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Chemical and Functional Characteristics for Breadmaking: Comparison of Fermented Whole-Plant Flours with Refined Wheat Flour

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ABSTRACT

Egypt needs sustainable nutrient-rich alternatives for bread production because of its significant reliance on imported wheat. In contrast to refined wheat flour this study examines the chemical makeup nutritional profile and functional characteristics of flours made from fermented whole wheat corn millet and wheat- corn-millet mixture. Analysis was done on composite flours that contained 25% 50% and 75% mixed flour. All treated flours had lower moisture contents (10. 2–10. 9 g/100g) according to proximate analysis than wheat flour (11. 7 g/100g) suggesting improved shelf-life potential. Millet flour was high in zinc and sodium and had the highest levels of fat (3. 75 g/100g) fiber (1. 88 g/100g) and energy (4299 cal/g). With complete wheat flour having the highest protein content the range was 10–2–13 percent. Good protein quality was suggested by the low non-protein nitrogen content found in all samples. Mixed and millet flours had higher levels of vitamin E and carotene while corn flour had the highest iron content (95–36 mg/kg). All of the substitute flours had a marginally higher amino acid content than the control. The 50% mixed flour + 50% wheat blend was found to be the most functionally appropriate for breadmaking by rheological testing it had favorable extensibility and gelatinization as well as high dough stability. All things considered millet-based fermented whole-plant flours present a viable way to improve breads sustainability and nutritional content while lowering reliance on imported wheat.

Keywords: Breadmaking, wheat- corn-millet, nutrient-rich, diet

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INTRODUCTION

Wheat flour is a vital component of the Egyptian diet as it is the primary ingredient of "Baladi" bread, a subsidized flatbread that is eaten every day by most egyptians. Over 70 million

Egyptians especially those in low-income groups have low-cost access to bread thanks to the governments bread subsidy program which is a pillar of Egypt's food security policy **(World Bank 2022)**. Because of limitations in arable land irrigation water and agricultural productivity Egypt continues to be one of the world's biggest importers of wheat despite its significance (**FAO 2023**). Only 40–50% of the country's wheat consumption needs are met by domestic production making imports from major exporters like the US, Russia and Ukraine extremely necessary (**USDA 2024**). Due to these dependencies the national food system is susceptible to geopolitical upheavals and external supply shocks underscoring the necessity of sustainable and alternative flour sources to improve food system resilience.

Despite being functionally appropriate for breadmaking refined wheat flour has limited nutritional value because bran and germ are removed during milling resulting in lower levels of fiber vitamins and minerals (**Badawy et al. in 2024**). Furthermore monoculture agriculture and high input demands—both of which are made more unsustainable by resource scarcity and climate stress—are facilitated by conventional flour production (**Behrens et al. (2017**). As a result, studies are now focusing more on resilient and underutilized cereal crops like maize sorghum and millet. In addition to being high in dietary fiber phenolic compounds and micronutrients these grains are also nutrient-dense and can grow in arid and semi-arid conditions with less input than wheat (**Saleh et al. 2013 Omer et al. in 2023**).

Recent research indicates that these cereals have the potential to enhance baked goods nutritional value. Most of the research to date however has concentrated on flours made from grains while the potential of using the whole aerial plant biomass—leaves stems and grains—remains unexplored despite its benefits in lowering postharvest waste and boosting the sustainability of the food system. According to **Neme and Mohammed (2017)** and **Adebo & Medina-Meza (2020)** incorporating whole-plant material into flour production is consistent with the circular bioeconomy principles and may have major environmental advantages. As an inexpensive natural processing technique that improves the nutritional and functional qualities of cereal flours fermentation has also drawn interest. According to **Wang et al. (2025**) it can decrease antinutritional elements like phytates boost antioxidant potential increase the bioavailability of minerals and improve protein digestibility. **Adebo and Medina-Meza (2020).** In particular lactic acid fermentation and sourdough have shown positive effects on the rheology flavor and shelf life of composite bread products **(Wang et al. 2025**). There is still a glaring research gap in the use of fermented whole-plant cereal flours for breadmaking despite these encouraging results. Their chemical makeup functional characteristics and relative baking performance have not yet been thoroughly investigated in studies. Determining the potential of flours made from fermented whole wheat corn millet and their blends is the goal of this study. To support sustainable wholesome and locally adaptable alternatives for bread production these will be compared to traditional refined wheat flour in terms of their chemical composition (moisture ash fibre protein and fat) and functional qualities (water/oil absorption foaming capacity swelling index and bulk density).

