



## Antioxidant activities, nutritional composition, and functional properties of traditionally fermented African locust bean condiment (dawadawa) from Kogi State, Nigeria

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### ABSTRACT

**Introduction:** Dawadawa, a protein-rich fermented condiment from African locust bean (*Parkia biglobosa*), is widely consumed in Nigeria, but its bioactive compound content and nutritional profile from North-Central regions remain poorly documented. This study represents the first comprehensive characterization of antioxidant activities, nutritional composition, and functional properties of traditionally fermented Dawadawa from North-Central Nigeria (Kogi State), revealing significant location-based differences in quality parameters.

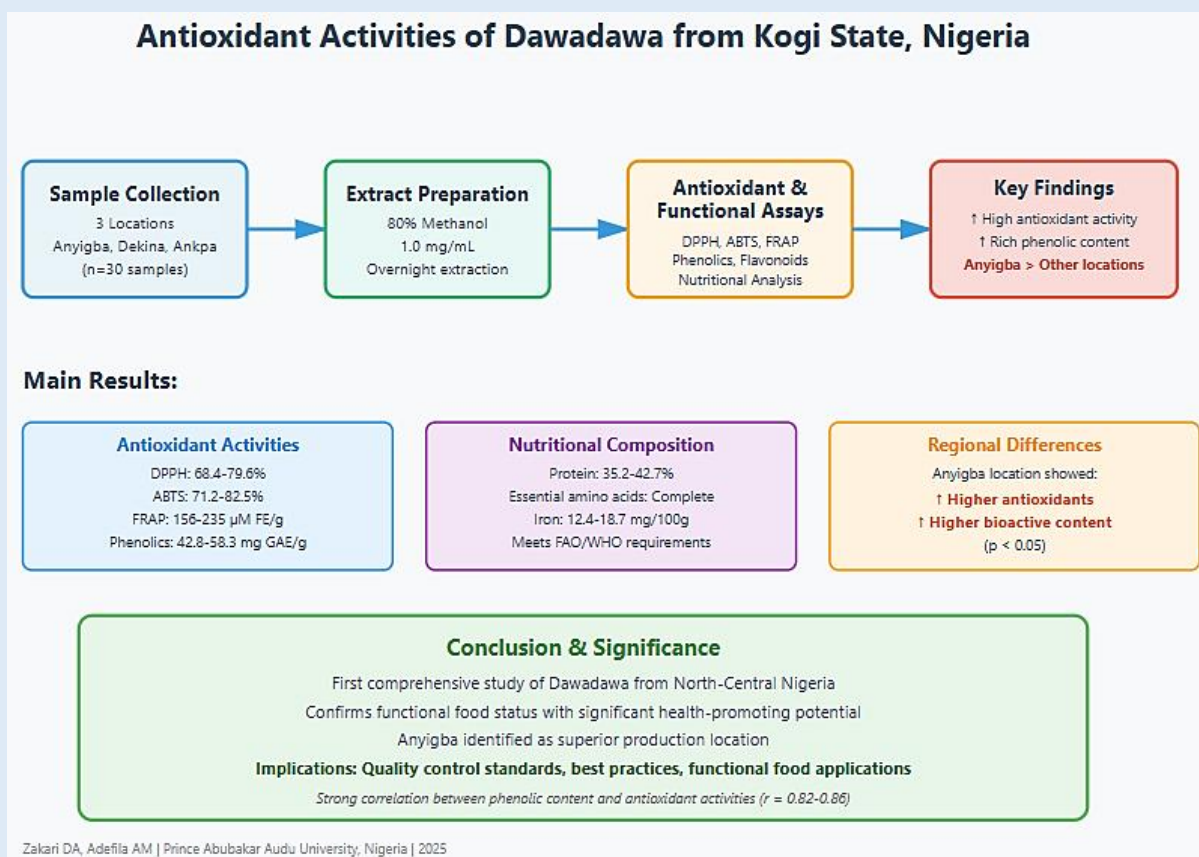
**Methods:** Thirty Dawadawa samples were collected from three local government areas in Kogi State (Anyigba, Dekina, and Ankpa) between June and August 2025. Antioxidant activities were evaluated using DPPH, ABTS, and FRAP assays at an extract concentration of 1.0 mg/mL. Total phenolic, flavonoid, and tannin contents were determined spectrophotometrically using validated standard curves. Proximate composition, amino acid profile, and mineral content were analyzed using AOAC methods. Functional properties, including water absorption capacity, oil absorption capacity, and bulk density, were assessed.

