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Optimization of fermentation techniques for enhancing nutritional value and shelf life of millet-based fermented beverages in West Africa: A comprehensive review

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Abstract

West Africa continues to grapple with profound food insecurity and micronutrient deficiencies, impacting over 70 million individuals, with rural and low-income communities facing the greatest risks due to reliance on limited, nutrient-poor diets dominated by staple cereals. Millet (*Pennisetum glaucum*), a highly drought-tolerant and climate-resilient crop, forms the backbone of traditional fermented beverages such as kunu (a non-alcoholic, cereal-based drink popular in Nigeria) and pito (a mildly alcoholic sorghum-millet beer prevalent in Ghana and other Sahelian countries), which are integral to cultural and social practices but often suffer from suboptimal nutritional profiles, short shelf lives (typically 2-3 days), and high levels of anti-nutritional factors like phytic acid and tannins. This comprehensive review delves into the transformative potential of advanced fermentation techniques including the use of mixed microbial cultures (e.g., *Lactobacillus plantarum*, *Lactobacillus fermentum*, *Bacillus subtilis*, and *Saccharomyces cerevisiae*), controlled temperature regimes (30-35°C), and extended fermentation durations (48-72 hours) to significantly enhance protein digestibility (up to 85%), vitamin B-complex synthesis (doubled levels of thiamine and riboflavin), mineral bioaccessibility (iron and zinc absorption improved by 40-60%), and shelf life extension (up to 14 days through pasteurization or natural preservatives like *Moringa oleifera*). Drawing on recent empirical studies from 2023-2025, the review highlights probiotic benefits (viable counts exceeding 10⁸ CFU/mL), antioxidant activity, and reduced anti-nutritional factors (50-70% decrease), positioning these optimized beverages as functional foods with applications in combating anemia, stunted growth, and diabetes. Economic advantages encompass local value addition through small-scale enterprises, income generation for women farmers, and reduced post-harvest losses (up to 30%), while environmental gains arise from millet's low water footprint and fermentation's role in waste minimization amid climate variability. Challenges, including microbial inconsistencies, scaling limitations, and sensory variations, are critically analyzed, with recommendations for standardized protocols, pilot-scale production, sensory-health trials, and policy frameworks for biofortification and market integration. This synthesis offers a blueprint for sustainable nutrition enhancement, fostering food security and livelihoods across West Africa.

Keywords: Millet; Fermented Beverages; Kunu; Pito; Nutritional Enhancement; Probiotics; Anti-Nutritional Factors; Shelf Life; Food Security; West Africa

1. Introduction

West Africa, home to approximately 400 million people across 16 nations, endures severe and multifaceted food insecurity and micronutrient deficiencies that affect over 70 million individuals, with prevalence rates exceeding 30% for stunting and anemia among children under five, and anemia rates reaching up to 60% in pregnant women, particularly in rural and periurban areas where dietary diversity is severely constrained by persistent poverty,

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escalating climate variability, limited access to fortified foods, and inadequate agricultural infrastructure (FAO, 2023; UNICEF, 2024; WHO, 2024). These nutritional challenges are deeply entrenched, compounded by diets heavily reliant on monotonous, cereal-based staples such as millet, which provide essential energy through a carbohydrate content of 65 to 75% (primarily as complex starches), yet often lack sufficient proteins (typically 8 to 12%), essential vitamins (e.g., B-complex vitamins like thiamine and riboflavin), and bioavailable minerals such as iron (3 to 8 mg/100g) and zinc (2 to 4 mg/100g), leading to widespread health issues including impaired cognitive development, weakened immunity, increased susceptibility to infectious diseases like malaria and diarrhea, and heightened maternal mortality rates (Banwo et al., 2023; Bouakkaz, S. et al., 2024). The region's vulnerability is further exacerbated by a prevalence of hidden hunger, where caloric intake masks micronutrient deficiencies, affecting over 40% of the population according to recent estimates (IFPRI, 2023).

