International Journal on Food, Agriculture, and Natural Resources
Volume 7, Issue 2, Page 1-6
ISSN: 2722-4066
http://www.fanres.org

Review Paper

Functional Composite Flour from Nigerian Indigenous Crops for Nutraceutical Applications: A Systematic Review and Proposed Open-Source Processing Framework

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Received: 22 April 2026; Revised: 26 June 2026; Accepted: 28 June 2026
DOI: *https://doi.org/10.46676/ij-fanres.v7i2.651*

Abstract*—Composite flour technology represents a strategic avenue for reducing wheat import dependence, elevating the nutritional quality of staple food products, and valorising Nigeria's rich portfolio of underutilised indigenous crops. This systematic review examines the published nutritional, functional, and nutraceutical properties of four candidate crops—Bambara groundnut (Vigna subterranea), tiger nut (Cyperus esculentus), unripe plantain (Musa paradisiaca), and Moringa oleifera leaf powder—with a focus on their suitability for composite flour formulation targeting nutraceutical applications. Evidence from 23 peer-reviewed sources published between 2007 and 2023 was synthesised. Bambara groundnut contributes protein concentrations of 17–23%, complementary amino acids, and demonstrated antioxidant phenolics. Tiger nut provides distinctive resistant starch, prebiotic oligosaccharides, and oleic-acid-rich lipid fractions. Unripe plantain supplies a high resistant starch content (18–32%), potassium, and B-group vitamins with documented glycaemic index-lowering potential. Moringa oleifera leaf powder constitutes an exceptional source of bioactive phenolics (120–380 mg GAE/100g), vitamins, and minerals. Published composite flour studies incorporating these crops confirm significant enhancements in protein, fibre, antioxidant activity, and techno-functional properties over wheat flour controls. Based on this evidence, a conceptual open-source processing framework covering pre-processing, drying, milling, sieving, and blending specifications for small-scale and community-scale production is proposed and released under a Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) licence. Critical research gaps are identified, including the need for in vivo bioavailability studies, anti-nutritional factor profiling at optimised processing conditions, and sensory acceptability evaluation of end products.

Keywords*—bambara groundnut; composite flour; Cyperus esculentus; functional food; Moringa oleifera; nutraceutical; open-source processing; unripe plantain; Vigna subterranea; wheat substitution

I. INTRODUCTION

Malnutrition, in its multiple forms—undernutrition, micronutrient deficiency, and diet-related non-communicable diseases—remains a defining public health challenge in Nigeria and across sub-Saharan Africa. According to the World Health Organization [1], an estimated 149 million children under five years of age globally suffered from stunting in 2022, with the burden disproportionately concentrated in West Africa. Nigeria's 2023 Demographic and Health Survey recorded childhood stunting prevalence of 37%, while iron deficiency anaemia affects more than 70% of children under two years in the country [2]. Concurrent with undernutrition, the prevalence of obesity, type 2 diabetes, hypertension, and cardiovascular disease is rising sharply as dietary patterns shift toward energy-dense, nutrient-poor ultra-processed foods [3].

A central contributor to this nutritional paradox is the near-exclusive dependence of Nigerian food processing and baking industries on imported wheat flour. Nigeria imports approximately 4–5 million metric tonnes of wheat annually, representing a substantial drain on foreign exchange reserves and leaving the food supply chain vulnerable to global commodity price shocks [4]. Composite flour technology—the partial or full substitution of wheat with flours derived from indigenous crops—offers a technically feasible and economically rational pathway to address both dimensions of this challenge simultaneously. Properly designed composite flours can elevate protein, dietary fibre, and micronutrient density while reducing import dependence and creating demand for locally grown crops [5].

Nigeria's agro-ecological diversity sustains a wide portfolio of underutilised food crops with well-documented nutritional and bioactive properties. Among the most promising are Bambara groundnut (Vigna subterranea), a drought-tolerant legume indigenous to West Africa; tiger nut (Cyperus esculentus), a tuber crop extensively cultivated in the northwest geopolitical zone; unripe plantain (Musa paradisiaca), a staple across Nigeria's humid forest belt; and Moringa oleifera, whose leaf powder is increasingly recognised globally as a functional food ingredient of exceptional phytochemical richness [6,7,8,9]. Despite substantial individual characterisation of these crops in the literature, a rigorous synthesis evaluating their combined potential as a functional composite flour system, accompanied by an open-source

processing framework enabling replication at community scale, has not previously been published.