**Results:** Dawadawa extracts exhibited significant antioxidant activities with DPPH radical scavenging capacity of 68.4-79.6%, ABTS radical scavenging of 71.2-82.5%, and FRAP values of 156.3-234.7  $\mu\text{M FE/g}$ . Total phenolic content ranged from 42.8-58.3 mg GAE/g, total flavonoids from 18.4-29.6 mg QE/g, and tannins from 8.4-14.2 mg TAE/g. Strong positive

correlations were observed between phenolic content and antioxidant activities ( $r = 0.82$  for DPPH and  $r = 0.86$  for FRAP). Proximate analysis revealed protein content of 35.2-42.7%, crude fat of 12.8-18.4%, crude fiber of 8.4-11.6%, and ash of 4.2-6.8%. Amino acid profiling identified seventeen amino acids with essential amino acid composition meeting FAO/WHO requirements. Mineral analysis showed high levels of calcium (184.6-246.8 mg/100g), iron (12.4-18.7 mg/100g), zinc (3.8-5.6 mg/100g), magnesium (86.4-124.6 mg/100g), and phosphorus (234.8-316.4 mg/100g). Samples from Anyigba demonstrated significantly higher antioxidant activity and bioactive compound content than those from other locations, establishing it as a superior production location.

**Conclusion:** This first comprehensive study of Dawadawa from North-Central Nigeria demonstrates that traditionally fermented products from Kogi State possess substantial antioxidant activities and excellent nutritional composition, confirming their status as functional foods with significant health-promoting potential. The identification of Anyigba as a producer of superior-quality Dawadawa with enhanced antioxidant properties has important implications for quality control, best-practice guidelines for commercial production, and the development of region-specific functional food applications.

**Keywords:** Dawadawa, antioxidant activity, phenolic compounds, nutritional composition, functional food, bioactive compounds, fermented legume, Nigeria, fermented condiments



**Graphical Abstract:** Antioxidant Activities, Nutritional Composition, and Functional Properties of Traditionally Fermented African Locust Bean Condiment (Dawadawa) from Kogi State, Nigeria

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## INTRODUCTION

Traditional fermented foods represent valuable sources of bioactive compounds and essential nutrients in African dietary systems [1]. The fermentation process enhances nutritional value through multiple mechanisms, including improvement of protein digestibility, synthesis of bioactive metabolites, reduction of anti-nutritional factors, and enrichment of vitamin content [2,3]. In contemporary nutritional science, fermented foods have gained recognition not only as nutrient sources but also as functional foods that deliver health benefits beyond basic nutrition [4,5].

Dawadawa, produced through spontaneous fermentation of African locust bean seeds (*Parkia biglobosa*), serves as a critical dietary component across West African communities, particularly in Nigeria [6]. This traditional condiment provides an affordable source of protein and serves as a flavoring agent in various indigenous dishes [7]. Beyond its culinary applications, Dawadawa has been associated with multiple health benefits in traditional medicine systems, including antimicrobial properties and support for digestive health [8].

The fermentation process induces substantial biochemical transformations in Dawadawa, including proteolysis that generates bioactive peptides, lipid modifications that alter fatty acid profiles, and synthesis of novel bioactive compounds [9]. These transformations may contribute to the accumulation of antioxidant compounds and enhance nutritional quality [10]. However, systematic characterization of bioactive compound content and antioxidant properties remains limited, particularly for samples from North-Central Nigeria.

Antioxidants play critical roles in preventing oxidative damage to cellular components and have been implicated in reducing risks of chronic diseases, including cardiovascular disease, diabetes, cancer, and neurodegenerative disorders [11-12]. Natural

antioxidants from dietary sources, particularly polyphenolic compounds, offer advantages over synthetic antioxidants, including better safety profiles and additional health benefits [13]. Fermented legumes have been identified as potential sources of natural antioxidants due to the release of bound phenolic compounds during fermentation and the synthesis of novel antioxidant metabolites by fermenting microorganisms [14-15].

The nutritional composition of fermented foods often exceeds that of their raw material precursors due to microbial synthesis of vitamins, enhanced mineral bioavailability, and improved protein quality [16]. Specifically, fermentation of legumes has been shown to improve essential amino acid profiles, reduce phytate content, thereby enhancing mineral absorption, and increase B-vitamin content [17-18]. Understanding the nutritional composition of traditional fermented foods is essential for documenting their contributions to dietary adequacy and supporting their recognition as valuable food resources [19].

Despite widespread consumption of Dawadawa across Nigeria, a comprehensive assessment of its antioxidant properties and nutritional composition remains limited, particularly in North-Central regions [20]. Existing literature predominantly focuses on samples from South-Western Nigeria, creating knowledge gaps regarding regional variations in bioactive compound content and nutritional attributes [21,22]. Kogi State, located in North-Central Nigeria, represents a significant production zone with distinct processing traditions that may influence the final product's chemical and nutritional characteristics [23].

Regional variations in Dawadawa characteristics may arise from differences in raw material quality, fermentation conditions, processing methods, and environmental factors [24]. Understanding these variations is essential for quality standardization

initiatives, preservation of traditional production methods that yield superior products, and development of region-specific functional food products [25]. Additionally, scientific documentation of antioxidant properties and nutritional composition provides evidence-based support for traditional knowledge regarding the health benefits of Dawadawa consumption [26].

The potential health implications of antioxidant-rich fermented foods extend beyond protection against oxidative stress to include anti-inflammatory effects, modulation of gut microbiota composition, enhancement of immune function, and support for metabolic health [27-28]. Regular consumption of foods rich in polyphenolic compounds has been associated with reduced chronic disease incidence and improved overall health outcomes in epidemiological studies [29-30].