Millet (*Pennisetum glaucum*), a highly resilient C4 grass crop well adapted to the semiarid Sahelian environments of West Africa, including countries like Niger, Mali, and Burkina Faso, serves as the primary substrate for a variety of traditional fermented beverages that are deeply embedded in the cultural, social, and economic fabrics of the region (Ajagekar, A. et al., 2023; Kumar, V., et al., 2024). Among these, kunu, a refreshing nonalcoholic beverage primarily produced in northern Nigeria, is crafted by fermenting millet flour with natural spices such as ginger, cloves, and occasionally pepper, offering hydration, mild nutritional benefits, and a cooling effect in hot climates, yet it is plagued by a short shelf life of 2 to 3 days under ambient conditions, variable quality due to uncontrolled fermentation, and limited probiotic consistency (Adegoke et al., 2024; Ndukwe, J.K., et al., 2023). Similarly, pito, a traditional sorghum millet beer widely consumed in Ghana, Burkina Faso, and parts of Nigeria, provides caloric density (approximately 200300 kcal/L) and significant social value during ceremonies and community gatherings, but it faces challenges with rapid spoilage within 48 to 72 hours, inconsistent microbial profiles, and suboptimal nutrient bioavailability due to residual antinutritional factors (Yirezang, F., et al., 2016). These beverages, while culturally significant, reflect the region's reliance on indigenous crops and traditional knowledge, yet their nutritional potential remains underutilized due to artisanal production methods.

Traditional fermentation practices in West Africa are predominantly artisanal, relying on spontaneous microbial activity from ambient environments, which yields beverages with potential probiotic benefits such as lactic acid bacteria (LAB) and yeasts that enhance gut health but limited nutritional optimization due to suboptimal microbial dynamics, fluctuating temperatures (often 25 to 40°C), and inconsistent hygiene standards (Obafemi, Y.D., et al., 2022; Navinraj S., et al., 2025). Advanced fermentation techniques, however, can harness a diverse consortium of lactic acid bacteria (e.g., *Lactobacillus plantarum*, *Lactobacillus fermentum*), yeasts (e.g., *Saccharomyces cerevisiae*), and occasionally bacilli (e.g., *Bacillus subtilis*) to degrade antinutritional factors such as phytic acid (by 50 to 70% through phytase activity) and tannins (by 40 to 60% via polyphenol oxidase), synthesize essential vitamins like thiamine and riboflavin, and extend shelf life through acidification (pH reduction to 3.5 to 4.5) and the production of bioactive compounds such as organic acids and peptides (Endalew, H. W., et al., 2024; Shambhvi, and Gupta, M. (2025); Singh, S. M., et al., 2025). The economic imperative is stark: the region spends an estimated \$2 billion annually on imported processed beverages and nutritional supplements, draining scarce foreign reserves, while climate change projected to reduce millet yields by 10 to 20% by 2030 due to increased drought frequency and heat stress threatens local food supply chains and exacerbates vulnerability (IPCC, 2022). Recent research from 2023 to 2025 underscores the transformative role of optimized fermentation, with studies demonstrating remarkable improvements such as up to 85% protein digestibility in kunu through enzymatic hydrolysis, probiotic counts exceeding 10^8 CFU/mL that support intestinal microbiota balance, and enhanced iron bioaccessibility (up to 60%) in pito, addressing anemia prevalent in 40% of children under five (Adegoke et al., 2024; Tomar, T., et al., 2025; Zakariya, M.I., et al., 2025). This article provides a detailed and evidence-based review of millet's nutritional foundation, encompassing its macro and micronutrient profiles, the scientific principles underlying fermentation optimization strategies, empirical findings from recent peer-reviewed studies, the multifaceted economic and environmental benefits, persistent challenges such as microbial variability and scaling constraints, and forward-looking recommendations for standardized protocols, pilotscale production, sensory and health impact trials, and robust policy frameworks for biofortification and market integration. By elevating these indigenous fermented beverages to the status of functional foods offering probiotic, antioxidant, and micronutrient benefits West Africa can advance sustainable nutrition, empower rural economies through value addition, and build resilience against global food crises, aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action) (UN, 2023).

2. Propagation and Planting of Millet

Millet propagation and planting in West Africa rely heavily on its adaptability to harsh agroecological conditions, particularly in semi-arid regions like the Sahel, where rainfall is erratic and soils are often nutrient-poor. The primary species, including pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*), are propagated predominantly through seeds, which are typically sourced from local varieties preserved by smallholder farmers or improved cultivars developed by institutions such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Sanjay K.T. et al., 2024). Seed selection is critical, with farmers prioritizing drought-tolerant, disease-resistant strains that yield 500 to 1,500 kg/ha under rain-fed conditions, though yields can reach 2,500 kg/ha with irrigation and fertilizer application (Muskan, F., et al., 2025). Planting occurs during the onset of the rainy season, typically between May and July, with optimal soil temperatures ranging from 25 to 30°C to ensure germination within 3 to 7 days (Hassan, Z. M., et al., 2021). Seeds are sown at a depth of 1 to 2 cm in rows spaced 30 to 50 cm apart, with a seeding rate of 5 to 10 kg/ha, adjusted based on soil fertility and rainfall patterns (Yadav, D. 2024).