This review addresses that gap with four specific objectives: (i) to synthesise published evidence on the nutritional, functional, and nutraceutical properties of Bambara groundnut, tiger nut, unripe plantain, and Moringa oleifera leaf powder; (ii) to survey existing composite flour studies incorporating these crops and evaluate their reported outcomes; (iii) to identify critical research gaps requiring future experimental investigation; and (iv) to propose and release an open-source processing framework for composite flour production from these crops in alignment with the open-source mandate of this journal.

II. Review Methodology

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines adapted for food science literature [10]. Eligible studies were identified through searches of three electronic databases: Scopus, Web of Science, and Google Scholar, using the following keyword combinations: ("Bambara groundnut" OR "Vigna subterranea"), ("tiger nut" OR "Cyperus esculentus"), ("unripe plantain" OR "Musa paradisiaca"), ("Moringa oleifera"), each crossed with ("composite flour" OR "nutraceutical" OR "functional food" OR "proximate composition" OR "phytochemical"). Searches were restricted to English-language peer-reviewed publications from 2007 to 2023 to capture contemporary analytical methods and reporting standards.

Studies were included if they reported: (a) proximate composition, functional properties, or phytochemical/antioxidant data for any of the four target crops in flour form; or (b) composite flour formulations involving at least one target crop evaluated against a wheat flour control. Studies were excluded if: raw grain rather than processed flour was characterised; analytical methods were not described; or data were drawn from conference abstracts without peer-reviewed publication. An initial pool of 147 records was screened by title and abstract, yielding 58 eligible full texts, of which 23 met all inclusion criteria and are synthesised in this review.

III. Bambara Groundnut: Nutritional and Functional Profile

Bambara groundnut (Vigna subterranea (L.) Verdc.) is a leguminous crop indigenous to West and Central Africa, prized for its drought tolerance, nitrogen-fixing capacity, and ability to thrive on marginal soils where other grain legumes fail [6]. Often described as a "complete food" on account of its balanced macronutrient profile, it constitutes a staple protein source for millions of smallholder households in the Nigerian savanna belt.

A. Proximate Composition

Published proximate values for Bambara groundnut flour (BGF) vary with variety, soil conditions, processing method, and analytical protocol, but consistently place protein in the range of 17.0–23.5% (dry weight basis) [6,11,12]. This exceeds the protein content of cassava (1–2%), plantain (3–6%), and approaches that of soybean (35–40%), making it the principal protein contributor in indigenous composite flour formulations. The amino acid profile of BGF is characterised by high lysine content (5.8–8.2 g/16g N), which complements the lysine-limiting cereal flours [13]. Crude fat ranges from 4.5 to 8.2% and crude fibre from 4.2 to 7.8%, while ash content of 2.1–3.8% indicates meaningful mineral density. Carbohydrate content, calculated by difference, ranges from 60 to 72% [6,11,12].

TABLE I. Published Nutritional and Functional Properties of Bambara Groundnut Flour from Selected Studies

Parameter	Reported Range (%)	Key References
Moisture	6.2–11.4	Arise et al. [6]; Nwosu et al. [12]
Crude Protein	17.0–23.5	Arise et al. [6]; Oyeleke et al. [11]
Crude Fat	4.5–8.2	Oyeleke et al. [11]; Nwosu et al. [12]
Crude Fibre	4.2–7.8	Arise et al. [6]
Ash	2.1–3.8	Oyeleke et al. [11]
Carbohydrate	60.0–72.0	Arise et al. [6]; Nwosu et al. [12]
WAC (g/g)	1.42–2.18	Arise et al. [6]
OAC (g/g)	0.98–1.84	Arise et al. [6]

WAC = Water absorption capacity; OAC = Oil absorption capacity. All proximate values on dry weight basis.

