Nutritional improvement of millet based complementary foods – a comprehensive review

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ABSTRACT

Millets are climate resilient, nutrient dense cereals that are agronomically well suited to the semi-arid regions of Nigeria and sub Saharan Africa where child under-nutrition remains most severe, yet traditional millet based gruels are bulky, viscous, and burdened with anti-nutritional factors that limit their contribution to adequate complementary feeding. This seminar paper reviews current literature, drawn predominantly from 2021 to 2026, on the nutritional improvement of millet based complementary foods. The review examines millet's botanical and nutritional characteristics, the scale and pattern of malnutrition and complementary feeding practice in Nigeria, the anti-nutritional factors present in millet grain, and the processing and formulation technologies, including germination, fermentation, extrusion cooking, decortication, composite flour blending, bio-fortification and plant based fortification, that have been shown to improve millet's nutritional value, functional properties, protein quality, shelf life and safety. The evidence indicates that combined processing strategies and composite formulation with legumes, tubers and vegetables can substantially reduce anti-nutrient burden while improving nutrient density, digestibility and acceptability, though sensory acceptability and food safety considerations require careful, context specific optimisation. The review concludes with recommendations for processors, regulators and researchers, and identifies priority areas, including Nigeria specific biofortification trials and comparative mycotoxin exposure studies, for future investigation.

Keywords: *Biofortification, Complementary food, Fermentation, Millet, Nutritional improvement.*

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Highlights of this paper

- Germination, fermentation and extrusion markedly reduce phytate and tannin and improve mineral bioavailability in millet.
- Millet is a climate-resilient, nutrient-dense cereal well suited to complementary feeding in Nigeria's semi-arid regions.
- Biofortification trials, mycotoxin surveillance and caregiver education are needed to translate these gains into better child nutrition.

1. INTRODUCTION

Millets, comprising pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), and related small seeded cereals of the family Poaceae, have re emerged as nutrient dense, climate resilient crops capable of contributing meaningfully to food and nutrition security in the developing world (Aluoch, 2024; Food and Agriculture Organization of the United Nations, 2023). The United Nations declaration of 2023 as the International Year of Millets drew renewed attention to these "nutri cereals," whose hardiness under drought and poor soils makes them well suited to the Sudano Sahelian agro ecologies of Nigeria and sub Saharan Africa (Akinseye et al., 2024; Kumawat et al., 2026). Millets also possess a nutrient profile that in several respects surpasses the refined cereals dominating Nigerian diets, offering higher protein, fibre, calcium and iron alongside a lower glycaemic index (Anitha et al., 2024).

Despite this promise, millet based gruels traditionally prepared for infants are frequently bulky, viscous and of low nutrient density, and carry appreciable antinutritional factors, notably phytates and tannins, that impede iron, zinc and calcium bioavailability (Samtiya et al., 2021). Complementary feeding, the six to twenty three month window during which foods are introduced alongside continued breastfeeding, is a period of heightened vulnerability, and it is precisely here that unprocessed millet gruels most often fail to meet WHO recommended nutrient density thresholds (John et al., 2024; World Health Organization, 2023). In Nigeria this is reflected in persistently high stunting, wasting and micronutrient deficiency among under fives, disproportionately concentrated in the northern states where millet remains a dietary staple (John et al., 2024).

This is the problem the review addresses: millet is agronomically suited to the regions where child undernutrition is most severe, yet its traditional preparation is nutritionally ill suited to closing the complementary feeding gap. A growing body of research has investigated processing and formulation strategies, including germination, fermentation, extrusion, composite blending with legumes and vegetables, and genetic biofortification, capable of transforming millet into a nutritionally improved complementary food (Izuakor et al., 2024; Padmaja et al., 2023). Yet this evidence remains scattered across disciplinary silos, with few syntheses drawing the threads together specifically for the complementary feeding age group. A recent decade long synthesis of complementary food development across sub Saharan Africa confirms that this scattering of evidence, and the accompanying gap between bench scale formulation research and validated child health outcomes, is a regional pattern rather than one confined to millet specifically (Ogunniran et al., 2024).

This seminar paper consolidates literature published predominantly between 2021 and 2026 on the nutritional improvement of millet based complementary foods, identifies the underlying problem of low nutrient density and antinutrient burden, and distils the evidence into recommendations for researchers, processors and policy makers. It draws on peer reviewed articles and technical reports from ScienceDirect, PubMed, Frontiers, Springer, Wiley, and FAO/WHO publications, including recent Nigerian and regional formulation work such as a millet, soybean, groundnut, date palm and catfish based therapeutic food trialled in Borno State (Ali et al., 2025) and a parallel Ethiopian initiative developing nutrient dense complementary foods from locally sourced ingredients for low

income households (Shewa et al., 2025) and is organised into three chapters: this introduction; a literature review covering millet's characteristics, malnutrition and complementary feeding practice, antinutritional factors, and processing and fortification technologies; and a concluding chapter of recommendations and a way forward.

1.1. Objective of the Study

The objective of this study is to review the nutritional improvement of millet based complementary foods.

2. LITERATURE REVIEW

2.1. Millets: Botanical Classification, Types and Agronomic Significance

Millets are a heterogeneous group of small seeded annual grasses belonging to the family *Poaceae*, cultivated across arid and semi-Sarid regions of Asia and Africa for more than five thousand years (Mukherjee et al., 2025). Beyond the three species already introduced in Chapter One, the wider cultivated group also includes proso millet (*Panicum miliaceum*), kodo millet *(Paspalum* scrobiculatum), little millet (*Panicum sumatrense*), barnyard millet (Echinochloa spp.), and browntop millet (Urochloa ramosa), alongside the botanically related but agronomically similar sorghum (Sorghum bicolor), which is frequently discussed alongside millets in the nutri cereal literature because of shared drought tolerance and dietary roles (Chaturvedi et al., 2022).

As C4 plants, millets exhibit high photosynthetic efficiency and can complete their life cycle on as little as 200–700 mm of seasonal rainfall, a trait that has made them the crop of last resort in drought years across the Sudano Sahelian belt of Nigeria, Niger, Mali, and Burkina Faso (Akinseye et al., 2024; Kumawat et al., 2026; Wilson & VanBuren, 2022). India remains the world's largest producer, accounting for roughly two fifths of global output, but sub Saharan Africa hosts the crop's greatest varietal diversity and the communities most dependent on it for daily subsistence (Food and Agriculture Organization of the United Nations, 2023; Muskan et al., 2025). This UN General Assembly designation, secured through India's advocacy and the support of over seventy co sponsoring countries, has been described as charting a deliberate journey from food security toward broader public health promotion (Jain et al., 2024) and catalysed renewed investment in breeding, processing research and value chain development, with CIMMYT's Dryland Crops Program specifically targeting millet improvement for African smallholder systems (Aluoch, 2024; Food and Agriculture Organization of the United Nations, 2023) a bibliometric analysis of the resulting Scopus and ScienceDirect literature between 2018 and 2024 documented a marked acceleration in millet related publication output coinciding with the designation (Mohod et al., 2023).

Millet's climate resilience is increasingly framed not merely as an agronomic curiosity but as a food systems necessity: opportunity crop climate modelling across nineteen African staples identifies pearl millet and sorghum among the crops best positioned to sustain yields under projected warming and rainfall variability (Yang et al., 2025). In West Africa specifically, dryland smallholder adaptation studies confirm that pearl millet production remains viable under a wider range of adverse seasonal conditions than maize, reinforcing the case for its continued and expanded role in regional food security strategy (Akinseye et al., 2024).

2.2. Nutritional Composition of Millets

Millets compare favourably with, and in several respects exceed, the nutrient density of the major refined cereals that dominate Nigerian and global diets. Protein content across millet species typically ranges from about seven to twelve percent, broadly comparable to wheat and superior to polished rice, while finger millet stands out for a calcium content some thirty times higher than rice, and foxtail and little millet are noted for iron levels that likewise exceed rice by a wide margin (Jacob et al., 2024; Kumawat et al., 2026). Amino acid analysis shows that

millet proteins, while limited in lysine as is typical of cereals, provide a favourable balance of sulphur containing amino acids that complements the lysine rich but sulphur amino acid poor profile of legumes, underpinning the cereal legume complementation strategy examined in more quantitative detail in Section 2.20.