This investigation comprehensively characterized the antioxidant activities, nutritional composition, and functional properties of traditionally fermented Dawadawa from Kogi State, Nigeria. The specific objectives included: evaluating antioxidant activities using multiple complementary assays, quantifying bioactive compound content including phenolics, flavonoids, and tannins, determining proximate composition and mineral content, analyzing amino acid profiles, assessing functional properties relevant to food applications, and examining regional variations in antioxidant and nutritional characteristics among samples from different locations.

## METHODS

**Study Design and Sample Collection:** A cross-sectional study was conducted from June to August 2025. Thirty Dawadawa samples were collected from traditional producers across three local government areas in Kogi State, Nigeria: Anyigba, Dekina, and Ankpa (ten samples per location). Informed consent was obtained from all traditional producers before sample collection. Samples

were collected in sterile containers immediately after fermentation completion, transported in insulated coolers to the laboratory within four hours, and stored at 4°C until analysis within 24 hours. The study protocol received approval from the Research Ethics Committee of Prince Abubakar Audu University (approval number PAAU/REC/2025/068).

### Sample Preparation for Antioxidant Analysis:

Dawadawa extracts were prepared by homogenizing 10 g of sample in 100 mL of 80% methanol, stirring overnight at room temperature, and filtering through Whatman No. 1 filter paper [31]. The choice of 80% methanol as extraction solvent was based on its reported efficiency for extracting both polar and moderately polar phenolic compounds from fermented legume matrices, though it is acknowledged that different solvent systems may yield varying phenolic profiles. The final extract concentration used for all antioxidant assays was 1.0 mg/mL (dry weight basis).

**DPPH Radical Scavenging Activity:** DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity was determined by mixing 100  $\mu$ L of extract (1.0 mg/mL) with 2.9 mL of 0.1 mM DPPH solution, incubating in the dark at room temperature for 30 minutes, and measuring absorbance at 517 nm [32]. A calibration curve was prepared using a Trolox standard (0-100  $\mu$ M;  $R^2 = 0.998$ ; linear range: 10-100  $\mu$ M). Scavenging activity was calculated as the percentage inhibition relative to the control.

**ABTS Radical Scavenging Activity:** ABTS radical cation was generated by mixing 7 mM ABTS with 2.45 mM potassium persulfate and incubating overnight at room temperature in the dark. The working solution was diluted to give an absorbance of  $0.70 \pm 0.02$  at 734 nm. Extract (100  $\mu$ L at 1.0 mg/mL) was mixed with 2.9 mL ABTS radical solution, and absorbance was measured at

734 nm after 6 minutes [33]. Standard curve was prepared using Trolox (0-1000  $\mu\text{M}$ ,  $R^2 = 0.997$ , linear range 100-1000  $\mu\text{M}$ ). Results were expressed as percentage scavenging activity.

**Ferric Reducing Antioxidant Power (FRAP):** FRAP was evaluated by mixing 100  $\mu\text{L}$  extract (1.0 mg/mL) with 3.0 mL FRAP reagent containing 10 mM TPTZ (2,4,6-tripyridyl-s-triazine) in 40 mM HCl, 20 mM ferric chloride, and 300 mM acetate buffer (pH 3.6) in a ratio 1:1:10, incubating at 37°C for 10 minutes, and measuring absorbance at 593 nm [34]. Standard curve was prepared using ferrous sulfate (0-2000  $\mu\text{M}$ ,  $R^2 = 0.999$ , linear range 100-2000  $\mu\text{M}$ ). Results were expressed as micromolar ferrous equivalent per gram ( $\mu\text{M FE/g}$ ).

**Total Phenolic Content:** Total phenolic content was determined using Folin-Ciocalteu reagent with gallic acid as a standard [35]. The extract (100  $\mu\text{L}$ ) was mixed with 500  $\mu\text{L}$  Folin-Ciocalteu reagent, allowed to stand for 5 minutes, and then 1.5 mL of 20% sodium carbonate was added. After 2 hours of incubation at room temperature, absorbance was measured at 765 nm. Gallic acid standard curve (0-500  $\mu\text{g/mL}$ ,  $R^2 = 0.998$ , linear range 10-500  $\mu\text{g/mL}$ ) was used for quantification. Results were expressed as milligrams gallic acid equivalent per gram (mg GAE/g).

**Total Flavonoid Content:** Total flavonoid content was determined using the aluminum chloride colorimetric method with quercetin as a standard [36]. The extract (500  $\mu\text{L}$ ) was mixed with 1.5 mL methanol, 100  $\mu\text{L}$  10% aluminum chloride, 100  $\mu\text{L}$  1 M potassium acetate, and 2.8 mL distilled water. After 30 minutes of incubation at room temperature, absorbance was measured at 415 nm. Quercetin standard curve (0-100  $\mu\text{g/mL}$ ,  $R^2 = 0.997$ , linear range 5-100  $\mu\text{g/mL}$ ) was used. Results were expressed as milligrams quercetin equivalent per gram (mg QE/g).