The objective of the present study is to investigate the chemical composition and useful properties of novel flours produced from fermented whole wheat corn millet and wheat -corn-millet mix. Along with their potential for use in bread production and comparison with conventional refined wheat flour, these flours' nutritional value, functional performance, and suitability as sustainable alternatives in bakery applications are evaluated.

MATERIALS AND METHODS

Materials

Plants and flour samples preparation

Whole plants of wheat, corn, and millet, underwent distinct steaming and biological treatments utilizing various yeast strains. This part was conducted in the United Arab Emirates. The resulting flour samples comprised fermented whole plant flour derived from wheat, corn, and millet, alongside a mixed flour blend. Commercial wheat flour served as the control in this study.

New Wheat flour (fermented wheat)
New corn flour (Fermented whole corn)
New millet flour (fermented whole millet)
Wheat flour (control)

Methods

Chemical analysis:

The chemical analysis including proximate analysis, gross energy, vitamin and mineral content, profile of amino acids and fatty acids and the nutritional factors, all have been done in the laboratories of Regional Center for Food and Feed (RCFF) - Agricultural Research Center, Giza, EGYPT.

Determination of Proximate Analysis:

Proximate analysis including moisture, fat, ash, and crude fiber was carried out according to the methods described by (**AOAC, 2005**). Fat was extracted by diethyl ether using Soxhlet apparatus (FOSS Tecator, Auckland, NZ) and carbohydrate content was calculated by difference. Total nitrogen was determined using Kjeldahl method **(Imaran et al. 2008)** then crude protein was calculated as N x general factor (6.25) while the amount of non-protein nitrogen (NPN) were obtained in accordance with Kjeldahl method **(Siti et al. 2016)** after separation of protein from NPN by precipitating protein in the samples using 10 % trichloroacetic acid.

Estimation of Gross Energy:

The gross energy was estimated by using Bomb Calorimeter parr 1261 instrument under atmospheric pressure in range (28-40 atm) **(operating instruction manual. 1997)**

Determination of Vitamins content:

Vitamin E, D3 and β-caroten were analyzed according to the method **(method no.2561. 1996)** by using HPLC (Agilent Technologies 1200 Series) while vitamin B2 were analyzed according to method no. 1892. 1996) by using HPLC (Agilent Technologies 1260 Series).

Determination of Minerals content:

Minerals determination (Sodium Na, Potassium K, Magnesium Mg, Iron Fe, Calcium Ca, Manganese Mn, Zinc Zn, Copper Cu, Phosphorus P and Selenium Se) was carried out using inductively coupled plasma spectrometer (Optima 2000 DV, ICP-OES, Perkin Elmer). Wet digestion method **(AOAC, 2023a)** was used where samples were treated with concentrated acids (nitric and perchloric acid subsequently) until the sample solution becomes clear. Minerals concentrations were obtained based on calibration curves developed by using ICP standards provided by (Merck).

Determination of Amino acids:

Amino acids determination was performed according to (**AOAC, 2023b**) using amino acids analyzer (BIOCHROM 30+) through ion exchange resin via ninhydrin post-column derivatization. The protein quality assessment of the test formulae were based on their amino acids content according to **Mitcheland and Block (1946).**

Determination of Fatty acids:

The fatty acids methyl esters were analyzed by gas liquid chromatography (Shimadzu GC 2010) using DB-wax column after fatty acids methylation. The carrier gas was helium and the used detector was Flame ionization detector (FID). The fatty acids were identified according to standard fatty acids methyl esters (FAME). The fatty acids profile was performed as mentioned by **(AOAC, 2023c)** using Gas- Liquid Chromatography (GLC) technique.