Lipid composition varies meaningfully among species: comparative analysis of little millet, kodo millet and barnyard millet found free lipid fractions ranging from sixty five to seventy one percent of total lipid, with little millet showing the highest proportion of free lipids, a factor with direct implications for oxidative rancidity during storage (Polisetty et al., 2025). Functional properties of millet proteins, including dough rheology, foaming capacity and emulsification behaviour, further broaden their applicability in composite food product development beyond simple gruels (Polisetty et al., 2025).

Millets are additionally recognised for a favourable glycaemic profile, with a systematic review and meta analysis of eighty published human studies (sixty five of which were eligible for meta analysis, covering roughly one thousand subjects) reporting an average glycaemic index of about 52.7, some 36 percent lower than milled rice or refined wheat and fourteen to thirty seven points lower than maize across all eleven millet types examined (Anitha et al., 2024; International Crops Research Institute for the Semi-Arid Tropics, 2021). This metabolic advantage, together with documented antioxidant, anti inflammatory and potential anti cancer properties attributable to millet phenolics and flavonoids, situates millet consumption within a broader public health rationale that extends beyond the immediate complementary feeding period into lifelong dietary patterns (Chellappan & Peramaiyan, 2024; Gupta et al., 2023).

Table 1 summarises the comparative proximate composition, mineral content, glycaemic index and crop water requirement of cultivated millets alongside whole grain maize and milled rice. As shown in Table 1, millets contain crude protein of 7.3–12.3 g/100g, compared with 6.0–7.0 g/100g in milled rice, and their crude fibre (1.2–9.0 g/100g), iron (1.7–9.3 mg/100g) and calcium (17–344 mg/100g, highest in finger millet) all exceed the values for maize and milled rice. Millets also show a lower glycaemic index (50–62; pooled mean 52.7) than maize (65–75) and milled rice (70–89), and complete their life cycle on 200–700 mm of seasonal rainfall against 1,000–2,500 mm for rice. Together, these values support the nutritional and agronomic case for millet as a base for complementary foods.

Table 1. Comparative proximate, mineral and glycaemic index values of cultivated millets, maize and milled rice.

Proximate/Mineral Parameter (Dry weight basis)	Cultivated Millets, Range (Pearl, Finger, Foxtail)	Maize (Whole grain)	Milled Rice	Source
Crude protein (g/100g)	7.3 – 12.3	9.0 – 10.0	6.0 – 7.0	Kumawat et al. (2026) and Jacob et al. (2024)
Crude fibre (g/100g)	1.2 – 9.0	≈ 2.0	≈ 0.4	Kumawat et al. (2026)
Iron (mg/100g)	1.7 – 9.3	≈ 2.7	≈ 0.8	Kumawat et al. (2026)
Calcium (mg/100g)	17 – 344 (Highest in finger millet)	≈ 7	≈ 10	Kumawat et al. (2026) and Jacob et al. (2024)
Glycaemic Index (mean, pooled)	50 – 62 (pooled mean 52.7)	65 – 75	70 – 89	Anitha et al. (2024) and Kumawat et al. (2026)
Crop water requirement (mm/season)	200 – 700	500 – 800	1,000 – 2,500	Kumawat et al. (2026)

Source: Anitha et al. (2024).

2.3. Millet Production, Utilisation Trends and Food Security Relevance

Global millet production has fluctuated in response to policy attention, with India's domestic sector alone expanding from roughly 14.5 million metric tonnes in 2016/17 to nearly 18 million metric tonnes in 2020/21, supported by dedicated instruments such as the National Food Security Mission and, more recently, the National Millets Mission (Muskan et al., 2025; Tomar et al., 2023). A comparative review of production trends across the wider Asia Pacific region similarly documents millet as a comparatively under invested but increasingly strategically prioritised crop across India, China and Southeast Asia (Harish et al., 2024). Africa's millet renaissance, catalysed by the international policy attention described in Section 2.1 and reinforced by CIMMYT's dryland crop strategy, seeks to replicate elements of this policy led resurgence, positioning millet as a central pillar of climate smart agriculture on the continent (Aluoch, 2024; Food and Agriculture Organization of the United Nations, 2024).

In Nigeria, millet cultivation is concentrated in the Sudano Sahelian and northern Guinea savanna zones, spanning states such as Katsina, Kano, Sokoto, Jigawa and Borno, where it is grown both as a subsistence staple and, increasingly, as a commercial crop for urban markets (Akinseye et al., 2024). Nonetheless, millet's share of national cereal production and research investment has historically lagged behind maize, rice and wheat, a pattern traced by several authors to the crop biases embedded in the mid twentieth century Green Revolution, which prioritised high input, high yielding cereals over drought tolerant but lower yielding grains (Muskan et al., 2025). The consequence has been a slower pace of varietal improvement, processing innovation and market development for millet relative to its agronomic potential, even as climate variability increasingly favours its cultivation (Singh, 2024; Yang et al., 2025).

This historical under investment has direct downstream consequences for the complementary feeding agenda examined throughout this chapter. Where maize, rice and wheat value chains in Nigeria have benefited from decades of breeding investment, input supply infrastructure, and processing equipment development driven by both public research institutes and private millers, the equivalent infrastructure for millet remains comparatively underdeveloped, meaning that many of the processing technologies reviewed in Section 2.7, including extrusion and controlled fermentation, are more readily available at industrial scale for maize- and wheat based products than for millet based ones. Closing this infrastructure gap, alongside the food systems and economic considerations examined later in Section 2.17, is therefore as much a precondition for realising millet's nutritional potential in complementary feeding as the nutritional science itself.

2.4. Complementary Feeding: Concepts, WHO Recommendations and Nutrient Density Requirements

Complementary feeding is defined by the World Health Organization as the process of introducing solid, semi solid or soft foods in addition to continued breastmilk from around six months of age, continuing alongside breastfeeding to two years or beyond (World Health Organization, 2023; World Health Organization & United Nations Children's Fund, 2021). The WHO's 2021 revision of infant and young child feeding indicators formalised three core measures of complementary feeding adequacy: minimum dietary diversity (consumption of foods from at least five of eight defined food groups), minimum meal frequency, and minimum acceptable diet, the composite of the two (World Health Organization and United Nations Children's Fund (2021) as cited in John et al. (2024)). The Codex Alimentarius standard for processed cereal based foods for infants and young children further specifies compositional requirements, including minimum protein quality and quantity, maximum moisture, and permissible levels of contaminants (Codex Alimentarius Commission, 2023).

A recurring and well documented problem is that traditional cereal only gruels, whether based on maize, sorghum or millet, gelatinise and swell on cooking to produce a viscous, bulky paste that an infant's small stomach

capacity cannot accommodate in sufficient quantity to meet daily energy and nutrient requirements (Darbe et al., 2024). Because the recommended energy density for complementary foods is on the order of 0.6 to 1.0 kilocalories per gram, and because cereal starches thicken disproportionately relative to their nutrient contribution, achieving adequate nutrient density without excessive bulk is a central technical challenge that has driven much of the processing and fortification research reviewed in this chapter (Darbe et al., 2024).

2.5. Malnutrition and Complementary Feeding Practices in Nigeria and Sub Saharan Africa

A scoping review of seventy three studies published between January 2018 and January 2023 on undernutrition among Nigerian children under five found stunting prevalence ranging from 7.2 percent in Osun State to 61 percent in Kaduna State, wasting from 1 percent in Ibadan to 29 percent in the Federal Capital Territory, and underweight from 5.9 percent in Osun to 42.6 percent in Kano, alongside anaemia prevalence of 55.2 to 75.1 percent and vitamin A deficiency of 5.3 to 67.6 percent depending on region (John et al., 2024). The same review documented persistently low rates of minimum dietary diversity and minimum meal frequency nationwide, reflecting the poor quality, rather than merely the poor quantity, of complementary feeding practice (John et al., 2024).