Traditional planting methods involve broadcasting or dibbling, often intercropped with legumes like cowpea or groundnut to enhance soil nitrogen and reduce pest pressure, a practice prevalent among 70% of millet farmers in Niger and Mali (Timilsina, R. R., et al., 2025). Modern techniques, such as precision planting with mechanical seed drills, are gaining traction in Ghana and Nigeria, improving stand uniformity and reducing seed waste by 10 to 15% (Ahmed, S., et al., 2024). Soil preparation includes minimal tillage to preserve moisture, supplemented with organic manure (5 to 10 tons/ha) or small amounts of nitrogen-phosphorus-potassium (NPK) fertilizer (20:10:10 at 50 kg/ha) to boost early growth, particularly in degraded lands (Ahmed, S., et al., 2024). Water management is crucial, with millet requiring 300 to 500 mm of rainfall per season, and supplemental irrigation in drought-prone areas like Burkina Faso increasing yields by 20 to 30% (IPCC, 2022). Weed control, a major challenge, is managed through hand weeding or herbicide application (e.g., atrazine at 1.5 kg/ha) within the first 3 weeks, as millet's slow initial growth leaves it vulnerable to competition (Hassan, Z. M., et al., 2021).

2.1. Growth and Development of Millet

Millet's growth and development are tailored to its role as a resilient staple in West Africa, progressing through distinct phenological stages that reflect its adaptation to stress-prone environments. Germination begins 3 to 7 days post-planting under optimal moisture and temperature (25 to 30°C), with seedling emergence marked by the development of 2 to 4 leaves within 10 to 14 days, supported by a deep root system that can extend 1 to 2 meters to access subsoil moisture (Sadh, P.K. et al., 2024). The vegetative phase, lasting 30 to 50 days depending on variety and water availability, involves rapid tillering (5 to 15 tillers per plant) and leaf expansion, with pearl millet producing 6 to 12 leaves and finger millet up to 20 leaves, enhancing photosynthetic efficiency (Olatoye, K.K. et al., 2023). This phase is critical for biomass accumulation, with dry matter increasing from 10 to 50% of total yield, influenced by intercropping and nutrient availability (Ajagekar, A. A. et al., 2023).

The reproductive phase, triggered by day-length sensitivity (12 to 14 hours) and adequate moisture, spans 20 to 40 days, beginning with panicle initiation and culminating in flowering and grain filling. Pearl millet forms dense, cylindrical panicles (15 to 30 cm long) containing 1,000 to 3,000 seeds, while finger millet develops compact heads with 500 to 1,000 seeds, with grain yield peaking at 80% of total biomass under favorable conditions (Hithamani, G., and Srinivasan, K. 2014). Grain filling, lasting 15 to 25 days, is highly sensitive to water stress, with drought reducing yields by 20 to 40%, though millet's C4 photosynthesis pathway confers heat tolerance up to 40°C (IPCC, 2022; Malleshi NG, et al., 2021). Maturity is reached 70 to 120 days after planting, with harvest occurring when grains harden and panicles dry to 12 to 15% moisture content, typically signaled by a change in panicle color from green to straw-yellow (Hithamani, G., and Srinivasan, K. 2014). Post-harvest losses, estimated at 20 to 30% due to improper drying and storage, are mitigated by threshing with wooden flails or small machines and storing in elevated granaries to deter pests like the millet head miner (Muskan, F., et al., 2025).

Growth is influenced by environmental stressors, with climate change projections indicating a 10 to 20% yield decline by 2030 due to increased drought frequency, necessitating cultivars with shorter growing cycles (70 to 90 days) and enhanced stress tolerance (Hassan, M.M., et al., 2024). Nutrient management, including organic amendments and microdosing of fertilizers, boosts nitrogen uptake by 15 to 25%, while intercropping with legumes increases soil fertility and yield stability by 10 to 15% (Shambhvi, and Gupta, M. 2025). Pest and disease management, including striga (a parasitic weed) and downy mildew, relies on resistant varieties and cultural practices, with losses reduced by 30% through integrated approaches (Gowda, N. A. N., et al., 2022).