**Total Tannin Content:** Total tannin content was determined using the Folin-Ciocalteu method after removal of simple phenolics by polyvinylpyrrolidone (PVPP) treatment [37]. Tannic acid standard curve (0-100  $\mu\text{g/mL}$ ,  $R^2 = 0.996$ , linear range 5-100  $\mu\text{g/mL}$ ) was prepared. Results were expressed as milligrams tannic acid equivalent per gram (mg TAE/g).

**Proximate Composition Analysis:** Proximate composition, including moisture, ash, protein, fat, and crude fiber, was determined following AOAC methods [38]. Protein content was determined by the Kjeldahl nitrogen method with a nitrogen conversion factor of 6.25 [39]. Carbohydrate content was calculated by difference: 100 - (moisture + protein + fat + fiber + ash).

**Amino Acid Profile Analysis:** The amino acid profile was analyzed by high-performance liquid chromatography after acid hydrolysis with 6 M HCl at 110°C for 24 hours [40]. Tryptophan was determined separately after alkaline hydrolysis with 4 M NaOH at 110°C for 16 hours to prevent degradation. Results were expressed as grams per 100 g protein.

**Mineral Content Analysis:** Mineral content, including calcium, iron, zinc, magnesium, and phosphorus, was determined by atomic absorption spectrophotometry after dry ashing at 550°C for 6 hours [41]. Phosphorus was determined colorimetrically using the molybdovanadate method at 470 nm.

**Functional Properties:** Water absorption capacity was determined by mixing 1 g of sample with 10 mL of distilled water, allowing it to stand at room temperature for 30 minutes, centrifuging at 3000  $\times g$  for 20 minutes, decanting the supernatant, and weighing the sediment [42]. Oil absorption capacity was determined similarly using vegetable oil. Bulk density was determined by gently filling a 10 mL graduated cylinder with the sample

and calculating the weight per unit volume without tapping.

**Statistical Analysis:** All experiments were performed in triplicate, and results were expressed as mean  $\pm$  standard deviation. Data was analyzed using SPSS version 28.0. A one-way ANOVA with Tukey's post hoc test was used to determine significant differences among sample locations at  $p < 0.05$ . Pearson correlation analysis was performed to assess relationships between bioactive compounds and antioxidant activities.

## RESULTS

### Antioxidant Activities and Bioactive Compound

**Content:** Methanolic extracts of Dawadawa samples exhibited substantial antioxidant activities across multiple assays. DPPH radical scavenging capacity ranged from 68.4 to 79.6% with a mean of  $73.8 \pm 3.4\%$ . ABTS

radical scavenging activity ranged from 71.2 to 82.5% with a mean of  $76.4 \pm 3.1\%$ . Ferric reducing antioxidant power values ranged from 156.3 to 234.7  $\mu\text{M FE/g}$  with a mean of  $192.8 \pm 22.6 \mu\text{M FE/g}$ .

Total phenolic content ranged from 42.8 to 58.3 mg GAE/g with a mean of  $50.2 \pm 4.7 \text{ mg GAE/g}$ . Total flavonoid content ranged from 18.4 to 29.6 mg QE/g with a mean of  $23.8 \pm 3.2 \text{ mg QE/g}$ . Total tannin content ranged from 8.4 to 14.2 mg TAE/g, with a mean of  $10.9 \pm 1.8 \text{ mg TAE/g}$ .

Statistical analysis revealed significant positive correlations between total phenolic content and antioxidant activities, with correlation coefficients of 0.82 for DPPH ( $p < 0.001$ ), 0.79 for ABTS ( $p < 0.001$ ), and 0.86 for FRAP ( $p < 0.001$ ). Samples from Anyigba demonstrated significantly higher antioxidant activity and bioactive compound content than those from Dekina and Ankpa. Detailed results are presented in Table 1.

**Table 1.** Antioxidant activities and bioactive compound content of Dawadawa samples.

Parameter	Anyigba (n=10)	Dekina (n=10)	Ankpa (n=10)	Overall Mean	p-value
DPPH scavenging (%)	$77.8 \pm 2.8^a$	$72.6 \pm 3.2^b$	$70.9 \pm 3.6^b$	$73.8 \pm 3.4$	0.001
ABTS scavenging (%)	$80.4 \pm 2.6^a$	$75.3 \pm 3.1^b$	$73.5 \pm 3.4^b$	$76.4 \pm 3.1$	0.002
FRAP ( $\mu\text{M FE/g}$ )	$218.6 \pm 19.4^a$	$186.4 \pm 21.3^b$	$173.4 \pm 23.8^b$	$192.8 \pm 22.6$	0.001
Total phenolics (mg GAE/g)	$54.7 \pm 4.2^a$	$48.9 \pm 4.6^b$	$47.0 \pm 4.9^b$	$50.2 \pm 4.7$	0.003
Total flavonoids (mg QE/g)	$27.3 \pm 2.9^a$	$22.8 \pm 3.1^b$	$21.3 \pm 3.4^b$	$23.8 \pm 3.2$	0.002
Tannins (mg TAE/g)	$12.8 \pm 1.6^a$	$10.4 \pm 1.8^b$	$9.7 \pm 1.9^b$	$10.9 \pm 1.8$	0.004

Values represent mean  $\pm$  standard deviation. Different superscript letters within rows indicate significant differences ( $p < 0.05$ ). DPPH: 2,2-diphenyl-1-picrylhydrazyl; ABTS: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); FRAP: ferric reducing antioxidant power; GAE: gallic acid equivalent; QE: quercetin equivalent; TAE: tannic acid equivalent; FE: ferrous equivalent.