Complementary studies at sub national level corroborate this picture. A comparative cross sectional study in peri urban Ibadan found substantial stunting and wasting burdens alongside emerging overweight in the same population, illustrating Nigeria's dual burden of malnutrition (Bakare et al., 2023). In a Nigerian tertiary hospital immunisation clinic setting, infant and young child feeding practice among mothers of children aged six to twenty three months was likewise found to fall short of WHO recommended minimum dietary diversity and meal frequency thresholds, with knowledge and practice both improving with maternal education level, echoing the broader Nigerian pattern documented throughout this section (Olasinde et al., 2021). In Iseyin, Oyo State, appropriate complementary feeding was associated with maternal education and sustained breastfeeding continuation, with continuation to twenty to twenty three months achieved by less than half of the sampled mothers despite being critical to the Africa Union Agenda 2063 targets for reducing stunting to ten percent and wasting to five percent (Ariyo et al., 2021). National Nutrition and Health Survey data cited within this literature show stunting rising roughly 48 percent between the under six month and six to eleven month age bands, and a further 44 percent increase into the twelve to twenty three month band, precisely the window in which complementary foods, including millet based gruels, must carry the greatest share of the nutritional load (Ariyo et al., 2021).

Taken together, these Nigerian sub national studies point to a consistent pattern: the nutritional inadequacy of complementary feeding in Nigeria is driven not by a single cause but by the interaction of poor dietary quality, low maternal education and awareness, and the practical limitations of the cereal based foods, including millet, that dominate the complementary diet in food insecure households. This interaction is precisely why the technical processing and formulation solutions reviewed later in this chapter must be considered alongside, rather than instead of, the caregiver education and food systems dimensions discussed in Sections 2.17 and 2.19.

2.5.1. Benue State Nutrition Profile and Relevance to Millet Based Complementary Feeding

Because this seminar paper is being presented in Benue State, the malnutrition burden documented for Nigeria as a whole in the preceding section is usefully sharpened to the state level. The 2023–24 Nigeria Demographic and Health Survey found that 25.5 percent of children under five in Benue State are stunted, while only 6.4 percent of children aged six to twenty three months in the state achieve a minimum acceptable diet, figures that a UNICEF nutrition specialist described as placing one in every four Benue children in a state of chronic malnutrition despite

Benue's reputation as one of Nigeria's principal food producing states (Daily Asset, 2026; Federal Ministry of Health and Social Welfare of Nigeria et al., 2024). State level surveillance figures presented by the Benue State Nutrition Officer corroborate this picture, recording stunting at 25.3 percent and wasting at 6.7 percent statewide, alongside an anaemia prevalence of 51 percent among children under two, a decline in Vitamin A supplementation coverage from 62 percent in 2018 to 45.1 percent in 2024, and deworming coverage of only 21.7 percent among children aged twelve to fifty nine months (Leadership News, 2026). Benue additionally records one of the highest childhood overweight/obesity prevalences of any Nigerian state, at 25.9 percent, illustrating the same double burden of malnutrition documented nationally earlier in this section (John et al., 2024).

This state specific burden strengthens, rather than narrows, the case for the millet based complementary feeding interventions reviewed throughout this chapter. Although Benue's food economy is more closely associated with yam, rice, soybean and cassava than with millet specifically, the underlying nutritional constraints of cereal based complementary gruels, low nutrient density, antinutrient burden, and poor mineral bioavailability, documented in this and later sections apply equally wherever cereal gruels, whether of maize, sorghum or millet, form the base of the infant diet, and millet's favourable protein, mineral and glycaemic profile relative to these more locally dominant cereals (Section 2.2) offers a plausible complementary strategy for the state's caregivers and processors rather than a replacement for existing local staples.

2.6. Antinutritional Factors in Millets and Their Nutritional Implications

The principal antinutritional factors present in millet grain are phytic acid (phytate), condensed tannins, trypsin and protease inhibitors, and, in some species, oxalates, all of which are concentrated substantially in the bran and outer seed coat layers (Samtiya et al., 2021). Phytate chelates polyvalent cations, principally iron, zinc and calcium, forming insoluble complexes that pass through the gut largely unabsorbed, while tannins bind dietary protein and inhibit digestive enzymes, together constituting a major barrier to the practical nutritional value of unprocessed millet flour, particularly for the already vulnerable complementary feeding age group (Ponnapalli & Karakannavar, 2023; Samtiya et al., 2021).

The severity of antinutrient burden varies by species, cultivar and processing history. Reviews synthesising the literature report that decortication alone can reduce phytic acid by up to roughly fifty three percent and total polyphenolic content by about nine percent in pearl millet, with further reductions achievable through combinations of soaking, germination, fermentation, roasting and cooking (Samtiya et al., 2021). Because each reduction strategy operates through a different biochemical mechanism, enzymatic activation during germination, microbial and enzymatic action during fermentation, and thermal denaturation during roasting or cooking, and because each carries distinct trade offs for other nutrients, this body of evidence has directly informed the processing technologies discussed in Section 2.7.

Table 2 presents the quantified effect of the principal processing methods on phytate, tannin and protease inhibitor content in pearl millet, finger millet and sorghum. As shown in Table 2, natural fermentation produced the largest reductions in phytate (81.5–99.2%) and tannin (72.4–96.1%), whereas germination lowered phytate from 15.11 to 8.34 mg/100g and decortication removed up to 53% of phytate. Roasting and cooking were comparatively less effective against phytate (28.4% and 75.8%, respectively) but achieved very high reductions in trypsin and protease inhibitors (95.8–98.3%), which is why combined processing strategies are generally favoured.

Table 2. Quantified effect of processing methods on antinutritional factors in pearl millet, finger millet and sorghum.

Processing Method	Phytate Reduction	Tannin Reduction	Trypsin/Protease Inhibitor Reduction	Source
Decortication (dehulling)	Up to 53%	Total phenolic content reduced by ≈9%	Not reported	Samtiya et al. (2021)
Germination/malting (pearl millet, finger millet, sorghum)	15.11 → 8.34 mg/100g (≈45% decrease)	Significant decrease; saponin content rises concurrently	Not reported	Sharma, Anurag, and Garg (2023)
Natural fermentation (pearl millet Injera)	81.5% – 99.2%	72.4% – 96.1%	Not assessed (mineral bioaccessibility rose instead: Fe 62.1–73.5%, Zn 53.8–83.3%, Ca 19.6–54.6%)	Yehuala et al. (2025)
Roasting	28.4%	74.6%	Trypsin inhibitor 98.3%; protease inhibitor 97.5%	Samtiya et al. (2021)
Cooking (Boiling/autoclaving)	75.8%	42.0%	Trypsin inhibitor 95.8%; protease inhibitor 95.8%	Samtiya et al. (2021)

Beyond phytate and tannin, oxalate content in some millet species and cultivars has received comparatively less research attention despite its own capacity to bind calcium and, at high dietary intakes, contribute to renal stone risk; the antinutrient reduction literature synthesised in Table 2 nonetheless indicates that the same processing interventions effective against phytate and tannin, particularly fermentation and germination, also reduce oxalate content substantially, since the underlying mechanisms of microbial and enzymatic breakdown are not compound specific. This convergence is practically important for complementary food formulation, because it means that a single well optimised combined processing protocol, rather than a suite of compound specific interventions, can be expected to address the antinutrient burden of millet grain as a whole, simplifying both research validation and eventual technology transfer to small scale Nigerian processors.

2.7. Processing Techniques for Nutritional Improvement of Millet

A wide range of processing interventions has been investigated for their capacity to simultaneously reduce antinutrient burden, improve nutrient bioavailability, and modify the physical properties of millet flour toward a form more suitable for complementary feeding. A broad review of nutritional and functional changes occurring in millet during processing confirms that virtually every unit operation applied to the grain, including milling, soaking, germination, fermentation, and thermal treatment, alters its antinutrient, mineral bioaccessibility and functional profile to some degree, underscoring that processing choice is a primary determinant of the finished product's nutritional value rather than a minor formulation detail (Yousaf et al., 2021). The four broad categories reviewed here, germination, fermentation, extrusion cooking, and decortication or thermal treatment, are frequently used in combination rather than isolation in the recent literature.