2.2. Anti-nutritional Components of Millet

Millet contains several anti-nutritional components that limit its nutritional value and bioavailability, posing challenges to its utilization as a primary food source in West Africa. Phytic acid, the most prevalent ANF, is present at concentrations of 0.5 to 1.5% in raw millet grains, acting as a strong chelating agent that binds divalent cations such as iron, zinc, calcium, and magnesium, reducing their bioavailability by 50 to 80% and contributing to hidden hunger in populations with high millet dependence (Singh, T. B., and Kaushik, R. 2025). This reduction is particularly detrimental in Sahelian regions where anemia affects 40% of children and stunting exceeds 30%, as phytic acid forms insoluble complexes in the gastrointestinal tract (UNICEF, 2024).

Tannins, ranging from 0.2 to 1% depending on millet species and environmental conditions, inhibit protein digestion by binding to digestive enzymes like trypsin and forming tannin-protein complexes that are poorly absorbed, lowering protein digestibility to 60 to 70% in unprocessed millet (Samtiya, M., et al., 2021; Endalew, H. W., et al., 2024). These polyphenolic compounds also impart a bitter taste, reducing palatability and consumer acceptance in some communities (Ndukwe, J.K., et al., 2023). Trypsin inhibitors, present at 10 to 20 mg/g, further limit amino acid absorption by inhibiting protease activity, exacerbating protein-energy malnutrition prevalent in rural areas (Salim, R., et al., 2023)

Oxalates, found at 50 to 150 mg/100g in finger millet and certain pearl millet varieties, pose a risk of calcium oxalate kidney stone formation when consumed in high amounts, particularly in diets lacking dietary diversity, though their impact is mitigated by processing (Navinraj S, et al., 2025; Yehuala, T. F., et al., 2025). Saponins, at 0.1 to 0.5%, can cause gastrointestinal irritation and reduce nutrient uptake by forming complexes with cholesterol and bile acids, though their levels are generally low in most millet types (Samtiya, M., et al., 2020). Cyanogenic glycosides, though minimal in millet compared to cassava, may reach trace levels (0.01 to 0.05 mg/100g) in some varieties, requiring careful processing to avoid toxicity risks (Tomar, T., et al., 2025).

These ANFs contribute to micronutrient deficiencies and growth impairments, with phytic acid and tannins linked to reduced iron absorption rates of 20 to 30% in traditional diets, necessitating processing interventions. Biofortification efforts by ICRISAT have increased mineral content, but fermentation with lactic acid bacteria reduces phytic acid by 50 to 70% and tannins by 40 to 60%, improving digestibility to 80 to 90% and mineral bioavailability to levels comparable to fortified foods (Agboola, S. A., et al., 2025). Soaking, cooking, and roasting can reduce ANFs by 30 to 50%, but optimized fermentation offers the most significant enhancement, positioning millet as a viable base for nutrient-dense beverages.

2.3. Nutritional Profile of Millet

Millet, encompassing a diverse array of species including pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), and proso millet (*Panicum miliaceum*), emerges as a nutritional powerhouse uniquely suited to the challenging agroecological conditions of West Africa, characterized by semi-arid climates, erratic rainfall, and nutrient-depleted soils (Banerjee P, et al., 2020). This resilient grain delivers a substantial carbohydrate content ranging from 65 to 75% of its dry weight, predominantly as complex starches that provide sustained energy release, making it a critical energy source for populations in regions like the Sahel where caloric intake is often marginal. Protein levels vary between 8 and 12% across species, with pearl millet offering a rich profile of essential amino acids such as leucine, methionine, and isoleucine, though it is notably limited in lysine, necessitating complementary protein sources to meet dietary requirements (Zakariya, M.I., et al., 2025). Dietary fiber content, ranging from 6 to 10 grams per 100 grams, supports gastrointestinal health, regulates blood sugar levels, and promotes satiety, while its low glycemic index (approximately 55) aids in diabetes management, a condition affecting over 24 million individuals in West Africa (WHO, 2024).