**Proximate Composition:** Proximate analysis revealed that the Dawadawa samples contained moisture content ranging from 8.4 to 12.6%, with a mean of  $10.3 \pm 1.3\%$ . Crude protein content ranged from 35.2 to 42.7% with a mean of  $38.6 \pm 2.4\%$ . Crude fat content ranged from 12.8 to 18.4% with a mean of  $15.2 \pm 1.8\%$ . Crude fiber content ranged from 8.4 to 11.6% with a mean of  $9.8 \pm 1.0\%$ . Ash content ranged from 4.2 to 6.8% with a mean of  $5.4 \pm$

0.8%. Carbohydrate content (by difference) ranged from 18.6 to 24.3% with a mean of  $21.2 \pm 1.7\%$ .

The high protein content confirms that Dawadawa is a valuable protein source for populations with limited access to animal protein. The substantial fiber content supports digestive health benefits. A regional comparison showed that Anyigba samples had significantly higher protein content than those from other locations. Results are presented in Table 2.

**Table 2.** Proximate composition of Dawadawa samples (%).

Parameter	Anyigba (n=10)	Dekina (n=10)	Ankpa (n=10)	Overall Mean	p-value
Moisture	9.8 ± 1.2 <sup>a</sup>	10.4 ± 1.3 <sup>a</sup>	10.7 ± 1.4 <sup>a</sup>	10.3 ± 1.3	0.234
Crude protein	40.3 ± 2.1 <sup>a</sup>	38.1 ± 2.4 <sup>b</sup>	37.4 ± 2.6 <sup>b</sup>	38.6 ± 2.4	0.019
Crude fat	15.8 ± 1.6 <sup>a</sup>	15.1 ± 1.8 <sup>a</sup>	14.7 ± 1.9 <sup>a</sup>	15.2 ± 1.8	0.312
Crude fiber	10.2 ± 0.9 <sup>a</sup>	9.7 ± 1.0 <sup>a</sup>	9.5 ± 1.1 <sup>a</sup>	9.8 ± 1.0	0.287
Ash	5.7 ± 0.7 <sup>a</sup>	5.3 ± 0.8 <sup>a</sup>	5.2 ± 0.9 <sup>a</sup>	5.4 ± 0.8	0.341
Carbohydrate*	18.2 ± 1.5 <sup>a</sup>	21.4 ± 1.7 <sup>b</sup>	22.5 ± 1.8 <sup>b</sup>	21.2 ± 1.7	0.002

Values represent mean ± standard deviation. Different superscript letters within rows indicate significant differences (p < 0.05). \*Carbohydrate calculated by difference: 100 - (moisture + protein + fat + fiber + ash).

**Amino Acid Profile:** Amino acid profiling identified seventeen amino acids, including all nine essential amino acids. The crucial amino acids detected included leucine (7.8-9.2 g/100g protein), lysine (6.4-7.8 g/100g protein), phenylalanine (5.6-6.9 g/100g protein), valine (5.2-6.4 g/100g protein), isoleucine (4.8-5.9 g/100g protein), threonine (4.2-5.3 g/100g protein), methionine (1.8-2.4 g/100g protein), histidine (2.6-3.4 g/100g protein), and tryptophan (1.2-1.6 g/100g protein).

Non-essential amino acids identified included glutamic acid (highest at 15.2-18.6 g/100g protein), aspartic acid (10.4-12.8 g/100g protein), arginine (6.8-8.4

g/100g protein), glycine (4.2-5.6 g/100g protein), alanine (4.6-5.8 g/100g protein), serine (4.8-6.2 g/100g protein), proline (4.2-5.4 g/100g protein), and tyrosine (3.6-4.8 g/100g protein).

The essential amino acid composition met the FAO/WHO recommended requirements for adult nutrition. The high content of leucine, lysine, and phenylalanine is particularly notable as these amino acids are often limiting in plant-based protein sources. The substantial glutamic acid content contributes to the characteristic savory flavor of Dawadawa. Results are presented in Table 3.