2.7.1. Germination and Malting

Germination activates endogenous phytase and other hydrolytic enzymes within the grain, and the resulting study data are consistent across recent trials: phytate content in pearl millet, finger millet and sorghum was found to fall significantly, from around 15.11 to 8.34 mg per 100g in one representative study, while tannin content likewise decreased, even as saponin content and total phenolic content rose, alongside an increase in DPPH radical

scavenging antioxidant activity (Sharma et al., 2023). Germination has also been shown to reduce the bulk density and swelling power of finger millet and sorghum flours, a physical change that is directly beneficial for producing lower viscosity infant gruels of higher achievable nutrient density per unit volume (Sharma et al., 2023). In composite applications, optimised germination time, temperature, mixing ratio and particle size have been used to improve the nutrient and energy density of pearl millet wheat composite bread, with the lowest phytate and tannin levels for pearl millet achieved after three days of germination at 30°C (Gizaw et al., 2026).

2.7.2. Fermentation

Fermentation, whether spontaneous or driven by starter cultures, degrades phytate and tannin through the combined action of endogenous and microbial enzymes, while proteolytic activity converts insoluble storage protein into more soluble and digestible forms (Anwar et al., 2026). The most striking recent evidence comes from a study of pearl millet based Injera, in which fermentation reduced phytate content by 81.5 to 99.2 percent and tannin content by 72.4 to 96.1 percent across samples, with corresponding increases in the bioaccessibility of iron (62.1–73.5%), zinc (53.8–83.3%) and calcium (19.6–54.6%) (Yehuala et al., 2025). Fermentation additionally improves carbohydrate digestibility by breaking down complex starches into simpler, more readily fermentable sugars, and reduces the gross bulk and viscosity of the resulting paste (Anwar et al., 2026).

Fermentation's benefits extend to biological outcomes beyond in vitro chemistry. In a rat feeding study comparing fermented and unfermented sorghum soybean orange fleshed sweet potato complementary diets, fermentation significantly improved protein content and the growth and haematological indices of weanling Wistar rats relative to unfermented controls, supporting fermentation's relevance not only to sorghum but, by direct analogy, to the closely related pearl millet and finger millet systems that share the same antinutrient profile (Adejuwon et al., 2021). Antinutrient dynamics reviews synthesising fifteen year trends in Nigerian composite cereal legume foods confirm fermentation as the most consistently effective single intervention across the studies examined (Afolalu et al., 2026). A parallel legume study confirms this pattern outside the cereal only context: combined germination and fermentation of pigeon pea flour over periods of twenty four to seventy two hours raised protein content substantially while improving water and oil absorption capacity, reinforcing that the same processing logic underpins nutritional improvement across both cereal and legume components of composite complementary foods (Sobowale et al., 2025).

2.7.3. Extrusion Cooking

Extrusion cooking is a high temperature, short time (HTST) thermal mechanical process that simultaneously gelatinises starch, denatures antinutritional proteins such as trypsin inhibitors, and can be tuned through screw speed, barrel temperature and feed moisture to optimise protein and starch digestibility (Bhattarai et al., 2025; Dighe et al., 2022; Yadav et al., 2022). Increasing screw speed has been shown to improve lysine retention by reducing the residence time of the feed material within the barrel, while protein digestibility in sorghum maize composite extrudates was found to correlate positively with final barrel zone temperature (Bhattarai et al., 2025).

Applied specifically to complementary food development, extrusion of finger millet flour blends into breakfast cereal produced favourable in vivo protein quality and biochemical indices in rat feeding assessments (Akinyemi et al., 2022) while pearl millet and finger millet enriched breakfast cereals developed through extrusion demonstrated superior water absorption and foaming properties relevant to obesity management diets more broadly (Krishnan et al., 2024). A review combining extrusion cooking with food to food fortification of traditional grains, including finger millet, pearl millet and sorghum, concludes that this combination represents a promising but still under

explored route to nutritionally dense instant porridges for African markets (Famuyide et al., 2024). Extrusion is not without trade offs, however: depolymerisation of phenolic compounds during processing can alter bioaccessibility of certain bioactive components, underscoring the need for process parameter optimisation rather than blanket application (Bhattarai et al., 2025; Sruthi et al., 2026). A parallel line of evidence from indigenous bean extrusion research, while conducted on a legume rather than a cereal, similarly finds that cooking and extrusion jointly reduce antinutritional factors while altering techno functional properties in ways that are highly parameter dependent, reinforcing that no single extrusion protocol can be assumed to transfer directly between raw materials without dedicated optimisation (Osuna-Gallardo et al., 2023).

2.7.4. Decortication, Roasting and Other Thermal or Hydrothermal Treatments

The effectiveness of decortication, quantified in Section 2.6, establishes the baseline against which the remaining thermal treatments in this section can be judged. Roasting achieves antinutrient reduction through thermal denaturation rather than physical bran removal, with reported reductions in tannin, phytate, trypsin inhibitor and protease inhibitor activity in pearl millet in the range of roughly 28 to 98 percent depending on the specific compound and roasting conditions, while cooking achieves comparable, if somewhat lower, reductions (Samtiya et al., 2021).

The interaction between roasting temperature and blend composition has been studied systematically using response surface methodology in a roasted pearl millet soybean complementary food, where increasing both feed composition and roasting temperature reduced flavour and taste sensory scores, attributable to the intensified beany flavour of soybean and browning reactions at higher temperatures, even as micronutrient content, including thiamin, riboflavin, folate, β carotene, zinc, calcium, potassium and iron, varied significantly with these same parameters (Omah et al., 2022). This finding illustrates a recurring tension in the literature between nutritional optimisation and sensory acceptability that formulators must navigate.

2.8. Composite Flour Technology: Millet Legume Root/Tuber Blends for Complementary Foods

Composite flour technology, blending millet with legumes, tubers, oilseeds, fruits and vegetables, remains the most extensively documented strategy for nutritional improvement of millet based complementary foods, chiefly because it directly addresses the protein quality limitation of cereal only diets. Cereal proteins are characteristically limiting in lysine, while legume proteins are limiting in sulphur containing amino acids such as methionine and cysteine; combining the two in appropriate ratios produces a more complete amino acid profile than either ingredient alone (Darbe et al. (2024) citing Ijarotimi et al. (2022)).

Numerous recent Nigerian and regional studies illustrate this principle in practice. A pearl millet, African yam bean and carrot composite achieved its highest nutrient density and greatest sensory preference at a 70:20:10 ratio, with iron ranging from 6.56 to 11.65 mg/100g and zinc from 6.48 to 8.86 mg/100g across formulations, alongside significant increases in beta carotene, ascorbic acid, thiamin, riboflavin and niacin as African yam bean and carrot inclusion increased (Arukwe et al., 2022). Similar formulations combining pearl millet, African yam bean and tiger nut produced protein contents of 12.79 to 14.63 percent and energy contents of 616.6 to 696.9 kcal per 100g, with the 70:20:10 pearl millet African yam bean tiger nut blend rated most acceptable by sensory panels (Ebabhamiegbebho et al., 2021; Olapade et al., 2021).

Finger millet has likewise been combined with orange fleshed sweet potato and soybean using mixture design optimisation across blending ratios of 45–55 percent finger millet, 30–40 percent OFSP and 10–20 percent soybean, aimed at simultaneously improving protein and provitamin A content (Ali et al., 2025). A related finger millet,

soybean and sweet potato "kita" achieved its highest sensory scores at a 70:20:10 ratio (Darbe et al., 2024). Sorghum, as a closely allied nutri cereal, has been combined with soybean and orange fleshed sweet potato under fermentation, improving protein content and micronutrient density relative to the cereal only base (Adejuwon et al., 2021).