Millet is also a notable source of essential minerals, with iron concentrations between 3 and 8 milligrams per 100 grams and zinc levels from 2 to 4 milligrams per 100 grams, though bioavailability is often low due to anti-nutritional factors. Biofortified varieties, developed through collaborative efforts by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and national agricultural programs, have successfully increased iron content by 50 to 100% and zinc by similar margins, addressing anemia prevalence exceeding 40% among West African children under five and contributing to reduced stunting rates through enhanced micronutrient intake (Isaac-Bamgboye, et al., 2019). Magnesium levels (approximately 100–150 mg/100g) support muscle and nerve function, while calcium (20–40 mg/100g) in finger millet bolsters bone health, particularly in populations with limited dairy access. Phenolic compounds, including ferulic acid, p-coumaric acid, and quercetin, contribute antioxidant activity with total phenolic content ranging from 200 to 500 milligrams per 100 grams, potentially mitigating oxidative stress, reducing inflammation, and lowering the risk of chronic diseases such as cardiovascular conditions and type 2 diabetes prevalent

in the region. The low fat content (3 to 5%) further enhances its suitability as a base for lightweight, digestible fermented products.

Biofortification efforts have made significant strides in enhancing millet's nutritional profile, with iron-enriched pearl millet varieties increasing hemoglobin levels by 10–15% in clinical trials among preschool children, and zinc-biofortified lines reducing zinc deficiency symptoms by 20–30% in rural communities (Ojo OI, et al., 2018). However, fermentation remains a critical processing step to unlock bioavailability, as it activates endogenous phytases and proteases that degrade ANFs, improving mineral absorption to levels comparable to fortified foods (Tomar, T., et al., 2025). Traditional soaking and cooking methods reduce phytic acid by 30 to 50%, but optimized fermentation with lactic acid bacteria can achieve reductions of 50 to 70%, alongside a 20 to 40% increase in soluble protein content (Singh, S., et al., 2025). Overall, millet's rich antioxidant profile, combined with its adaptability to low-input agriculture and potential for nutritional enhancement through processing, positions it as an ideal foundation for functional beverages when subjected to appropriate technological interventions, offering a sustainable solution to West Africa's dietary challenges.

3. Optimization of Fermentation Techniques

Fermentation of millet-based beverages traditionally involves spontaneous microbial action, but optimization through controlled parameters dramatically enhances nutritional value and stability. Mixed microbial cultures, combining LAB (e.g., *Lactobacillus plantarum*, *L. fermentum*) with yeasts (*Saccharomyces cerevisiae*) and bacilli (*Bacillus subtilis*), promote synergistic effects: LAB produce lactic acid to lower pH (3.5–4.5), inhibiting pathogens and extending shelf life from 3 days to 14+ via hurdle technology (Ogunremi OR., et al., 2025). Optimal temperatures of 30–35°C for 48–72 hours maximize enzyme activity, degrading phytic acid by 50–70% through phytase production and tannins by 40–60% via polyphenol oxidase (Abdolshahi, A., et al., 2021).

Extended fermentation increases protein digestibility to 85% by hydrolyzing complex proteins into peptides, while synthesizing B-vitamins (thiamine up to 2x, riboflavin 1.5x) via microbial metabolism (Zakariya, M.I., et al., 2025). For kunu, adding sweeteners like honey or date syrup post-fermentation preserves probiotics ($>10^8$ CFU/mL) and enhances sensory appeal (Jolayemi, O. S., et al., 2023). In pito, pasteurization at 75–80°C after fermentation with *Moringa oleifera* extract extends shelf life to 10–14 days by reducing microbial load while retaining antioxidants (Ayirezang, F., et al., 2016; Sawadogo-Lingani, H., et al., 2024). These techniques also boost mineral bioaccessibility: iron from 20% to 60% and zinc to 50% by chelation breakdown. Emerging methods like back-slopping (using previous batches as starters) ensure consistency, reducing variability in artisanal production (Obafemi, Y.D., et al., 2022).

3.1. Economic and Environmental Benefits

Optimized millet beverages, such as kunu and pito, drive substantial economic empowerment in West Africa by facilitating the establishment of small-scale processing enterprises that leverage local resources and traditional knowledge, particularly benefiting women who have historically dominated the production of these fermented drinks as a means of household income generation and cultural preservation. In countries like Nigeria and Ghana, where women constitute over 60% of the informal food processing workforce, optimized fermentation techniques enable the transition from artisanal, low-margin sales of fresh kunu or pito to higher-value, packaged ready-to-drink formats that can be sold in urban markets or through micro-entrepreneurial networks, resulting in income increases of 20 to 30% for producers (Reid, G., et al., 2020). For instance, in northern Nigeria, women-led kunu enterprises have expanded to include flavored variants with ginger or baobab, tapping into the growing demand for healthy, low-sugar alternatives to imported carbonated sodas, which alone represent a \$500 million market in Nigeria's beverage sector and allow for 40 to 50% cost reductions compared to imports through localized sourcing and minimal equipment needs.

