace in model dough: Rheology and microstructure. *Journal of Food Engineering*, *223*, 109–115.
Sun, X., Koksel, F., Nickerson, M. T., & Scanlon, M. G. (2020). Modeling the viscoelastic behavior of wheat flour dough prepared from a wide range of formulations. *Food Hydrocolloids*, *98*, 105129.
Tadesse, W., Bishaw, Z., & Assefa, S. (2019). Wheat production and breeding in Sub-Saharan Africa. *International Journal of Climate Change Strategies and Management*, *11*, 696–715.
Takahama, U., & Hirota, S. (2018). Interactions of flavonoids with α-amylase and starch slowing down its digestion. *Food & Function*, *9*, 677–687.
Vouris, D. G., Lazaridou, A., Mandala, I. G., & Biliaderis, C. G. (2018). Wheat bread quality attributes using jet milling flour fractions. *LWT*, *92*, 540–547.
Wang, J., Rosell, C. M., & De Barber, C. B. (2002). Effect of the addition of different fibres on wheat dough performance and bread quality. *Food Chemistry*, *79*, 221–226.
Yovchev, A. G., Stone, A. K., Hucl, P., Scanlon, M. G., & Nickerson, M. T. (2017). Effects of salt, polyethylene glycol, and water content on dough rheology for two red spring wheat varieties. *Cereal Chemistry*, *94*, 513–518.
Zhou, Y., Dhital, S., Zhao, C., Ye, F., Chen, J., & Zhao, G. (2021). Dietary fiber-gluten protein interaction in wheat flour dough: Analysis, consequences and proposed mechanisms. *Food Hydrocolloids*, *111*, 106203.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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