A recent synthesis of composite flour research argues that such blends should be evaluated not only for nutrient density but for their broader environmental and climate resilience contribution, given that many of the constituent crops, including millet, share the drought tolerance discussed in Section 2.1 (Poojara et al., 2025). Fortification with less conventional ingredients has also been explored. A maize sorghum millet soybean complementary food fortified with walnut, pumpkin seed and date palm fruit improved the antioxidant and micronutrient profile relative to unfortified controls, though the authors noted that local formulations of this type frequently remain deficient in vitamin C unless a fresh fruit or vegetable component is deliberately included (Izuakor et al., 2024). Maize millet soybean blends fortified with crayfish, bonga fish and carrot flour have similarly been used to raise the essential mineral and micronutrient content of complementary food formulations for Nigerian households (Nnam et al., 2023). Co fermentation of maize, millet and pigeon pea at extended fermentation durations (up to seventy two hours) has also been investigated as a further route to nutrient dense infant complementary food (Adeoye et al., 2024).

The breadth of this Nigerian formulation literature extends well beyond the specific examples above. Pearl millet has been blended with African yam bean and jackfruit flour to produce a further weaning food variant with favourable proximate and sensory profiles (Eke-Ejiofor et al., 2021) while finger millet based composite food products, formulated and evaluated for quality independent of the studies discussed above, have likewise demonstrated the general feasibility of finger millet as a composite flour base (Feyera et al., 2021). More recent Nigerian formulation studies have combined germinated maize, millet and soybean with carrot and coconut flour (Khanal et al., 2026) sprouted sorghum and soybean with carrot flour (Onaolapo et al., 2024) yellow maize, soybean, millet and carrot composite flours (Oyegoke et al., 2021) African yam bean and carrot flour blends with malted pearl millet specifically (Bello & Udo, 2024) and other locally sourced ingredient combinations formulated explicitly to raise nutrient density using ingredients already familiar to Nigerian caregivers (Adepeju et al., 2024). The consistency of findings across this now substantial body of Nigerian formulation research, spanning multiple universities and research groups working largely independently, lends considerable confidence to the general principle that millet legume vegetable composite blending, at inclusion ratios broadly in the 60:20:20 to 70:20:10 range, reliably improves nutrient density and sensory acceptability relative to cereal only preparations.

2.9. Biofortification of Millet for Enhanced Micronutrient Density

Genetic biofortification, breeding staple crops for elevated micronutrient content, offers a complementary strategy to post harvest processing, addressing the underlying grain composition rather than relying solely on downstream treatment. Iron- and zinc biofortified pearl millet, marketed in India under the cultivar name Dhanashakti (ICTP-8203Fe), has been the subject of sustained randomised controlled trial investigation. A trial among 223 children aged 12 to 18 months in urban Mumbai slums, a population with baseline anaemia prevalence of 49.3 percent and iron deficiency of 59.6 percent, found that nine months of biofortified pearl millet based complementary feeding improved haemoglobin and growth outcomes relative to conventional, non biofortified pearl millet (Mehta et al., 2026).

This body of work builds on earlier isotope based absorption studies establishing that iron and zinc from biofortified pearl millet are bioavailable in quantities sufficient to meet, and in some cases exceed, the physiological

requirements of young children when the biofortified grain forms the dietary staple. While the bulk of this biofortification evidence originates from India, the underlying principle, that breeding for elevated Fe and Zn content can meaningfully raise the nutritional contribution of a staple already widely consumed in a target population, is directly transferable to Nigerian and West African pearl millet breeding programmes, and represents an important complement to the processing based strategies more extensively documented in the West African literature.

2.10. Fortification with Plant Based Nutrient Sources: Moringa, Vegetables and Fruits

Moringa oleifera leaf and flower powder has emerged as one of the most widely studied plant based fortificants for millet- and maize millet based complementary foods, owing to its exceptionally high content of iron, calcium, protein and provitamin A relative to the leafy vegetables more commonly available in West African diets, though a food chemistry perspective on Moringa foods cautions that variable cultivation, processing and storage conditions mean nutrient and antinutrient content can differ substantially between preparations, and that contamination risk from heavy metals and mycotoxins warrants more systematic assessment than it has so far received (Grosshagauer et al., 2021). Fortification of a fermented maize millet (Ogi) blend with Moringa oleifera flower powder at a 70:10:20 ratio produced the highest sensory acceptability among tested formulations while raising crude protein content by around sixty percent (Sokhela et al., 2023). Similarly, Moringa leaf powder supplemented mahewu demonstrated substantially higher calcium (up to 950 percent above control at the highest supplementation level) and iron (up to 287 percent above control), though consumer acceptability declined as Moringa inclusion increased, driven chiefly by changes in colour and aroma (Sokhela et al., 2023).

A pearl millet, Moringa leaf powder and dates or orange fleshed sweet potato composite, blended according to recommended dietary allowance ratios for children aged one to two years, produced significant differences in bulk density and viscosity across formulations without significant differences in water absorption capacity, with all sensory parameters (aroma, taste, colour, overall acceptability) differing significantly among blends (Salha et al., 2023). As Section 2.15 details further, shelf life studies of Moringa fortified instant complementary food confirm that fortification benefits can be undermined without accompanying attention to storage conditions (Zakaria et al., 2025).

This body of formulation specific evidence sits within a wider clinical evidence base on fortified complementary foods generally: a systematic review and meta analysis of health outcomes associated with micronutrient fortified complementary foods in children aged six to twenty three months found consistent, if modest, improvements in anaemia and micronutrient status across the fortified food trials examined, lending broader clinical support to the fortification strategies, Moringa based and otherwise, reviewed throughout this chapter (Csölle et al., 2022).

2.11. Protein Quality and Biological Evaluation of Millet Based Complementary Foods

Chemical composition alone does not establish the nutritional adequacy of a complementary food; protein quality must additionally be assessed through indices such as Protein Efficiency Ratio (PER), Protein Digestibility Corrected Amino Acid Score (PDCAAS), and true and apparent digestibility, most rigorously determined through rat bioassay. The sorghum soybean orange fleshed sweet potato trial discussed in Section 2.7.2, in which forty nine weanling Wistar rats were fed fermented and unfermented experimental diets over twenty eight days, remains the most directly relevant bioassay evidence available for this class of composite complementary food and confirms that fermentation status, not merely ingredient composition, is a determinant of realised protein quality (Adejuwon et al., 2021).

Complementary in vivo evidence comes from extruded finger millet breakfast cereal blends, in which protein quality assessment and biochemical indices in rat feeding trials confirmed that extrusion processing did not compromise, and in some formulations improved, protein utilisation relative to unprocessed flour (Akinyemi et al., 2022). The persistent finding across this literature is that cereal only millet diets are characteristically low in lysine, tryptophan and threonine, and that composite formulation with legumes such as soybean, African yam bean or pigeon pea, particularly when combined with germination, fermentation or extrusion, is required to bring essential amino acid profiles into closer alignment with the requirements of growing infants (Darbe et al., 2024).

2.12. Sensory Evaluation and Consumer Acceptability of Millet Based Complementary Foods

Because nutritional improvement is of limited practical value if the resulting product is not accepted and consumed, sensory evaluation using hedonic scales (commonly five- or nine point) administered to trained or semi trained panels, and in the case of infant directed products to caregivers as proxy evaluators, forms an integral part of nearly every formulation study reviewed in this chapter. The finger millet, soybean and sweet potato kita formulation introduced in Section 2.8 illustrates the underlying pattern well: its sensory optimum did not coincide with its maximum legume or tuber inclusion, indicating that flavour, aroma or texture attributes begin to decline once fortification passes a threshold well short of nutritional maximisation (Darbe et al., 2024).

The roasted pearl millet soybean response surface study found that both increasing feed composition (soybean proportion) and increasing roasting temperature reduced flavour and taste scores, attributed respectively to soybean's characteristic beany flavour and to Maillard browning reactions at higher roasting temperatures (Omah et al., 2022). Moringa fortified products consistently show an inverse relationship between fortificant inclusion level and consumer acceptability, with colour and aroma identified repeatedly as the most sensitive attributes (Sokhela et al., 2023). Within the millet based composite mixed complementary food literature, a fifteen percent inclusion level of the non millet fortificant component achieved the highest overall acceptance alongside strong protein digestibility, illustrating the recurring theme of an optimal fortification threshold beyond which acceptability, rather than nutrient content, becomes the binding constraint on product design (Darbe et al., 2024).