This economic model stimulates broader market dynamics by creating supply chains that link smallholder millet farmers with processors, reducing post-harvest losses which affect 20 to 30% of millet production due to spoilage and inefficient storage through extended shelf life from fermentation, thereby increasing overall profitability by 15 to 25% for rural households. In conflict-affected areas of Mali and Burkina Faso, women's groups supported by initiatives like those from the CGIAR have scaled millet beverage production, generating collective incomes of \$200 to \$500 per month per group, fostering financial independence and community resilience while aligning with gender equity goals under SDG 5 (Ndukwe, J.K., et al., 2023). Furthermore, the promotion of millet beverages contributes to national food security by diversifying export potential, with processed products like probiotic-enriched pito gaining traction in regional markets (ECOWAS), potentially adding \$100 to \$200 million to West Africa's agro-food economy by 2030 through value addition and branding as sustainable, health-focused alternatives (Obafemi, Y.D., et al., 2022; Swain, S. R., et al., 2024). The rise of millet-based value chains also creates employment opportunities, with estimates suggesting 50,000 to

100,000 new jobs in processing and distribution across the region by 2035, particularly for youth and women, supported by cooperative models that reduce transaction costs by 10 to 20% (Dorvlo, S. Y., et al., 2025).

From an environmental standpoint, millet's natural low-input needs and the eco-friendly nature of fermentation processes establish optimized beverages as a key element for climate adaptation in West Africa, especially in the drought-vulnerable Sahel region, where limited water and deteriorating soils pose significant risks to traditional farming practices. Millet cultivation demands only 300 to 500 mm of seasonal rainfall compared to 1,000 mm for maize, conserving water resources in arid zones like Niger and Chad, while its deep root system (up to 2 meters) prevents soil erosion and enhances water infiltration, reducing runoff by 20 to 30% during heavy rains. Fermentation further amplifies these benefits by minimizing post-harvest waste converting 20 to 30% of otherwise lost millet into stable products and requiring no additional energy-intensive processing, thereby lowering the carbon footprint of beverage production by 40 to 50% relative to imported alternatives. The process also utilizes byproducts like spent grains as livestock feed, reducing waste by an additional 15 to 20% and supporting integrated farming systems.

Probiotic fermentation reduces the need for chemical preservatives like sodium benzoate, cutting pollution from packaging waste and effluent discharge by 30 to 40%, while millet's nitrogen-fixing intercropping with legumes like cowpea improves soil fertility, increasing organic matter by 10 to 15% and sequestering carbon at rates of 1 to 2 tons per hectare annually, contributing to mitigation against climate change impacts projected to reduce Sahel crop yields by 10 to 20% by 2030 (Kumawat L., 2025). In the Sahel, millet's adaptability aids in conserving biodiversity, as its varied cultivars help safeguard genetic resources against desertification, while the low-energy fermentation process, relying on ambient temperatures, supports sustainable development by cutting greenhouse gas emissions from transport and refrigeration by 25 to 35% compared to traditional food processing methods.

Overall, these practices promote a circular economy by repurposing millet waste from brewing into animal feed or compost, boosting resource efficiency and environmental care amid growing climate challenges, with projections suggesting a potential 50% decrease in food system emissions through millet-based fermentation by 2040.

4. Challenges and Future Directions

The optimization of fermentation techniques for millet-based beverages like kunu and pito in West Africa faces significant challenges due to the variability of traditional artisanal methods, which rely on inconsistent microbial starters from ambient sources or prior batches. This leads to off-flavors from undesirable yeasts and molds, a short shelf life of 2 to 3 days under ambient conditions (25 to 30°C) due to spoilage organisms like *Bacillus* and *Enterobacter*, and batch-to-batch inconsistencies in pH (3.5 to 5.0), alcohol content (1 to 4% ABV in pito), and probiotic viability, undermining safety and consumer trust. Environmental factors, such as seasonal temperature fluctuations and poor rural hygiene, worsen these issues, while high equipment costs (over \$500 per unit) pose barriers for small-scale producers, particularly women-led enterprises with limited incomes (\$50 to \$100 monthly). Unoptimized fermentation leaves 40 to 60% of anti-nutritional factors (ANFs) like phytic acid and tannins, reducing mineral bioavailability below 30% and limiting nutritional benefits. Scaling is hindered by inadequate infrastructure, including unreliable electricity, poor road networks, and lack of quality control, resulting in 20 to 30% grain losses and up to 50% spoilage in unpasteurized drinks, especially in remote Sahel areas. Additional risks include microbial contamination (e.g., aflatoxins, *Salmonella*) causing foodborne illnesses, regulatory gaps for probiotic claims, supply chain disruptions in conflict zones like northern Mali, climate-induced yield drops (15 to 25%), and sensory inconsistencies deterring urban consumers.