B. Functional Properties

The water absorption capacity (WAC) of BGF reported in the literature ranges from 1.42 to 2.18 g/g and oil absorption capacity (OAC) from 0.98 to 1.84 g/g [6]. These values are considerably higher than those of wheat flour (WAC ~1.2 g/g; OAC ~0.9 g/g), attributable to the greater hydrophilic surface area presented by BGF's globular protein fractions (vicilin and legumin) and its porous starch granule morphology [6,14]. High WAC is technologically advantageous in baked goods, extruded products, and weaning foods where moisture retention improves texture and shelf life.

Soaking and dehulling, commonly applied pre-processing steps, reduce trypsin inhibitor activity by 55–72% and phytic acid content by 40–60% without significant loss of protein or functional properties [12]. Fermentation of BGF has been reported to further improve protein digestibility from approximately 62% to 78% while marginally reducing mineral-binding anti-nutrients [15].

IV. Tiger Nut: Nutritional and Functional Profile

Tiger nut (Cyperus esculentus L.), known locally as "aya" (Hausa) or "ofio" (Yoruba), is a sedge whose small tubers have been consumed in Nigeria and across the Mediterranean for centuries. The brown ecotype predominates in northern Nigeria and produces the flour most widely investigated in Nigerian food science literature [7,8].

A. Proximate Composition

Tiger nut flour (TNF) is characterised by a distinctive macronutrient profile that sets it apart from legume and cereal flours alike. Crude fat ranges from 18.4 to 28.7% [7,8,16], with oleic acid constituting approximately 70–73% of the total fatty acid profile—a composition comparable to olive oil and associated with cardiovascular protective effects including LDL cholesterol reduction and improved arterial

TABLE II. PUBLISHED NUTRITIONAL AND FUNCTIONAL PROPERTIES OF TIGER NUT FLOUR FROM SELECTED STUDIES

Parameter	Reported Range	Key References
Moisture (%)	6.4–10.8	Jimoh et al. [7]; Chinma et al. [8]
Crude Protein (%)	4.5–9.8	Jimoh et al. [7]; Oladele & Aina [16]
Crude Fat (%)	18.4–28.7	Chinma et al. [8]; Oladele & Aina [16]
Crude Fibre (%)	9.2–16.8	Jimoh et al. [7]
Ash (%)	1.8–3.4	Chinma et al. [8]
Carbohydrate (%)	44.0–62.0	Oladele & Aina [16]
Resistant Starch (%)	10.0–18.0	Eleazu [17]
WAC (g/g)	1.08–1.76	Chinma et al. [8]
OAC (g/g)	1.12–2.34	Oladele & Aina [16]

WAC = Water absorption capacity; OAC = Oil absorption capacity. All proximate values on dry weight basis.

elasticity [7]. Protein content is modest at 4.5–9.8% but contributes a surface-active amphiphilic fraction that confers notable emulsifying and foaming functional properties [8]. Crude fibre is exceptionally high at 9.2–16.8%, with insoluble fibre predominating and providing a prebiotic substrate for colonic fermentation [7]. Resistant starch content of 10–18% has been documented in unroasted tiger nut flour, supporting its classification as a low glycaemic index ingredient [17].

B. Functional Properties and Bioactive Significance

The oil absorption capacity of TNF (1.12–2.34 g/g) is the highest among the four candidate crops reviewed, a direct consequence of the large non-polar surface area presented by its abundant lipid globules and hydrophobic protein domains [16]. This property is particularly valuable in food systems requiring flavour retention, fat emulsification, or mouthfeel enhancement. The prebiotic oligosaccharide fraction of tiger nut (principally inulins and fructo-oligosaccharides) has been demonstrated in vitro to selectively stimulate Bifidobacterium and Lactobacillus species while suppressing pathogenic Clostridium, supporting its classification as a functional ingredient for gut microbiome modulation [7].

V. UNRIPE PLANTAIN: NUTRITIONAL AND FUNCTIONAL PROFILE

Unripe plantain (Musa paradisiaca, AAB genome group) is one of Nigeria's most widely consumed staple foods, produced across the humid and sub-humid zones of the south and middle belt. Its characterisation as a flour ingredient has attracted substantial research interest on account of its exceptionally high resistant starch content in the unripe state, which falls progressively with ripening as starch is hydrolysed to soluble sugars by amylolytic enzymes [9,17].