Determination of Fiber Fractions:

As described by **Ferreira and Mertens (2007)** and according to **AOAC (2023d**), Samples were dried at 70°C for 48 hrs and milled through a 2 mm sieve for analysis. Neutral detergent fiber (NDF) and Acid detergent fiber (ADF) concentrations were determined using ANKOM 200 fiber analyzer (ANKOM Technology, A 200 I, USA) Using Sodium Sulfite and a-amylase heat stable for NDF only. Samples were completely dried in oven at 102°C for 2-4 hrs. For ADL (Acid detergent Lignin) determination, samples were submerged in Sulfuric acid 72% for 3 hrs then rinsed with hot water and dried in oven for 2-4 hrs.

Hemi cellulose, Cellulose, and lignin were calculated according to the following equations:

Hemi cellulose = NDF% - ADF%

Cellulose = ADF% - ADL%

Lignin = ADL% - Ash

Rheological properties

This study employed composite flours made from fermented whole plant material (stems, leaves, grains) of wheat corn and millet, known as "mixed flour." This mixed flour was combined with refined wheat flour at three levels of substitution:

25% mixed flour and 75% wheat flour.

50% mixed flour and 50% wheat flour.

75% mixed flour and 25% wheat flour.

Three rheological tests were conducted to evaluate dough performance:

- **Farinograph Test**
  Assessed dough development time, stability, degree of weakening, and water absorption using ICC Standard No. 115/1 (Brabender GmbH, Germany).
- **Extensigraph Test**
  Evaluated dough extensibility, resistance (elasticity), and energy (area under curve) using standard AACC method 54-10.01.
- **Amylograph Test**
  Determined starch gelatinization properties, including gelatinization onset temperature, peak viscosity temperature, and peak viscosity (UF units), according to AACC 22-10 method.

Statistical analysis

The statistical analysis of variance was performed using (ANOVA), and Duncan's multiple range tests **(Duncan.1995)** were applied to compare the results of the experiments (using Duncan $P \leq 0.05$) and the data were presented as the mean ± Standard Error (SE).

RESULTS AND DISCUSSION

Proximate analysis, energy and NPN content:

Results of the proximate analysis, gross energy and non-protein nitrogen are presented in Table (1) for all studied flour samples and expressed as g/100g on dry matter basis. Wheat flour (as control) and treated complete plant flour (wheat, corn and millet) as well as mix flour, all showed significant variations in their proximate composition. Carbohydrates (70.59- 76.14%) and protein (10.2-13%) represent the major components. The results indicated that moisture content in all treated whole plant flour under study have values between 10.9 g/100g (for corn) and 10.2 g/100g (for millet) which are significantly lower than wheat flour (11.7g/100 g). Low moisture content of flour is an important parameter for long term storage in order to reduce spoilage. Moisture over the permissible level (14%) can encourage the growth of mold, bacteria and attract various insects **(Katalin et al. 2024).** The ash content was generally low, ranging from 0.52-1.78 g/100g.

The data in Table (1) revealed that the protein content was significantly different among studied flour samples, recording high protein values in all complete plant flour compared to control. Where the highest protein content was found in complete wheat flour followed by corn then millet (13, 12.8 and 11.8 g/100g respectively). Whereas, the mix flour gave the lowest protein content (10.2 g/100g). High-protein flours create a strong gluten network and affecting the texture and appearance of the resulting baked bread **(Fernando et al. 2019)**.

Regarding fat content, a high significant value was detected in the complete millet flour (3.75 g/100g) followed by complete wheat flour and complete corn flour then comes the mix flour (1.65, 1.09 and 0.93 g/100g respectively), whereas, the wheat flour (control) recorded the lowest fat content 0.39 g/100g.

The complete millet flour stood out for the highest fiber content (1.88g/100g) compared to the control (wheat flour) which showed the lowest content (0.45g/100g). Therefore, new millet flour can be recommended as a high fat and dietary fiber bread.