**Table 3.** Amino acid profile of Dawadawa samples (g/100g protein).

Essential Amino Acids	Range	Mean ± SD	FAO/WHO Requirement*
Leucine	7.8-9.2	8.4 ± 0.4	5.9
Lysine	6.4-7.8	7.0 ± 0.4	4.5
Phenylalanine	5.6-6.9	6.2 ± 0.4	3.8**
Valine	5.2-6.4	5.8 ± 0.4	3.9
Isoleucine	4.8-5.9	5.3 ± 0.3	3.0
Threonine	4.2-5.3	4.7 ± 0.3	2.3
Methionine	1.8-2.4	2.1 ± 0.2	1.6***
Histidine	2.6-3.4	3.0 ± 0.2	1.5
Tryptophan	1.2-1.6	1.4 ± 0.1	0.6
<b>Non-essential Amino Acids</b>			
Glutamic acid	15.2-18.6	16.8 ± 1.0	-
Aspartic acid	10.4-12.8	11.5 ± 0.7	-
Arginine	6.8-8.4	7.5 ± 0.5	-
Glycine	4.2-5.6	4.8 ± 0.4	-
Alanine	4.6-5.8	5.1 ± 0.4	-
Serine	4.8-6.2	5.4 ± 0.4	-
Proline	4.2-5.4	4.7 ± 0.4	-
Tyrosine	3.6-4.8	4.1 ± 0.3	-

\*FAO/WHO requirements for adults (g/100g protein). \*\*Phenylalanine + tyrosine. \*\*\*Methionine + cysteine.

**Mineral Content:** Mineral analysis revealed substantial concentrations of essential minerals. Calcium content ranged from 184.6 to 246.8 mg/100g, with a mean of  $212.4 \pm 19.6$  mg/100g. Iron content ranged from 12.4 to 18.7 mg/100g with a mean of  $15.2 \pm 2.0$  mg/100g. Zinc content ranged from 3.8 to 5.6 mg/100g with a mean of  $4.6 \pm 0.6$  mg/100g. Magnesium content ranged from 86.4 to 124.6 mg/100g with a mean of  $103.8 \pm 12.4$  mg/100g. Phosphorus content ranged from 234.8 to 316.4

mg/100g with a mean of  $272.6 \pm 26.8$  mg/100g.

The high iron content is particularly significant given widespread iron deficiency in developing countries. The substantial calcium and phosphorus contents support bone health. Zinc content is adequate for supporting immune function and metabolic processes. Regional comparison showed no significant differences in mineral content among the three locations. Results are presented in Table 4.

**Table 4.** Mineral content of Dawadawa samples (mg/100g).

Mineral	Anyigba (n=10)	Dekina (n=10)	Ankpa (n=10)	Overall Mean	p-value
Calcium	$218.4 \pm 18.2^a$	$209.6 \pm 19.8^a$	$209.2 \pm 21.4^a$	$212.4 \pm 19.6$	0.456
Iron	$15.8 \pm 1.8^a$	$15.1 \pm 2.0^a$	$14.7 \pm 2.2^a$	$15.2 \pm 2.0$	0.389
Zinc	$4.8 \pm 0.5^a$	$4.6 \pm 0.6^a$	$4.4 \pm 0.7^a$	$4.6 \pm 0.6$	0.312
Magnesium	$108.6 \pm 11.2^a$	$102.4 \pm 12.6^a$	$100.4 \pm 13.8^a$	$103.8 \pm 12.4$	0.267
Phosphorus	$284.2 \pm 24.6^a$	$268.4 \pm 27.2^a$	$265.2 \pm 29.4^a$	$272.6 \pm 26.8$	0.234

Values represent mean  $\pm$  standard deviation. Different superscript letters within rows indicate significant differences ( $p < 0.05$ ).

**Functional Properties:** Water absorption capacity ranged from 1.82 to 2.34 g/g with a mean of  $2.06 \pm 0.16$  g/g. Oil absorption capacity ranged from 1.46 to 1.94 g/g with a mean of  $1.68 \pm 0.15$  g/g. Bulk density values ranged from 0.54 to 0.68 g/mL, with a mean of  $0.60 \pm 0.04$  g/mL.

The moderate water and oil absorption capacities

indicate good potential for incorporation into various food formulations. The bulk density values are within typical ranges for legume-based powders. These functional properties support the application of Dawadawa as a functional ingredient in food product development. Results are presented in Table 5.

**Table 5.** Functional properties of Dawadawa samples.

Property	Anyigba (n=10)	Dekina (n=10)	Ankpa (n=10)	Overall Mean	p-value
Water absorption capacity (g/g)	$2.14 \pm 0.14^a$	$2.04 \pm 0.16^a$	$2.00 \pm 0.18^a$	$2.06 \pm 0.16$	0.178
Oil absorption capacity (g/g)	$1.74 \pm 0.13^a$	$1.66 \pm 0.15^a$	$1.64 \pm 0.17^a$	$1.68 \pm 0.15$	0.267
Bulk density (g/mL)	$0.61 \pm 0.04^a$	$0.60 \pm 0.04^a$	$0.59 \pm 0.05^a$	$0.60 \pm 0.04$	0.456

Values represent mean  $\pm$  standard deviation. Different superscript letters within rows indicate significant differences ( $p < 0.05$ ). Practical significance: Water absorption capacity (WAC) values of 2.0-2.3 g/g are favorable for bakery products, soups, and sauces where moisture retention improves texture and shelf life. Oil absorption capacity (OAC) values of 1.5-2.0 g/g are desirable for meat analogues, sausages, and emulsion-based products. Bulk density of 0.54-0.68 g/mL is suitable for instant food formulations and ensures good flowability during processing and packaging.