A. Resistant Starch and Glycaemic Properties

Unripe plantain flour (UPF) contains 18–32% resistant starch (RS2 fraction), making it one of the richest non-cereal RS sources among tropical staple crops [17]. RS2 starch granules resist amylolytic digestion in the small intestine and proceed to the colon, where they undergo fermentation to short-chain fatty acids (principally butyrate), stimulating colonocyte proliferation, suppressing inflammatory cytokines, and exerting prebiotic effects comparable to tiger nut oligosaccharides [9]. The glycaemic index of unripe plantain-based foods has been reported in the range of 38–55 (compared to 70–75 for wheat bread), supporting its application in dietary interventions targeting type 2 diabetes and metabolic syndrome [17].

B. Proximate and Mineral Composition

UPF proximate composition reflects its starch-dominated dry matter content: carbohydrate ranges from 78 to 88% (dry basis), protein from 3.2 to 5.8%, and fat from 0.8 to 2.4% [9,17]. Crude fibre content ranges from 2.8 to 6.4%, and ash from 2.4 to 4.8%, indicating a meaningful potassium, magnesium, and phosphorus content consistent with the known mineral density of plantain. B-group vitamins, particularly B6 (pyridoxine), are present in concentrations sufficient to make UPF a practical dietary contributor to neurological health in populations with low animal food consumption [9].

Blanching in dilute citric acid (0.05–0.1%) prior to drying effectively inhibits polyphenol oxidase activity responsible for enzymatic browning of plantain chips, preserving both colour and ascorbic acid content during drying [9]. This step is incorporated as a critical control point in the open-source processing framework proposed in Section IX.

VI. MORINGA OLEIFERA: PHYTOCHEMICAL AND NUTRACEUTICAL PROFILE

Moringa oleifera Lam. (family Moringaceae) has been described as "the most nutritious plant yet discovered" [18], a characterisation supported by its documented content of vitamins A, B, C, and E; calcium, iron, potassium, and zinc at concentrations exceeding those of conventional vegetables on a dry weight basis; and a remarkable spectrum of bioactive phytochemicals including isothiocyanates, glucosinolates, quercetin, kaempferol, and chlorogenic acid derivatives [18,19].

A. Phytochemical and Antioxidant Properties

Total phenolic content (TPC) of Moringa leaf powder (MLP) reported across the reviewed literature ranged from 120 to 380 mg gallic acid equivalents (GAE) per 100g dry weight [19,20], exceeding the TPC of Bambara groundnut flour (40–110 mg GAE/100g) and unripe plantain flour (25–65 mg GAE/100g) by a substantial margin. Total flavonoid content ranged from 65 to 180 mg quercetin equivalents (QE) per 100g [19,20]. DPPH radical scavenging activity of 70–95% and ABTS inhibition of 65–90% have been documented in MLP, attributable principally to quercetin-3-glucoside, kaempferol-3-glucoside, and the isothiocyanate moringin [18,19].

B. Nutritional and Safety Considerations

While MLP is nutritionally exceptional, its incorporation into food formulations requires consideration of two factors: (i) heat-labile bioactive compounds, including ascorbic acid and some glucosinolates, are substantially degraded at temperatures above 60°C [18], necessitating shade drying or low-temperature forced-air drying in the processing framework; and (ii) the strong green colour and slightly bitter taste imparted by MLP can adversely affect the sensory acceptability of end products at inclusion levels above 10–15% [20]. Published sensory studies consistently identify 5–10% MLP inclusion as

TABLE III. PUBLISHED PHYTOCHEMICAL AND PROXIMATE PROPERTIES OF UNRIPE PLANTAIN FLOUR AND MORINGA OLEIFERA LEAF POWDER

Parameter	Unripe Plantain	Moringa Leaf	Key References
Protein (%)	3.2–5.8	25.0–31.0	Oluwajuyitan & Ijarotimi [9]; Ijarotimi et al. [20]
Fat (%)	0.8–2.4	4.2–9.6	Oluwajuyitan & Ijarotimi [9]
Crude Fibre (%)	2.8–6.4	7.8–14.2	Oluwajuyitan & Ijarotimi [9]; Fuglie [18]
Ash (%)	2.4–4.8	6.4–12.8	Fuglie [18]
Carbohydrate (%)	78.0–88.0	30–45	Eleazu [17]; Ijarotimi et al. [20]
Resistant Starch (%)	18.0–32.0	N/A	Eleazu [17]
TPC (mg GAE/100g)	25–65	120–380	Singleton & Rossi [21]; Ijarotimi et al. [20]
TFC (mg QE/100g)	12–38	65–180	Ijarotimi et al. [20]
DPPH Scavenging (%)	20–55	70–95	Ijarotimi et al. [20]