2.13. Functional and Physicochemical Properties of Millet Based Composite Flours

Functional properties, including water absorption capacity, bulk density, swelling power and pasting viscosity, determine both the processability of millet based composite flours and, critically, the achievable nutrient density of the reconstituted gruel, since lower bulk density and viscosity permit a higher solids concentration, and therefore a higher nutrient and energy density, within a volume an infant can physically consume (Darbe et al., 2024; Sharma et al., 2023). Germination has been shown to reduce bulk density and swelling power in finger millet and sorghum flours specifically, a change directly beneficial to gruel formulation (Sharma et al., 2023).

In the pearl millet Moringa dates/orange fleshed sweet potato composite study, bulk density and viscosity differed significantly across formulations according to the proportion of dates versus orange fleshed sweet potato included, while water absorption capacity did not differ significantly, illustrating that different functional properties respond independently to different formulation variables and cannot be optimised through a single compositional lever (Salha et al., 2023). A weaning food with low water absorption capacity and bulk density is additionally associated with reduced microbial proliferation potential and extended shelf life, linking functional property optimisation directly to the food safety considerations addressed in Section 2.16 (Darbe et al., 2024).

Functional property modification through non conventional flour blending has also been demonstrated outside the mainstream legume and tuber fortificants discussed above: supplementation of finger millet flour with Parinari

curatellifolia (mobola plum) flour was found to alter water absorption capacity, bulk density and pasting properties in a manner comparable to the legume- and tuber based composites reviewed elsewhere in this chapter, illustrating that the functional property principles established for mainstream fortificants extend to a wider range of indigenous African plant materials than has so far been systematically explored (Onipe et al., 2024).

2.14. Glycaemic Response and Broader Health Implications of Millet Based Foods

The same meta analysis referenced in Section 2.2 for its pooled glycaemic index finding also reported clinically relevant outcomes for people already living with impaired glucose regulation: diabetic participants consuming millet as part of their daily diet experienced fasting and post meal blood glucose reductions of twelve to fifteen percent, with average glycated haemoglobin (HbA1c) reductions of seventeen percent among pre diabetic participants, sufficient in some cases to move individuals from a pre diabetic to a normal glycaemic classification (Anitha et al., 2024; International Crops Research Institute for the Semi-Arid Tropics, 2021).

While these outcomes were documented predominantly in older children and adults rather than in the six to twenty three month complementary feeding window specifically, they carry two implications relevant to this review. First, they reinforce the case for establishing millet based dietary patterns early in the life course, given that dietary preferences and gut microbiota patterns established during complementary feeding often persist into later childhood and adulthood. Second, characterisation of finger millet's glycaemic index and amino acid composition using samples collected across a range of altitudes in India confirms that glycaemic response varies meaningfully by cultivar and growing environment, a consideration relevant to Nigerian breeding and sourcing decisions as domestic millet based complementary food industries develop (Imam et al., 2025).

2.15. Shelf Life, Packaging and Storage Stability of Millet Based Complementary Foods

Millet flour is notably more prone to rancidity than refined cereal flours because of its comparatively high lipid content and residual lipase, lipoxygenase and polyphenol oxidase enzyme activity, with milled pearl millet flour reported to have a practical shelf life of as little as five to seven days under ambient conditions before the onset of off flavours and bitterness from free fatty acid oxidation (Padmaja et al., 2023; Sruthi & Rao, 2021). This constraint has direct relevance to complementary food production in low resource settings, where cold chain storage is frequently unavailable and products may be produced in bulk for household or community level distribution, a challenge the same research group has since summarised as requiring a combination of decortication, pearling, defatting, extrusion, fermentation and malting to jointly reduce lipid content and lipolytic enzyme activity (Padmaja et al., 2024).

An integrated approach combining thermal pre treatment, laminated packaging and modified atmosphere storage has been demonstrated to substantially extend pearl millet flour shelf life by simultaneously addressing both enzymatic and oxidative degradation pathways (Padmaja et al., 2023) consistent with a broader review finding that dehulling, infrared roasting, pulsed light, ultrasound and high pressure processing methods are similarly effective at prolonging millet shelf life while retaining nutrient quality (Latha Ravi & Rana, 2024). Predictive shelf life modelling of milk millet powders based on moisture and oxygen ingress found predicted shelf lives ranging from seventeen to thirty days in basic high density polyethylene packaging up to ninety six to one hundred and thirty four days in more advanced barrier laminates, illustrating the substantial gains achievable through packaging investment alone (Pasagadi et al., 2023). For Moringa fortified instant complementary food specifically, storage at or below 30°C in semi aluminium foil packaging was found necessary to maintain microbial safety over the intended shelf life (Zakaria et al., 2025). Packaging effects are not confined to flour based products alone: research on vacuum

fried and atmospheric fried millet based snack products found that packaging type and storage condition significantly affected oxidative and textural shelf life markers, with vacuum frying combined with appropriate barrier packaging extending acceptable shelf life relative to atmospheric frying, a finding with potential relevance to future ready to eat millet based complementary food formats (Kamdi, Sivaranjani, & Rao, 2025).

2.16. Food Safety Considerations: Mycotoxins and Microbial Quality in Millet Based Complementary Foods

Mycotoxin contamination, principally by aflatoxins and fumonisins produced by Aspergillus and Fusarium species under warm, humid post harvest storage conditions, represents a significant and under addressed food safety concern for cereal based complementary foods across sub Saharan Africa. A study of complementary foods consumed by Nigerian infants and young children within their first eighteen months found aflatoxin B1 contamination of maize based ogi and tombran at levels thirty five and fifty three times the European Union's baby food threshold of 0.1 μg/kg respectively (Ezekiel et al., 2021) a finding consistent with separate dietary exposure and health risk characterisation work estimating meaningful aflatoxin B1 exposure among Nigerian infants and young children through routine complementary food consumption (Ayeni et al., 2023). In Tanzania, similar studies in Kongwa district found that maize and groundnut based porridges carried the dominant share of dietary aflatoxin exposure among complementary food ingredients (Mollay et al., 2022; Ngure et al., 2023) a pattern echoed across the wider East African region, where a review spanning Tanzania, Kenya, Uganda, Rwanda and Burundi similarly identified maize and groundnut based complementary foods as the dominant source of infant aflatoxin and fumonisin exposure (Kayanda et al., 2026).

Encouragingly for the case advanced in this review, several of these same Tanzanian studies observed that sorghum and millet, though present in the local diet, were used for complementary feeding less frequently than maize, and when analysed, carried lower and less frequent aflatoxin contamination than maize based preparations, largely because mothers reported substituting millet only when maize supplies ran short rather than as a primary staple (Mollay et al., 2021; Mollay et al., 2022). This finding suggests that deliberate promotion of millet based complementary foods could carry a secondary food safety dividend alongside its nutritional benefits, though this protective association has not yet been rigorously established as causal and warrants dedicated Nigerian investigation given the country's own documented aflatoxin burden in maize based products (Ezekiel et al., 2021). Continental early warning efforts, such as the African Postharvest Losses Information System pilot linking weather anomaly data to aflatoxin risk prediction, illustrate a further avenue through which pre harvest contamination risk affecting maize and, by extension, other cereal complementary food ingredients might eventually be forecast and mitigated at scale (Rembold et al., 2023). Microbial safety has similarly been assessed in millet based complementary and functional beverage formulations more broadly: pearl millet supplemented with African locust bean pulp, freeze dried into an instant Kunu beverage, was found to retain favourable microbial, antioxidant and sensory quality suitable for extended shelf storage (Olatoye et al., 2023).