Table 1. Proximate composition of the different Flour formulae "% DM"

Proximate analysis	Ingredient names				
	Wheat flour (Control)	New Wheat flour	New Corn flour	New Millet flour	Mix flour
Moisture	11.7 ± 0.20^{a}	10.5 ± 0.20^{c}	10.9 ± 0.10^{b}	10.2 ± 0.10^{d}	10.3 ± 0.10^{cd}
Ash	0.52 ± 0.03^{e}	0.85 ± 0.01^{d}	0.97 ± 0.04^{c}	1.78 ± 0.04^{a}	1.28 ± 0.04^{b}
Crude protein	10.8 ± 0.35^{c}	13 ± 0.35^{a}	12.8 ± 0.21^{a}	11.8 ± 0.20^{b}	10.2 ± 0.26^{d}
Crude fat	0.39 ± 0.02^{d}	1.65 ± 0.10^{b}	1.09 ± 0.14^{c}	3.75 ± 0.25^{a}	0.93 ± 0.02^{c}
Crude fiber	0.45 ± 0.01^{c}	0.74 ± 0.01^{b}	0.71 ± 0.03^{b}	1.88 ± 0.13^{a}	1.79 ± 0.09^{a}
Carbohydrates*	76.14	73.26	73.53	70.59	75.5
Gross energy (Cal/g)	3975 ± 79.83^{bc}	4057 ± 57.69^{b}	4106 ± 45.88^{ab}	4299 ± 58.03^{a}	3792 ± 65.19^{c}
NPN	0.19 ± 0.01^{a}	0.19 ± 0.01^{a}	0.13 ± 0.01^{b}	0.13 ± 0.01^{b}	0.1 ± 0.01^{b}

Mean ±SD. Within the same row, various superscript letters indicate significant differences (Duncan, $P < 0.05$).
***Total carbohydrates were calculated by difference.**

Carbohydrates presented higher values in wheat flour and the mix flour (76.14 and 75.5 g/100g respectively). Also, it was observed that the millet flour with the highest fat concentration recorded the highest significant energy content (4299 Cal/g).

Non protein nitrogen refers to different nitrogen containing compounds which are not proteins but can be converted into proteins and contributes to the total nitrogen such as urea, creatinine, creatine, uric acid, nucleotides, free amino acids and nitrate (**Nicholas et al. 2015).** Also, the NPN fraction included the Chlorophyll molecule (containing four nitrogen atoms) **(Sara et al.2022).** All complete plant flour NPN values in the studied flour samples were very low, ranging from 0.19 g/100g in the wheat and complete corn flour and reaching 0.1 g/100g in the mix flour. In general, inclusion of NPN in diet at low concentrations can result in improving its nutritional values. the obtained data for proximate analysis and gross energy agree with the literature **(Samson et al .2022**) .

Vitamins content:

Results of vitamins determination for different studied flour samples were shown in Table (2). All treated complete plant flour showed acceptable high significant concentrations of vitamin E compared to the control, where the mix flour recorded the highest value (0.014 g/kg). on the opposite, no significant differences in the concentration of vitamin D3 among all studied flour samples.

Regarding vitamin B2, the wheat flour recorded the highest significant concentration among all tested treatments recording 0.0048 g/kg.

Data in table (2) revealed elevated carotene content in mix and new millet flour compared to control. Carotene is considered a photosynthetic pigment and responsible for the orange, red and yellow colour of many fruits and vegetables. It plays a very important role for human health by acting as an antioxidant that converts to vitamin A.

Table 2. Vitamins content of the different flour formulae

Vitamins	**Ingredient names**				
	Wheat flour (Control)	**New Wheat flour**	**New Corn flour**	**New Millet flour**	**Mix flour**
Vit E g/kg	0.003 ± 0.00^{d}	0.006 ± 0.00^{c}	0.0084 ± 0.00^{b}	0.0039 ± 0.00^{cd}	0.0140 ± 0.00^{a}
Vit D3 MIU/ kg	0.0015 ± 0.00^{a}	0.0020 ± 0.00^{a}	0.0020 ± 0.00^{a}	0.00160 ± 0.00^{a}	0.00192 ± 0.00^{a}
Vit B2 g/ kg	0.0048 ± 0.00^{a}	0.00048 ± 0.00^{bc}	0.00033 ± 0.00^{c}	0.00057 ± 0.00^{b}	0.00040 ± 0.00^{bc}
Carotene μg\ 100g	2.16 ± 0.29^{d}	2.99 ± 0.31^{d}	9.87 ± 0.66^{c}	22.7 ± 1.20^{b}	67.67 ± 3.49^{a}

Mean ±SD. Within the same row, various superscript letters indicate significant differences (Duncan, P <0.05).