TPC = Total phenolic content; TFC = Total flavonoid content; DPPH = 2,2-diphenyl-1-picrylhydrazyl; N/A = not applicable. Dry weight basis.

the acceptable ceiling in most composite flour applications, a boundary that has informed the formulation framework proposed in Section IX.

VII. COMPOSITE FLOUR TECHNOLOGY: PRINCIPLES AND INDIGENOUS APPLICATIONS

Composite flour technology, formally proposed by the Food and Agriculture Organization in the 1960s as a wheat import reduction strategy for developing nations [5], involves blending flours from two or more food crops to achieve nutritional and functional complementarity. The theoretical basis rests on the principle of protein complementation: lysine-rich legume flours compensate for the lysine limitation of cereal and starchy tuber flours, elevating the composite's protein digestibility-corrected amino acid score (PDCAAS) toward values approaching those of animal proteins [13].

In the Nigerian context, published composite flour studies have demonstrated that partial wheat substitution with Bambara groundnut flour at 20–40% improves protein content by 40–85% while maintaining acceptable loaf volume and crumb texture in bread [5,6]. Tiger nut flour substitutions of 10–25% in chin-chin and biscuit formulations improved oil absorption and imparted a pleasant nutty flavour, with overall acceptability scores remaining within the acceptable range [22]. Moringa leaf powder addition at 5–10% significantly elevated iron and vitamin A content in weaning foods, with no adverse effect on sensory properties at the 5% level [20]. Unripe plantain flour at 30–50% substitution in composite cookies and noodles reduced glycaemic index by 18–28% relative to wheat controls [9,17].

A. Techno-Functional Considerations

The success of composite flour formulations depends critically on matching the functional properties of the component flours to the target product's technological requirements. Water absorption capacity, oil absorption capacity, bulk density, swelling power, gelatinisation temperature, and pasting profile all change significantly as wheat substitution increases [14]. Products requiring an open gluten network (yeast-leavened bread) are more sensitive to wheat substitution than those relying on starch gelatinisation or fat-based structure (cookies, extrudates, porridges), explaining why the latter category is more amenable to high indigenous flour inclusion rates [5,14]. For nutraceutical applications—including complementary foods, functional porridges, and therapeutic food products—the texture constraints applicable to bread are relaxed, permitting higher substitution and therefore greater nutritional enhancement.

VIII. NUTRACEUTICAL POTENTIAL OF INDIGENOUS CROP COMPOSITE FLOURS

The nutraceutical value of a composite flour system is determined not merely by the arithmetic sum of its components' bioactive contents but also by the interactions—synergistic, additive, or antagonistic—among phytochemicals, proteins, starches, and dietary fibre during blending, storage, and digestion. Published evidence on multi-crop indigenous composite flours indicates that synergistic antioxidant interactions between legume isoflavones and Moringa polyphenols can elevate total antioxidant activity above predicted additive values in binary and tertiary mixtures [19,20].

The prebiotic fibre contributions of tiger nut (fructooligosaccharides, inulin) and unripe plantain (resistant starch) are functionally complementary rather than redundant: RS2 granules from plantain preferentially stimulate butyrate-producing Firmicutes, while tiger nut oligosaccharides primarily enrich Bifidobacterium populations, together producing a broader spectrum microbiome modulation response than either substrate alone [7,17]. This dual prebiotic mechanism has potential therapeutic relevance for irritable bowel syndrome, colorectal cancer risk reduction, and immune system priming in early childhood, conditions for which dietary fibre diversity is a recognised protective factor.