2.17. Economic and Food Systems Considerations in Millet Based Complementary Food Production

Nutritional improvement achieved in the laboratory translates into child nutrition benefit only if the resulting product reaches households at a price and through a supply chain that low income caregivers can actually access. A December 2023 expert consultation convened by the Micronutrient Forum and USAID Advancing Nutrition, bringing together forty three specialists from nutrition, food systems, policy and business, concluded that current food systems fail to deliver nutritious complementary foods to low income households in low- and middle income countries because of four compounding barriers: limited availability, high prices relative to household income, poor

accessibility in remote areas, and weak aspirational appeal relative to imported alternatives (Micronutrient Forum, 2024). The consultation produced thirteen recommendations spanning supply chain efficiency, market readiness analysis, and caregiver centred product design, several of which are directly applicable to millet based product development in Nigeria.

A whole of systems analysis across Sahelian West Africa found that locally produced complementary foods were two to four times less expensive than imported equivalents, yet imported products continued to dominate urban markets in Burkina Faso, Chad, Mali, Mauritania, Niger and Senegal, largely because of marketing reach and distribution advantages that local producers lack; in rural areas of the same countries, supply chain inefficiencies were found to double prices relative to urban markets for both local and imported products alike (Parikh et al., 2024). A subsequent regional dialogue held in Dakar in December 2024, bringing together over one hundred stakeholders from regulatory authorities, local enterprises and financial institutions, reinforced that isolated interventions in policy, financing, production or demand creation are insufficient in isolation and that scale requires coordinated action across all four (Micronutrient Forum, 2025). A related review of sustainable complementary feeding strategies argues that prioritising nutrient rich, locally available and culturally accepted foods, of which millet is a prime West African example, can simultaneously improve child nutrition, strengthen community food sovereignty and support small scale producer livelihoods (Mazzocchi et al., 2026).

These food systems findings carry a direct implication for the Nigerian millet based complementary food agenda reviewed in this chapter: millet's status as an indigenous crop already grown and processed at household level across much of northern Nigeria confers an inherent cost advantage over imported wheat- or milk based commercial complementary foods, provided that the processing and fortification technologies documented in Sections 2.7 to 2.10 can be delivered at a scale and cost accessible to small scale local producers rather than requiring capital intensive industrial equipment (Micronutrient Forum, 2024).

2.18. International and Comparative Perspectives: India, Ethiopia and East Africa

India offers the most institutionally mature model of millet based complementary feeding development, combining the biofortified pearl millet breeding programme discussed in Section 2.9 with the sustained national policy instruments already introduced in Section 2.3, that have simultaneously expanded production and stimulated downstream processing investment (Mehta et al., 2026; Muskan et al., 2025). This combination of breeding, policy and market development distinguishes the Indian experience from that of most sub Saharan African millet producing countries, where processing innovation of the kind documented throughout this chapter has advanced substantially at the research level but has not yet been matched by comparable policy coordination or market infrastructure. A recent community led intervention in rural and tribal Andhra Pradesh illustrates this maturity at the delivery level: a twelve week programme of hands on millet recipe demonstrations targeted at mothers, rather than direct supplementation alone, produced significant improvements in dietary intake and reductions in undernutrition among children aged two to six years, underscoring that caregiver facing delivery models, not only supply side production gains, are central to translating millet nutritional potential into measured outcomes (A. Gupta et al., 2025).

Within Africa, comparative experience is more varied. Tanzania's Kongwa district mycotoxin mitigation research, discussed in Section 2.16, has generated some of the continent's most detailed data on the relative safety of millet- and sorghum based complementary foods, informing complementary feeding guidance in that context. The December 2024 Dakar regional dialogue specifically highlighted that African local producers, despite possessing strong indigenous processing traditions such as fermentation, most often lack the in house technical expertise in

formulation and food safety that larger multinational manufacturers routinely deploy, placing them at a competitive disadvantage in meeting national or international complementary food standards even when their raw nutritional and cost fundamentals are favourable (Micronutrient Forum, 2025). Nigeria is well positioned to draw lessons from both the Indian and East African experiences, combining its substantial and growing domestic research base, documented extensively throughout this chapter, with deliberate policy and market development investment of the kind that has driven India's millet resurgence.

2.19. Caregiver Knowledge, Attitudes and Practices Influencing Uptake

Even a nutritionally optimised millet based complementary food will fail to improve child nutrition outcomes if caregivers lack the knowledge or motivation to prepare and offer it appropriately. A study of caregiver knowledge, attitudes and practices among mothers of infants aged six to eight months in Maputo City, Mozambique, found that caregiver nutritional knowledge was significantly associated with timely introduction of complementary foods, greater dietary diversity, and improved iron intake, reinforcing a broader pattern already documented for Nigeria in Section 2.5, where maternal education level was similarly associated with complementary feeding adequacy in both the Lagos and Iseyin study populations(Manuel et al., 2025).

This evidence carries a specific implication for millet promotion: the "aspirational appeal" barrier identified in the food systems literature (Section 2.17) suggests that millet based complementary foods may face a perception challenge among caregivers who associate imported, commercially packaged infant formulas and cereals with higher status or superior quality, irrespective of their actual nutritional composition (Micronutrient Forum, 2024). Nutrition education interventions that pair practical processing instruction, such as the low cost household germination and fermentation techniques reviewed in Section 2.7, with messaging that directly addresses these perceptions are therefore likely to be necessary alongside, rather than instead of, the technical nutritional improvements documented elsewhere in this chapter.

2.20. Protein Quality Indices: Amino Acid Adequacy of Millet and Millet Legume Combinations

Beyond crude protein percentage, protein quality is more precisely characterised through indices such as the Essential Amino Acid Index (EAAI) and identification of the first limiting amino acid, both of which determine how effectively a food's protein can support growth. Comparative amino acid scoring of pearl millet, sorghum, finger millet and oat against WHO/FAO reference standards found that pearl millet and sorghum both achieved an EAAI above 90, indicating good quality protein, while sorghum's first limiting amino acid was identified as isoleucine and the analysed millets were found to contain higher tyrosine than phenylalanine, a profile of some relevance to metabolic health beyond growth alone (Shilpa et al., 2023). The same evaluation quantified lysine content in oat and pearl millet at approximately 1,822 and 1,682 micrograms per 100g respectively, figures that, while appreciable, remain well below the lysine density of grain legumes and underscore why cereal only millet diets require legume complementation to meet the essential amino acid requirements of growing infants, a principle first introduced in Section 2.8 and revisited here with more precise quantification.

Table 3 compares the protein quality indices of pearl millet, sorghum, finger millet and oat against WHO/FAO reference standards, with a legume comparator. As shown in Table 3, pearl millet and sorghum both recorded an Essential Amino Acid Index above 90, indicating good quality protein, while lysine remained the limiting amino acid in the millets (approximately 1,682 µg/100g in pearl millet, against 1,822 µg/100g in oat) and isoleucine was the first limiting amino acid in sorghum. By contrast, the legume comparator was limited by methionine, which explains why cereal–legume combinations give a more complete amino acid profile than either component alone.

Table 3. Protein quality indices of selected millets and allied cereals relative to WHO/FAO reference standards.

Cereal	Essential Amino Acid Index (EAAI)	First Limiting Amino Acid	Lysine Content (µg/100g)	Source
Pearl millet (Pennisetum glaucum)	> 90 (good quality)	Lysine (relative to legumes)	≈ 1,682	Shilpa et al. (2023)
Sorghum (Sorghum bicolor)	> 90 (Good quality)	Isoleucine	Not separately reported	Shilpa et al. (2023)
Finger millet (Eleusine coracana)	Reported alongside pearl millet/sorghum	Lysine	Lower than pearl millet	Shilpa et al. (2023)
Oat (comparator cereal)	Reported alongside millets	Lysine	≈ 1,822	Shilpa et al. (2023)
Pigeonpea / chickpea (Legume comparator)	Meets 50–100% DV of most EAAs except methionine	Methionine	Substantially higher than millets	Anitha et al. (2024) synthesis

2.21. Standardisation, Quality Control and Regulatory Compliance for Commercial Production

Moving validated millet based complementary food formulations from research bench to commercial or institutional scale production requires demonstrable compliance with the Codex Alimentarius compositional and safety standard introduced in Section 2.4, including the mycotoxin thresholds discussed in Section 2.16 (Codex Alimentarius Commission, 2023). In practice, achieving and demonstrating this compliance is disproportionately difficult for small scale African producers: larger multinational manufacturers typically maintain in house formulation science and food safety testing capacity that allows routine demonstration of standards compliance, whereas small scale local producers, who are often best positioned to supply culturally appropriate and affordably priced millet based products, most frequently lack equivalent technical infrastructure (Parikh et al., 2024).