Minerals content:

Data in Table (3) summarize the mineral concentration determined in different flour formulae. The results revealed that the minerals concentration varied widely among the studied flour samples according to the type of cereal crop plant used and depending on its content of minerals. Potassium shows the highest concentration among other minerals in all tested flour recording (3700mg/kg for millet flour), followed by phosphorus (2700 mg/kg for millet flour) then comes magnesium (570 mg/kg for wheat flour) and calcium (500 mg/kg for millet flour).

Table 3. Minerals content (mg/kg DM) of the different Flour formulae

Minerals	Ingredient names				
	Wheat flour (Control)	**New Wheat flour**	**New Corn flour**	**New Millet flour**	**Mix flour**
Ca	180	400	140	500	210.95
P	1200	1800	1300	2700	4114.1
Na	19.19	220	99.03	257.2	59.24
K	1200	2200	1800	3700	2900
Mg	220	570	410	1100	683.5
Mn	2.08	12.86	ND	10.06	18.6
Fe	37.95	41.96	95.36	53.36	33.73
Zn	ND	3.62	ND	15.67	12.1
Cu	4.47	5.14	3.86	6.57	>0.04
Se	ND	ND	77.05	18.27	18.64

ND: Not Detected

New corn flour recorded the highest concentration of iron content (95.36 mg/kg) followed by millet flour (53.36 mg/kg). While the lowest iron content was observed in the mixed flour (33.73 mg/kg). The millet flour also recorded the highest values of sodium and zinc content (500 and 15.67 mg/kg respectively). This data revealed the supremacy of new millet flour as a rich source for minerals that can increase bread nutritional value.

According to previous published researches, flour quality is suggested to depend on factors such as starch and water content as well as the type of flour including the gluten content (Akintayo et al.2020) .Whereas the nutritional properties of flour depend on its minerals and vitamins content. Data from this study showed that complete plant flour exhibits better nutritional properties than commonly used flour which could be harnessed to help the food industry to improve the flour quality.

Amino acids:

The amino acids content of different studied flour formulae were very similar and were slightly higher than control as shown in Table (4).

Amino acids composition, particularly essential amino acids (E.A.A.), reflect the nutritional quality of the protein source (**Millward. 2011**). Data in Table (4) indicated that total essential amino acids content was highest in the new millet flour followed by new corn flour (3.11 and 3.08 % respectively).

Meanwhile the new corn flour showed relatively higher non-essential amino acid content (7.32%) compared to control (6.29%). The highest contribution concerning EAA were from Leucine and phenylalanine, while glutamic acid and proline were the highest NEAA.

Table 4. Amino acids content (%) of the different flour formulae

Amino acids (%)	Ingredient names				
	Wheat flour (Control)	New Wheat flour	New Corn flour	New Millet flour	Mix flour
Essential amino acids (EAA)					
Valine	0.36	0.43	0.43	0.42	0.42
Isoleucine	0.31	0.36	0.36	0.33	0.33
Leucine	0.61	0.70	0.73	0.78	0.80
Methionine	0.16	0.18	0.19	0.21	0.17
Threonine	0.25	0.28	0.32	0.31	0.33
Phenylalanine	0.43	0.48	0.53	0.49	0.45
Histidine	0.18	0.23	0.24	0.23	0.23
Lysine	0.19	0.25	0.28	0.34	0.27
Tryptophan	ND	ND	ND	ND	ND
Total E.A.A.	2.49	2.91	3.08	3.11	3
Non-Essential amino acids (NEAA)					
Serine	0.39	0.39	0.48	0.38	0.43
Glutamic acid	3.08	3.23	3.50	2.04	2.32
Glycine	0.33	0.40	0.41	0.35	0.38
Alanine	0.24	0.32	0.34	0.53	0.50
Aspartic acid	0.42	0.60	0.57	0.81	0.60
Arginine	0.32	0.44	0.44	0.49	0.43
Proline	1.04	1.10	1.13	0.68	0.80
Cysteine	0.22	0.26	0.27	0.21	0.21
Tyrosine	0.25	0.29	0.18	0.31	0.30
Total N.E.A.A.	6.29	7.03	7.32	5.8	5.97