From a mineral nutrition perspective, the combination of Moringa leaf powder (rich in calcium, iron, and zinc) with Bambara groundnut (rich in potassium, phosphorus, and magnesium) produces a composite mineral profile that addresses the most prevalent micronutrient deficiencies in Nigerian populations [1,18]. However, the bioavailability of these minerals is substantially modulated by anti-nutritional factors—principally phytic acid and tannins—present in Bambara groundnut. Soaking and dehulling have been shown to reduce phytate content by 40–60% [12], improving the predicted fractional absorption of iron and zinc by 1.5–2.3-fold, and this pre-processing step is therefore a critical quality assurance element in the proposed framework.

IX. PROPOSED OPEN-SOURCE PROCESSING FRAMEWORK

Based on the evidence synthesised above, a composite flour processing framework is proposed for small-scale and community-scale production of functional composite flour from Bambara groundnut, tiger nut, unripe plantain, and Moringa oleifera leaf powder. The framework draws its processing parameters exclusively from published literature and is not premised on original experimental data. It is

TABLE IV. PUBLISHED PHYTOCHEMICAL AND PROXIMATE PROPERTIES OF UNRIPE PLANTAIN FLOUR AND MORINGA OLEIFERA LEAF POWDER

Study	Crops Blended	Substitution Level	Key Improvement	Reference
Makinde et al., 2020	Soy+Moringa+Plantain	30:10:60	Protein +62%; DPPH +74%	Makinde et al. [4]
Oluwajuyitan & Ijarotimi, 2019	Plantain+Moringa	90:10	Antioxidant +80%; GI reduction	Oluwajuyitan & Ijarotimi [9]
Arise et al., 2016	Bambara+Cassava	40:60	Protein +44%; WAC +38%	Arise et al. [6]
Adebayo et al., 2016	Wheat+Tiger nut	75:25	Fat +85%; Fibre +60%	Adebayo-Oyetoro et al. [22]
Ijarotimi et al., 2013	Moringa seed flour	100	TPC: 140 mg GAE; DPPH 83%	Ijarotimi et al. [20]

GI = Glycaemic index; DPPH = 2,2-diphenyl-1-picrylhydrazyl; TPC = Total phenolic content; WAC = Water absorption capacity.

intended as a conceptual design guide to be validated experimentally in future studies. All specifications are released under CC BY-SA 4.0.

A. Raw Material Sourcing and Quality Criteria

Bambara groundnut: mature dry seed, moisture ≤12%, free from mould and insect damage; reject rate < 2% on visual inspection. Tiger nut: fresh brown ecotype tubers, or sun-dried tubers with moisture ≤10%; absence of aflatoxin contamination verified by rapid lateral flow immunoassay. Unripe plantain: full green fingers, harvested at ≥85 days post-anthesis; peel-to-pulp ratio 35:65 by weight. Moringa oleifera leaves: freshly harvested mature leaves from at least 6-month-old trees; free from pesticide residue and soil contamination [18].

B. Unit Operations and Critical Parameters

Bambara groundnut pre-processing: Sort → Wash (3× potable water) → Soak (grain:water = 1:3 w/v, 8 h, 28–30°C) → Dehull (manual or mechanical) → Rinse → Dry (cabinet or solar dryer, 60°C, 8 h, target moisture ≤7.5%) → Mill (hammer mill, 0.5 mm screen) → Sieve (250 µm mesh). Critical control point: soaking duration ≥8 h to achieve ≥40% phytate reduction [12].

Tiger nut pre-processing: Sort → Wash → Dry (forced-air or solar dryer, 55°C, 10 h, target moisture ≤7%) → Mill (hammer or plate mill, 0.5 mm gap) → Sieve (250 µm). No soaking: to preserve oleic acid-rich lipid fraction and fat-soluble vitamins [7].

Unripe plantain pre-processing: Wash → Peel → Slice (5 mm chips, stainless steel slicer) → Blanch (0.1% citric acid solution, 70°C, 3 min)—critical anti-browning step [9] → Drain → Dry (60°C, 8 h, target moisture ≤7%) → Mill (0.5 mm) → Sieve (250 µm).

Moringa leaf processing: Harvest → Wash (0.05% $KMnO_4$ solution, then 3× distilled water rinse) → Shade dry on clean raised mesh racks (28–32°C, 5 days)—low temperature is mandatory to preserve heat-labile isothiocyanates and ascorbic acid [18] → Mill (high-speed blender) → Sieve (150 µm to ensure particle homogeneity in the composite).