## DISCUSSION

This comprehensive investigation represents the first detailed characterization of antioxidant activities, nutritional composition, and functional properties of

traditionally fermented Dawadawa from North-Central Nigeria, specifically Kogi State. The findings reveal substantial antioxidant activity, an impressive nutritional profile, and favorable functional properties, supporting

Dawadawa's status as a functional food with significant health-promoting potential.

**Antioxidant Activities and Bioactive Compounds:** The substantial antioxidant activities exhibited by Dawadawa extracts, with DPPH scavenging of 68.4-79.6% and total phenolic content of 42.8-58.3 mg GAE/g, demonstrate significant accumulation of bioactive compounds during fermentation. These values exceed those reported for many other fermented legume products and are comparable to those of certain fruits and vegetables recognized for their antioxidant properties [1-2].

The fermentation process likely enhances the bioavailability of phenolic compounds through multiple mechanisms. Microbial enzymes, particularly  $\beta$ -glucosidases and esterases produced by fermenting bacteria, hydrolyze glycosidic and ester bonds that bind phenolic compounds to cell wall components [3]. This enzymatic hydrolysis releases free phenolic compounds that exhibit greater antioxidant activity than their bound precursors [4]. Additionally, fermenting microorganisms may synthesize novel phenolic compounds through amino acid metabolism and other biosynthetic pathways [5].

The strong positive correlations between phenolic content and antioxidant activities ( $r=0.82$  for DPPH,  $r=0.86$  for FRAP) confirm that polyphenolic compounds constitute major contributors to radical scavenging capacity [6]. These correlations suggest that phenolic compounds, rather than other potential antioxidants such as peptides or vitamins, are primarily responsible for the observed antioxidant effects. The high FRAP values (156.3-234.7  $\mu\text{M FE/g}$ ) indicate substantial electron-donating capacity, which represents an essential mechanism of antioxidant action [7].

The antioxidant properties of Dawadawa carry significant health implications. Oxidative stress, resulting from an imbalance between pro-oxidant and antioxidant systems, has been implicated in the pathogenesis of

chronic diseases, including cardiovascular disease, diabetes, neurodegenerative disorders, and cancer [8,9]. Dietary antioxidants help neutralize reactive oxygen species and protect cellular components from oxidative damage [10]. Regular consumption of antioxidant-rich fermented foods may help reduce oxidative stress and support overall health [11].

**Nutritional Composition:** The protein content of 35.2-42.7% validates Dawadawa as a valuable protein source for populations where animal protein access may be limited. This protein content is comparable to or exceeds that of many plant-based protein sources, including soybeans (approximately 36%), chickpeas (approximately 20%), and lentils (approximately 26%) [12]. The high protein content is particularly remarkable considering that fermentation typically reduces total protein through proteolysis [13]. However, this proteolysis enhances protein digestibility and generates bioactive peptides with various physiological activities, including antihypertensive, antioxidant, and antimicrobial effects [14-15]. Fermentation-induced protein modifications likely contribute to the functional properties of Dawadawa beyond its fundamental nutritional value [16]. The amino acid profiling, which reveals all essential amino acids in proportions meeting FAO/WHO requirements, represents a significant nutritional advantage. The high content of leucine (7.8-9.2 g/100g protein), lysine (6.4-7.8 g/100g protein), and phenylalanine (5.6-6.9 g/100g protein) is particularly notable as these amino acids are often limiting in plant-based diets [17]. Lysine, frequently deficient in cereal-based diets, is abundantly present in Dawadawa, suggesting its potential as a complementary protein source when combined with cereals [18]. The substantial glutamic acid content (15.2-18.6 g/100g protein) contributes to the characteristic umami flavor of Dawadawa, enhancing its palatability and culinary applications [19]. This flavor-active amino acid may

partially explain the widespread traditional use of Dawadawa as a flavoring agent in various dishes.

**Mineral Content and Micronutrient Significance:** The mineral analysis, revealing high levels of calcium (184.6-246.8 mg/100g), iron (12.4-18.7 mg/100g), zinc (3.8-5.6 mg/100g), magnesium (86.4-124.6 mg/100g), and phosphorus (234.8-316.4 mg/100g) addresses critical micronutrient needs. The iron content is particularly significant, given that iron deficiency is the most prevalent micronutrient deficiency worldwide, affecting approximately 1.6 billion people [20]. The fermentation process may enhance mineral bioavailability by reducing phytic acid, a potent inhibitor of mineral absorption [21]. Phytases produced by fermenting microorganisms hydrolyze phytic acid, releasing bound minerals and improving their absorption [22]. This enhancement of mineral bioavailability represents a significant nutritional advantage of fermented legumes over their unfermented counterparts [23]. The substantial calcium and phosphorus contents support bone health, particularly important for populations with limited dairy consumption [24]. The zinc content is adequate for supporting immune function, wound healing, and numerous metabolic processes [25]. Magnesium plays critical roles in energy metabolism, protein synthesis, and cardiovascular function [26].