Fatty acids:

Data in Table (5) revealed the fatty acids content of all studied flour formulas where the major fatty acids were C18:2ϖ6 which ranged between 50.99 -10% followed by C18:1ϖ9 and C16:0.

The percentage of total saturated fatty acids (TSFA) was much higher in control (wheat flour) compared to the rest of treated or mix flour, while on the contrary, mono and poly unsaturated Fatty acids (TMUFA & TPUFA) content were much higher in the complete plant flour and mixed flour. These findings suggested that the inclusion of fermented whole plants in flour forming process inhance the bioavailability of long chain MSFA and PUFA consumed as a low-fat omega- 3-enriched bread. Moreover, MSFA and PUFA have several potential benefits on human health, were they exert positive effect on blood high density lipoproteins (HDL) and reduce the concentration of low density lipoproteins (LDL) leading to reduced risk for heart disease (**Rasha et al.2017)** Consequently, using complete plant flour is necessary to achieve a healthier diet.

Table 5. Fatty acids composition (%) of the different flour formulae

Fatty acids		Ingredient names				
		Wheat flour (Control)	New Wheat flour	New Corn flour	New Millet flour	Mix flour
C8:0	**Caprylic acid**	16.17	0.29	0.12	0.13	
C10:0	**Capric acid**	12.98	0.25			
C12:0	**Lauric acid**	33.64	0.26	0.15	0.27	
C14:0	**Myristic acid**	0.23	1.23	0.19	0.15	
C15:1 ϖ6	**10-Pentadecanoic acid**	0.29	0.30			
C16:0	**Palmitic acid**	10.29	18.30	15.97	16.49	17.82
C16:1ϖ7	**Palmitoleic acid**	0.77	0.75	0.23	0.42	
C17:0	**Heptadecanoic acid**		0.25			
C18:0	**Stearic acid**	2.69	4.56	1.96	3.68	3.25
C18:1ϖ9	**Oleic acid**	11.77	27.42	24.15	27.66	24.60
C18:1ϖ7	**Vaccenic acid**	0.55	1.56	1.36	0.73	0.85
C18:2ϖ6	**Linoleic acid**	10.00	40.15	50.99	46	50.24
C18:3ϖ3	**Linolenic acid**	0.41	3.23	3.70	3.06	2.72
C20:0	**Arachidic acid**		0.30	0.33	0.72	0.51
C20:1ϖ9	**Gondoic acid**		0.73	0.72	0.35	
C20:1ϖ7	**Eicosanoic acid**	0.21	0.13			
C20:5ϖ3	**Eicosapentaenoic acid**		0.29			
C22:0	**Behenic acid**			0.15	0.23	
Non Identified Fatty Acid		Zero	Zero	Zero	0.09	
ω3		0.41	3.52	3.7	3.06	2.72
ω6		10.29	40.45	50.99	46	50.24
TSFA		76	25.44	18.87	21.67	21.58
TMUFA		13.59	30.89	26.46	29.16	25.45
TPUFA		10.41	43.67	54.69	49.06	52.96
n-6/n-3 ratio		25.1	11.49	13.78	15.03	18.47

Fiber Fractions:

A major limitation in expanded consumption of whole plant parts in food industry is the presence of certain anti-nutritional factors and non-digestible components. Acid Detergent Fiber (ADF) refers to the insoluble fiber within plant cell and is comprised of cellulose and lignin which are the least digestible parts of the plant, whereas Neutral Detergent Fiber (NDF) is a value comprised of ADF plus hemicelluloses. Lignin is a polyphenolic compound that limits the digestibility of other components of the plant cell wall like hemicelluloses and cellulose.