Future strategies focus on standardizing microbial strains using back-slopping or commercial freeze-dried inoculants (e.g., *Lactobacillus*, *Saccharomyces*) to ensure consistent probiotic counts ($>10^8$ CFU/mL) and reduce off-flavors by 50 to 70%. Randomized controlled trials (RCTs) in Nigeria and Ghana could assess health benefits, such as 10 to 20% ferritin improvement in children consuming optimized kunu over 6 to 12 months. Response surface methodology (RSM) can optimize variables (temperature 28 to 35°C, time 36 to 72 hours, inoculum 1 to 5%) to achieve 80 to 90% digestibility and 60 to 80% ANF reduction, as shown in pito pilot models (desirability 0.85). Policy support should include subsidies for biofortified seeds (15% yield increase) and training, covering 50 to 70% of equipment costs, drawing from Ethiopian models. Pilot plants in Kano and Tamale, using solar-powered fermenters, could test scalability with 20 to 30% profit margins, supported by public-private partnerships for certification and ECOWAS trade, potentially earning \$50 to \$100 million annually by 2030. Longitudinal RCTs on gut health and genomic screening for resilient strains will bolster probiotic claims, enhancing market potential.

5. Recent Studies and Findings

Empirical research from 2023 to 2025 has provided robust validation for the optimization of fermentation techniques in millet-based beverages, offering quantitative evidence of substantial nutritional, functional, and microbial improvements that transform traditional kunu and pito into viable functional foods. A pivotal 2025 study on fermented kunu utilized co-cultures of *Lactobacillus plantarum*, *Lactobacillus fermentum*, *Bacillus subtilis*, and *Saccharomyces cerevisiae* under controlled conditions (32°C for 60 hours), reporting significant protein increases to 12 to 15% from an initial 8%, ash content elevation by 20% indicating enhanced mineral enrichment, and reductions in fat and fiber by 15 to 25% through enzymatic hydrolysis, with antioxidant activity measured via DPPH scavenging rising 30 to 50% due to the release of bound phenolics during fermentation (Agboola, S. A., et al., 2025). Probiotic viability in this optimized kunu exceeded 10^8 CFU/mL, supporting gut health by promoting beneficial microbiota like *Bifidobacterium* and *Lactobacillus* species, while shelf life extended to 12 days under refrigeration through natural acidification (pH 3.8 to 4.2) and the addition of ginger extract as a preservative, reducing spoilage organisms by 60% compared to controls (Agboola, S. A., et al., 2025).

In a comprehensive 2025 analysis of kunu zaki variants produced from different millet types including gero (white pearl millet), maiwa (brown pearl millet), acha (fonio), and finger millet, controlled fermentation with *Lactobacillus plantarum* and *Saccharomyces cerevisiae* for 48 hours yielded proline levels of 14.73 to 23.70 mg/100g and essential amino acids increased by 20 to 30%, with vitamin profiles showing doubled niacin (from 1.2 to 2.4 mg/100g) and folate (from 25 to 50 µg/100g), directly contributing to anemia prevention by improving red blood cell formation and oxygen transport (Zakariya, M.I., et al., 2025). Sensory evaluations using a 9-point hedonic scale revealed high scores of 7 to 8 for millet-based kunu variants, outperforming non-fermented controls in taste, aroma, and mouthfeel, attributed to the production of volatile compounds like esters and aldehydes during yeast activity, while overall acceptability reached 85% among panelists in northern Nigeria (Jolayemi, O. S., et al., 2023).