**Regional Variations and Quality Implications:** The regional variations in antioxidant activities and bioactive compound content across the three collection locations reflect complex interactions among multiple factors. Anyigba samples consistently demonstrated superior characteristics, including higher antioxidant activity and greater phenolic content, compared to Dekina and Ankpa samples. These differences may relate to several factors, including variations in raw material quality influenced by soil conditions and agricultural practices, differences in fermentation temperature and duration based on

seasonal timing and local practices, variations in microbial communities influenced by fermentation vessels and environmental factors, and differences in processing methods such as boiling duration and seed preparation techniques [27-28].

Understanding these regional variations is essential for quality standardization initiatives and preservation of traditional production methods that yield superior products. The identification of Anyigba as a producer of Dawadawa with enhanced antioxidant properties could inform best-practice guidelines for commercial production and serve as a model for quality improvement in other production locations [29].

**Functional Properties and Application Potential:** The functional properties, including water absorption capacity (1.82-2.34 g/g), oil absorption capacity (1.46-1.94 g/g), and bulk density (0.54-0.68 g/mL), indicate good potential for incorporation into various food formulations. These properties influence texture, mouthfeel, and overall acceptability of food products [30]. The moderate water absorption capacity suggests potential applications in bakery products, soups, and sauces where moisture retention is desirable [31]. The oil absorption capacity indicates potential for use in meat products and emulsion systems [32].

**Health Implications and Functional Food Status:** The combination of substantial antioxidant activity, excellent nutritional composition, and favorable functional properties confirms Dawadawa's status as a functional food. Functional foods are defined as foods that provide health benefits beyond basic nutrition, often through bioactive compounds that modulate physiological functions [33]. Dawadawa meets this definition through multiple mechanisms, including the provision of antioxidants that protect against oxidative stress, the supply of high-quality protein and essential amino acids, the delivery of vital minerals with enhanced

bioavailability, and the potential generation of bioactive peptides through fermentation [34-35].

Regular consumption of Dawadawa may confer several health benefits, including reduced risk of chronic diseases through antioxidant protection, support for muscle maintenance and growth through high-quality protein, prevention of micronutrient deficiencies through mineral supplementation, and support for digestive health through its fiber content [36-37]. These potential benefits align with traditional knowledge systems that recognize Dawadawa as a health-promoting food [38].

**Study Limitations and Future Directions:** Several limitations warrant acknowledgment. The sample size of thirty may not capture the full extent of regional variation within Kogi State. The antioxidant assays employed, while validated and widely used, represent *in vitro* assessments that may not fully reflect *in vivo* antioxidant activities [39]. Bioavailability studies are needed to confirm that the observed bioactive compounds and nutrients are absorbed and utilized by the human body.

Future research should include comprehensive metabolomic profiling to identify specific bioactive compounds responsible for antioxidant activities, *in vivo* studies using animal models to validate antioxidant and health-promoting effects, human clinical trials to assess impact on oxidative stress markers and health outcomes, investigation of bioavailability and metabolism of bioactive compounds, and shelf-life studies to evaluate stability of antioxidant compounds during storage [40-42].

## CONCLUSIONS

This study provides the first comprehensive characterization of the antioxidant activities, nutritional composition, and functional properties of traditionally fermented Dawadawa from North-Central Nigeria, specifically Kogi State. The findings demonstrate

substantial antioxidant activity, with DPPH scavenging capacities of 68.4-79.6% and ABTS scavenging capacities of 71.2-82.5%, and significant phenolic content of 42.8-58.3 mg GAE/g. The excellent nutritional profile includes a protein content of 35.2-42.7%, a complete essential amino acid composition meeting FAO/WHO requirement, and substantial mineral content, particularly iron, calcium, and zinc.

Strong positive correlations between phenolic content and antioxidant activities confirm that polyphenolic compounds are major contributors to the functional properties of Dawadawa. Regional variations observed, with Anyigba samples demonstrating superior antioxidant characteristics, highlight the importance of location-specific production practices and quality control measures. The identification of Anyigba as a location producing superior-quality Dawadawa has important implications for establishing best-practice guidelines for commercial production, developing quality-control standards for the industry, and creating region-specific functional food products that capitalize on enhanced nutritional and bioactive properties.

These results provide scientific validation for the traditional consumption of Dawadawa and confirm its status as a functional food with significant health-promoting potential. The findings support the development of region-specific functional food products, the establishment of quality standards for commercial production, the preservation of traditional fermentation practices that yield products with enhanced nutritional and functional characteristics, and potential industrial applications in the nutraceutical and functional food sectors.

**Abbreviations:** ABTS: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); AOAC: Association of Official Analytical Chemists; DPPH: 2,2-diphenyl-1-picrylhydrazyl; FAO: Food and Agriculture Organization; FRAP: Ferric reducing antioxidant power; GAE: Gallic acid

equivalent; PVPP: Polyvinylpyrrolidone; QE: Quercetin equivalent; TAE: Tannic acid equivalent; TPTZ: 2,4,6-tripyridyl-s-triazine; WHO: World Health Organization

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**Authors' Contributions:** ZDA: Conceptualization, methodology, investigation, formal analysis, data curation, writing-original draft preparation. AAM: Conceptualization, validation, resources, writing-review and editing, supervision, project administration.

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