TABLE V. PROPOSED OPEN-SOURCE COMPOSITE FLOUR FORMULATION FRAMEWORK (CONCEPTUAL; REQUIRES EXPERIMENTAL VALIDATION)

Blend Code	BGF (%)	TNF (%)	UPF (%)	MLP (%)	Target Application
PF-A	55	25	20	0	General composite flour; infant porridge
PF-B	55	25	15	5	Weaning food; functional biscuit
PF-C	50	25	15	10	Nutraceutical porridge; therapeutic diet
PF-D	45	25	15	15	Micronutrient supplement flour

BGF = Bambara groundnut flour; TNF = Tiger nut flour; UPF = Unripe plantain flour; MLP = Moringa leaf powder. Ratios derived from published literature review; not based on original experimental data. Released under CC BY-SA 4.0. Validation studies are required before commercial or clinical application.

C. Proposed Formulation Ratios

Formulation ratios are proposed based on the following optimisation logic drawn from published evidence: (i) Bambara groundnut flour as the primary protein source at ≥45% to meet WHO/FAO [13] protein density targets for supplementary foods; (ii) tiger nut flour at 25% to provide the prebiotic fibre and healthy fat fraction; (iii) unripe plantain flour at 15–20% to contribute resistant starch without excessive starch dilution of protein; and (iv) Moringa leaf powder at 5–10% to achieve meaningful mineral and phytochemical enrichment within the sensory acceptability ceiling documented in the literature [20].

D. Blending, Quality Control, and Packaging

Blending: Ribbon blender or equivalent (minimum 40 rpm, 15 min) to achieve coefficient of variation < 5% for protein content across sub-samples, as recommended by AOAC [23] homogeneity guidelines. Packaging: Moisture-barrier kraft pouches with inner polyethylene lining (WVTR < 2 g/m²/day) and oxygen absorbers (300 cc/pack). Storage: 25±2°C, relative humidity < 65%, target shelf life 6 months; validated by moisture sorption isotherm modelling using the Guggenheim-Anderson-de Boer (GAB) equation, as recommended by Ihekoronye and Ngoddy [24]. Open-source community-scale equivalent: sealed opaque polypropylene containers stored in a cool, dry room away from direct sunlight.

X. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the substantial individual characterisation of Bambara groundnut, tiger nut, unripe plantain, and Moringa oleifera in the peer-reviewed literature, several critical evidence gaps limit the immediate translation of the composite flour concept into clinical or commercial food applications.

First, no published study has evaluated the in vivo bioavailability of iron, zinc, or calcium from a composite flour incorporating all four candidate crops simultaneously, despite the recognised dependence of mineral absorption on the phytate:mineral molar ratio of the whole food matrix. Future studies should conduct rat balance trials or stable isotope

studies with processed composite flours to establish iron and zinc absorption coefficients under realistic dietary conditions.

Second, sensory evaluation data for composite flour products incorporating tiger nut at >20% and Moringa leaf powder at >10% remain sparse and methodologically heterogeneous. Standardised hedonic testing across demographically representative Nigerian consumer panels is urgently needed to define the practical inclusion ceiling for each ingredient in each product format.

Third, the shelf-life stability of the composite flour's phenolic and antioxidant fractions under realistic storage conditions (fluctuating temperature and humidity) has not been reported. Given that Moringa isothiocyanates and Bambara groundnut isoflavones are prone to oxidative degradation, kinetic stability studies are essential before shelf-life claims can be made.

Fourth, the environmental and economic sustainability of upscaling Bambara groundnut and tiger nut cultivation for flour production has not been subjected to life cycle assessment (LCA) at the crop-to-consumer level. Such analysis is necessary to ensure that the environmental benefits of wheat import reduction outweigh land-use and water-use trade-offs associated with expanded indigenous crop production.

ACKNOWLEDGMENT

The authors acknowledge the Department of Food Science and Technology, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, for academic and library support during the preparation of this manuscript, and the management of Oba Hills National Park (OHNP), Osun State, for institutional encouragement. No external funding was received for this review.

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