For pito, a 2024 study focused on shelf life optimization through the incorporation of *Moringa oleifera* leaf extract (1 to 2% w/v) and pasteurization at 75 to 80°C for 15 minutes, successfully extending storage stability to 14 days under ambient conditions (25 to 30°C) with minimal quality loss, maintaining pH at 3.8 to 4.2 and alcohol content at 2 to 3% ABV, while boosting iron bioaccessibility by 40% (from 25% to 65%) via phytase-mediated degradation of phytic acid and reducing anti-nutritional factors by 60% overall (Maleke, M. S., et al., 2024). Probiotic lactic acid bacteria counts in this optimized pito reached 10^9 CFU/mL, correlating with improved gut microbiota diversity in *in vitro* trials simulating human digestion, where beneficial strains like *Lactobacillus fermentum* dominated and reduced pathogenic *E. coli* adhesion by 70% (Bouakkaz, S., et al., 2025). This study also noted a 25% increase in total phenolic content (to 350 mg GAE/100mL), enhancing antioxidant capacity and potential anti-diabetic effects through inhibition of α -amylase activity by 35%.

Broader findings from 2023 include a trial on kunu supplemented with African locust bean (*Parkia biglobosa*) seeds during fermentation, achieving 85% protein digestibility through synergistic protease activity from *Bacillus subtilis* and LAB, alongside doubled B-vitamin levels (thiamine from 0.15 to 0.30 mg/100g and riboflavin from 0.10 to 0.20 mg/100g), with probiotics aiding digestion and reducing gastrointestinal discomfort in consumer panels (Olatoye, K.K. et al., 2023).

Further supporting evidence comes from a 2025 study on the microbial diversity in African fermented millet beverages, which identified dominant LAB strains in pito and kunu achieving 10^8 to 10^9 CFU/mL viability post-fermentation, with functional attributes including 30 to 50% improvement in DPPH radical scavenging and a 20% reduction in glycemic index, positioning these drinks as adjuncts for diabetes management affecting 7% of West African adults (Atter, A., et al., 2024). A 2025 review on plant-based fermented foods highlighted that millet fermentation yields up to 40% higher vitamin B synthesis and 60% ANF reduction compared to unfermented grains, with probiotic benefits linked to improved immune response in animal models (Dhiman, S., et al., 2025).

Collectively, these studies from 2023 to 2025 affirm fermentation's pivotal role in elevating millet beverages to probiotic-rich, nutrient-dense functional foods, with quantifiable gains in digestibility, bioaccessibility, and stability that address regional health burdens while supporting scalable production.

6. Conclusion

The optimization of fermentation techniques for millet-based beverages like kunu and pito in West Africa offers a comprehensive solution to food insecurity, micronutrient deficiencies, and climate challenges. Advanced methods,

including mixed microbial cultures (e.g., *Lactobacillus plantarum*, *Bacillus subtilis*, *Saccharomyces cerevisiae*) at 30-35°C for 48-72 hours, improve protein digestibility to 85%, double B-complex vitamins (thiamine, riboflavin), enhance iron and zinc absorption by 40-60%, and extend shelf life to 14 days with pasteurization or *Moringa oleifera*. Supported by 2023-2025 studies, these techniques reduce anti-nutritional factors by 50-70% and provide probiotics ($>10^8$ CFU/mL), addressing anemia, stunted growth, diabetes, and gastrointestinal issues affecting over 70 million rural residents.

Economically, optimized fermentation boosts small-scale enterprises, especially women-led ones in Nigeria and Ghana, increasing incomes by 20-30%, reducing post-harvest losses by 30%, and tapping into a \$500 million market, supporting SDG 5. Environmentally, millet's low water use (300-500 mm) and fermentation's waste reduction lower carbon emissions by 40-50%, enhance soil fertility, and align with SDG 13 in the drought-prone Sahel, where yields may drop 10-20% by 2030.

Challenges include microbial inconsistencies, high equipment costs, residual anti-nutritional factors, and scaling barriers. Future steps involve standardizing strains with back-slopping or inoculants, conducting trials for health impacts like anemia reduction, optimizing digestibility to 80-90% with response surface methodology, and offering subsidies for biofortified seeds and training. Pilot plants in Kano and Tamale could validate scalability, with public-private partnerships potentially generating \$50-100 million by 2030 under ECOWAS.

By leveraging millet's resilience and fermentation, West Africa can transform these beverages into nutrient-rich, stable functional foods, enhancing health, economic self-sufficiency, and sustainability, aligning with zero hunger goals and offering a model for other regions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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