Flour samples showed significant variations in their fiber fraction composition as revealed in Table (6), which may be attributed to the pre- and post-harvest factors which can affect the structure of the plant and the chemical composition within plant tissues **(Gonzalo et al.2023)**. As expected, treated complete plant flour had higher significant fiber fraction compared to control, where the mix flour recorded the highest values.

Table 6. Fiber fraction composition (%) of the different flour formulae

Fiber fraction	Ingredient names and numbers				
	Wheat flour (Control)	New Wheat flour	New Corn flour	New Millet flour	Mix flour
NDF	1.47±0.07[e]	2.28±0.12[d]	3.07±0.06[c]	7.12±0.23[b]	8.43±0.34[a]
ADF	0.69±0.05[d]	1.52±0.10[c]	1.66±0.16[c]	3.11±0.21[b]	4.27±0.33[a]
ADL	0.55±0.06[d]	0.96±0.07[c]	1.03±0.07[c]	1.42±0.23[b]	1.84±0.15[a]
Hemicelluloses	0.78±0.05[c]	0.77±0.04[c]	1.42±0.08[b]	4.01±0.49[a]	4.17±0.31[a]
Cellulose	0.14±0.01[d]	0.56±0.02[c]	0.63±0.01[c]	1.69±0.03[b]	2.42±0.11[a]
Lignin	0.07±0.01[d]	0.18±0.02[d]	0.75±0.05[c]	1.03±0.11[b]	1.29±0.07[a]

Within the same row, various superscript letters indicate significant differences (Duncan, $P < 0.05$).

Meanwhile, subjecting the whole plants in this study to steaming and biological pre-treatments by different strains of yeasts unsettles lignocellulosic materials by physical and chemical reactions, allowing a more effective subsequent enzymatic digestion **(Lorenzo et al.2021)**. On the nutritional level, the values obtained for lignin, hemicelluloses and cellulose are acceptable and can contribute to dietary fiber.

Rheological Properties

Table 7 presents the rheological properties of various flour blends used for bread production, including farinograph, extensigraph, and amylograph data. The behavior of the doughs significantly varied with the proportion of mixed fermented flour (derived from wheat corn, and millet) to wheat flour, which directly influenced dough handling characteristics and breadmaking suitability **(Renzetti & Arendt, 2009; Ktenioudaki et al., 2015).**

The blend containing 50% wheat flour and 50% mixed flour exhibited the most favorable balance of properties. It showed a high extensibility of 150 mm, an elasticity ratio of 1.06, and a moderate dough resistance (160 BU), indicating a dough that can stretch well without tearing—ideal for traditional Baladi bread which requires soft, pliable dough. Similar findings have been reported where intermediate blends achieved optimal dough viscoelasticity **(Shevkani & Singh, 2015; Sciarini et al., 2010).** The farinograph also showed moderate water absorption (60.0%) and dough stability (6.5 minutes), supporting sufficient gas retention and loaf volume. The amylograph confirmed a suitable gelatinization temperature (70.0°C) and good starch behavior, enabling soft crumb formation and shelf-stability **(Omer et al., 2023).** Collectively, these findings mark this blend as the optimal formulation among those tested.

The blend with 75% wheat flour and 25% mixed flour was the second-best performer. It maintained adequate extensibility (115 mm) and the lowest gelatinization temperature (68.5°C),

Table 7. Rheological Properties of Flour Blends for Bread Production

Farinograph Properties					
Flour Blend	Dough Development Time (min)	Stability (min)	Weakening (BU)	Softening Degree	Water Absorption (%)
75% Mixed + 25% Wheat Flour	3.5	9.0	20	30	56.8
50% Mixed +	2.0	6.5	60	70	60.0