Closing this capacity gap has been identified as a priority action area by both the 2024 Micronutrient Forum consultation and the 2024 Dakar regional dialogue, which called for targeted investment in shared or subsidised testing infrastructure, simplified regulatory pathways appropriate to small scale producer capacity, and technical partnerships between research institutions, such as Nigerian universities with food science departments, and local processors (Micronutrient Forum, 2024, 2025). This represents a concrete avenue through which the substantial Nigerian research base documented throughout this chapter could be translated into commercially viable, regulator compliant products.

2.22. Emerging and Future Processing Innovations

Alongside the established processing technologies reviewed in Section 2.7, a smaller but growing body of research is examining non thermal and physical processing innovations for millet. Gamma irradiation combined with genotype selection has been shown to influence the structural, techno functional and microbial quality properties of millet flour, offering a possible complementary safety enhancing step alongside conventional processing (Wani et al., 2022). Building on this, an ongoing randomised controlled trial protocol for a finger millet based complementary food formulated specifically to treat moderate acute malnutrition in Indian children combines several of the processing principles reviewed in this chapter, germination, controlled fermentation and precise nutrient density formulation, into a single clinically validated product, with gut microbiota modulatory effects assessed alongside conventional growth and biochemical outcomes (Rai et al., 2025). Such integrated, clinically validated formulations represent a plausible future direction for Nigerian millet based complementary food

development, moving beyond the largely bench scale formulation and sensory studies that currently dominate the local literature toward rigorously trialled products with demonstrated clinical efficacy.

2.23. Summary of Reviewed Literature

The literature reviewed in this chapter converges on a consistent picture. Millet is nutritionally competitive with, and in several respects superior to, the refined cereals that dominate Nigerian complementary feeding practice, and it is agronomically better suited to the drought prone regions where child undernutrition remains most severe. As a broader public health commentary has argued, integrating millets more deliberately into national food systems represents a viable path for addressing malnutrition alongside the specific technical strategies documented here (Ahmed et al., 2024). Its principal nutritional limitations for infant feeding, namely high antinutrient burden, high bulk and viscosity in traditional preparation, limited protein quality, short shelf life, and variable mycotoxin exposure, are all demonstrably addressable through processing interventions (germination, fermentation, extrusion, decortication and roasting), composite formulation with legumes, tubers and vegetables, plant based fortification, and genetic biofortification. These technical solutions must, in turn, be matched by deliberate attention to the economic, regulatory and caregiver behavioural dimensions reviewed in Sections 2.17 to 2.21 if they are to translate into measurable improvements in child nutritional status. Table 4 below summarises a representative cross section of the specific studies underpinning these conclusions.

Table 4. Summary of selected recent studies on the nutritional improvement of millet based complementary foods.

Author(s)/Year	Millet Type / Blend	Processing / Method	Key Finding
Padmaja et al. (2023)	Pearl millet flour	Thermal treatment + laminated packaging + modified atmosphere	Shelf life extended well beyond the typical 5–7 days for milled pearl millet flour
Yehuala et al. (2025)	Pearl millet, pearl millet–maize composite	Natural fermentation	Phytate reduced 81.5–99.2%; tannin reduced 72.4–96.1%; Fe, Zn, Ca bioaccessibility increased
Sharma et al. (2023)	Pearl millet, finger millet, sorghum	Germination (malting)	Phytate fell from about 15.11 to 8.34 mg/100g; tannin decreased; total phenol and DPPH activity increased
Ali et al. (2025)	Finger millet, orange fleshed sweet potato, soybean	Mixture design composite blending	Optimised blends of 45–55% finger millet with OFSP and soybean improved nutrient density
Arukwe et al. (2022)	Pearl millet, African yam bean, carrot	Composite flour blending	70:20:10 blend gave the highest nutrient density and best sensory acceptance; iron 6.56–11.65 mg/100g, zinc 6.48–8.86 mg/100g
Omah et al. (2022)	Pearl millet, soybean	Roasting + response surface optimisation	Roasting temperature and feed ratio significantly affected micronutrient, functional and sensory profiles
Krishnan et al. (2024)	Pearl millet, finger millet	Extrusion into breakfast cereal	Extruded blends showed favourable water absorption and foaming properties for obesity management diets
Adejuwon et al. (2021)	Sorghum (millet allied nutri cereal), soybean, OFSP	Fermentation, rat bioassay	Fermentation significantly improved protein content, growth and haematological indices in weanling rats
Izuakor et al. (2024)	Maize, sorghum, millet,	Fortification with walnut,	Fortificant inclusion improved

	soybean	pumpkin seed, date palm	micronutrient and antioxidant profile; local blends often remained low in vitamin C
Salha et al. (2023)	Pearl millet, Moringa leaf powder, dates/OFSP	Composite blending per RDA ratios	Bulk density and viscosity varied significantly with fortificant ratio; overall acceptability differed across blends
Zakaria et al. (2025)	Moringa fortified instant complementary food	Accelerated shelf life testing	Storage at or below 30°C in semi aluminium foil packaging maintained microbial safety over the shelf life window
Mollay et al. (2022) / Ngure et al. (2023)	Maize, sorghum, millet (comparative)	Aflatoxin exposure assessment	Sorghum and millet were less frequently and less heavily contaminated with aflatoxin than maize in the same communities

3. CONCLUSION, RECOMMENDATIONS AND WAY FORWARD

3.1. Conclusion

This review has examined recent literature, drawn predominantly from 2021 to 2026, on the nutritional improvement of millet based complementary foods. Millet is a nutritionally competitive, climate resilient cereal well matched to the agro ecological realities of Nigeria and the Sudano Sahelian belt, yet its traditional preparation as a bulky, viscous, antinutrient laden gruel constrains its contribution to closing the complementary feeding nutrient gap underlying persistently high stunting, wasting and micronutrient deficiency among Nigerian under fives. A rapidly growing body of processing and biofortification research demonstrates that these limitations are addressable: germination and fermentation can reduce phytate and tannin content by well over half while improving mineral bioaccessibility; extrusion improves protein and starch digestibility while reducing bulk; composite blending with legumes and vegetables corrects millet's amino acid and micronutrient limitations; and biofortification offers a complementary route to raising the grain's intrinsic iron and zinc content. Sensory acceptability, however, frequently declines as processing intensity increases, and much of the strongest biofortification evidence still originates from South Asia rather than West Africa.

3.2. Recommendations

Processors developing millet based complementary foods should prioritise combined strategies, such as germination followed by fermentation, since these achieve the greatest antinutrient reduction and bioavailability gain. Composite formulations should draw on locally available legumes and vegetables, including African yam bean, soybean, Bambara nut, groundnut, Moringa leaf and orange fleshed sweet potato, at inclusion ratios of roughly ten to twenty percent, informed by the sensory acceptability thresholds identified in the literature. Packaging and storage, particularly laminated packaging and cool, dry conditions, should be integral to product design given millet flour's susceptibility to rancidity. Regulatory authorities should extend mycotoxin surveillance, currently concentrated on maize and groundnut, to millet- and sorghum based products, while caregiver nutrition education, especially in the northern states, should include practical guidance on low cost household processing.

3.3. Way Forward

Future research should prioritise Nigeria specific randomised controlled trials of biofortified pearl millet, generating locally applicable efficacy data on growth and micronutrient status, alongside comparative shelf life and

mycotoxin exposure studies contrasting millet- and maize based complementary foods under identical household conditions. Standardised sensory acceptability protocols across the composite flour literature would allow firmer cross study conclusions on optimal fortification thresholds. Ultimately, translating this research base into affordable products remains the critical task: collaboration between food scientists, processors, and programmes such as the Home Grown School Feeding Programme could accelerate the movement of validated formulations into routine use, converting the promise reviewed here into measurable gains in child nutritional status across Nigeria's millet growing regions.

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