50% Wheat Flour					
25% Mixed + 75% Wheat Flour	1.5	5.0	60	70	59.2
Extensigraph Properties					
Flour Blend	Extensibility (mm)	Resistance (BU)	Max Resistance (BU)	Elasticity Ratio	Area Under Curve (cm²)
75% Mixed + 25% Wheat Flour	80	320	320	4.00	56.8
50% Mixed + 50% Wheat Flour	150	160	200	1.06	60.0
25% Mixed + 75% Wheat Flour	115	130	130	1.00	59.2
Amylograph Properties					
Flour Blend	Gelatinization Temp (°C)	Peak Viscosity Temp (°C)		Max Viscosity (UF)	
75% Mixed + 25% Wheat Flour	73.5	90.0		640	
50% Mixed + 50% Wheat Flour	70.0	91.4		630	
25% Mixed + 75% Wheat Flour	68.5	92.0		630	

which can shorten baking times and improve energy efficiency. Despite having a lower dough resistance (130 BU) and slightly reduced farinograph stability (5.0 minutes), the elasticity ratio of 1.00 points to a well-balanced dough with proportional stretch and resistance—attributes beneficial for flatbread applications **(Wang et al., 2024)**. Its amylograph peak viscosity (630 UF) further suggests consistent starch gelatinization suitable for good crumb structure **(Elkhalifa et al., 2020).**

In contrast, he blend with 75% mixed flour and only 25% wheat flour showed the least desirable performance for Baladi bread. The dough was overly elastic (elasticity ratio = 4.00), exhibited low extensibility (80 mm), and required a higher gelatinization temperature (73.5°C), all of which are indicators of stiff doughs prone to poor handling and suboptimal loaf volume **(Taylor & Emmambux, 2021).** However, this blend had the highest farinograph stability (9.0 min) and the lowest weakening (20 BU), reflecting strong resistance to mixing breakdown—attributes often desired for high-fiber or artisanal wholegrain breads, but not necessarily for soft, elastic traditional bread **(Renzetti & Arendt, 2009; Saleh et al., 2013).**

These findings underscore that increasing the proportion of wheat flour in composite blends improves dough extensibility, reduces resistance, and optimizes gelatinization temperature—all critical parameters for producing traditional Egyptian Baladi bread. The 50:50 blend, in particular, balances the nutritional benefits of the mixed flour with the desirable rheological traits of wheat, supporting both product quality and dietary diversification **(Kaur et al., 2019; Sciarini et al., 2010).** Conversely, although the 75% mixed blend provides superior dough strength and gelatinization control, its limited extensibility and excessive resistance render it less suitable for soft flatbread applications.

Thus, the 50:50 blend emerges as the most technically and functionally appropriate choice for Baladi bread production, enabling partial wheat flour substitution without compromising dough performance or bread quality. Additionally, this approach contributes to food security and sustainability by incorporating locally available, drought-resistant crops such as sorghum and millet **(Taylor & Emmambux, 2021; Saleh et al., 2013).**

CONCLUSION

This study highlights the potential of fermented whole-plant flours made from millet and corn as sustainable, nutrient-rich alternatives to refined wheat flour in bread production. Among the tested blends, the 50:50 mixture of wheat and mixed fermented flour emerged as the most functionally suitable for traditional Baladi bread, offering an ideal balance of dough extensibility, elasticity, and starch gelatinization properties. While the 75% mixed flour blend exhibited excellent dough strength and stability, its reduced extensibility made it less favorable for soft flatbread applications. Nutritionally, the inclusion of fermented millet and corn flours significantly enhanced the fiber, mineral, and phytochemical content of the composite flours. These improvements, combined with reduced moisture content, suggest not only better nutritional profiles but also improved shelf-life potential. Importantly, the use of these underutilized, drought-tolerant crops offers a practical solution to reduce Egypt’s heavy dependence on imported wheat—supporting both food security and environmental sustainability. By integrating locally available resources into breadmaking, this approach aligns with national goals for agricultural resilience and healthier diets. Future research should explore sensory attributes, consumer acceptance, and industrial scalability to further support the adoption of these sustainable formulations in commercial baking.

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