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Emerging fermentation technologies for nutrient-dense foods: Lessons from industrialized nations to Sub-Saharan Africa

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Abstract

Fermentation remains a critical technique for food preservation and nutritional enhancement in developing regions. Yet, traditional practices often lack consistency, safety, and scalability. In contrast, industrialized nations have adopted advanced fermentation technologies, such as precision fermentation, defined starter cultures, controlled bioreactors, and AI-assisted monitoring, to produce nutrient-dense foods with enhanced quality, safety, and functional attributes. This review explores how these approaches can be adapted to Sub-Saharan Africa, with Nigeria as a focal case study. A literature survey spanning 2017–2025 demonstrates that deploying starter cultures, improving hygienic processing, and implementing simplified bioreactor systems can significantly enhance safety, nutritional outcomes, and supply chain resilience. The main barriers include inadequate infrastructure, fragmented regulatory frameworks, and a lack of specialized training among local producers. We propose inclusive strategies involving technology transfer, low-cost fermenter designs, capacity building, and supportive policy development. Two comparative tables illustrate both existing advanced fermentation technologies and their plausible, scalable adaptations for local use. Integrating modern fermentation practices with indigenous food systems can empower developing nations to transform native crops into safer, more nutritious, and economically sustainable fermented products, ultimately improving public health and livelihoods.

Keywords: Emerging Fermentation Technology; Precision Fermentation; Food Safety; Nutritional Enhancement and Technology Transfer

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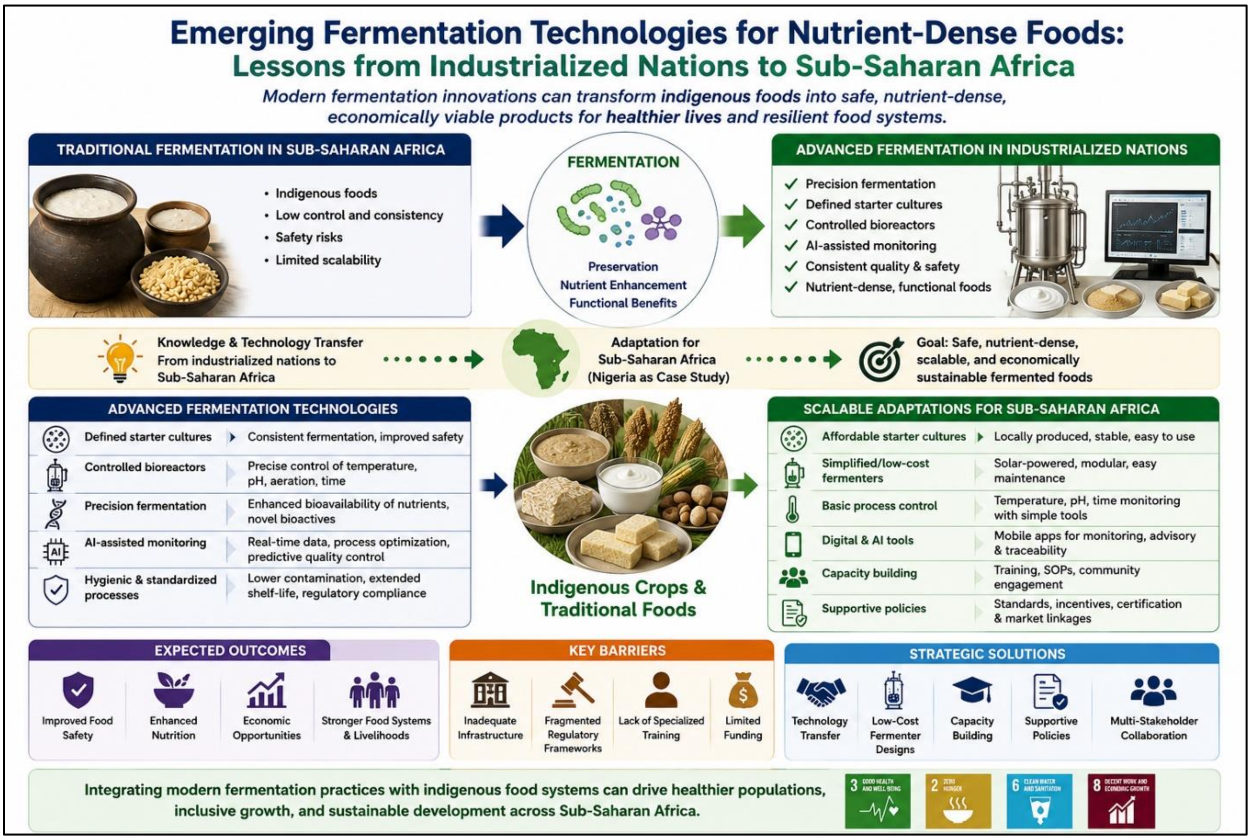
Graphical Abstract



1. Introduction

Fermentation is a cornerstone of traditional food processing throughout Sub-Saharan Africa, offering preservation, enhanced digestibility, improved flavor, and nutritional benefits for staple foods such as ogi (fermented maize or sorghum porridge), fufu (cassava or yam paste), kunu (millet or maize beverage), and dawadawa (fermented locust bean condiment) [1, 2]. These fermented foods remain vital in food-insecure communities, particularly rural areas, due to their low-cost production, ease of preparation, and extended shelf life. Moreover, fermentation enriches food with beneficial organic acids, vitamins, and bioactive compounds while reducing anti-nutritional factors like phytates and cyanogenic glycosides [3].

However, traditional fermentation practices are often spontaneous and uncontrolled, resulting in inconsistent product quality, unpredictable sensory attributes, and, critically, potential microbial contamination such as mycotoxin formation or pathogenic organism growth. Numerous studies have documented the public health risks associated with these methods, including foodborne illnesses and variability in nutritional outcomes [4, 5, 6].

In contrast, industrialized countries have embraced modern fermentation technologies. These include precision fermentation, where genetically engineered microbes are used to produce targeted nutrients or functional compounds; starter-culture systems that ensure reproducibility and safety; bioreactor systems allowing controlled and scalable production; and AI-powered monitoring systems that optimize fermentation processes in real time [7, 8]. These innovations have enabled the development of mainstream functional food products, fortified with health-promoting compounds and guaranteed for quality and safety.

Bridging the technological gap between advanced fermentation systems and traditional practices presents an opportunity: indigenous crops, rich in biodiversity, could be transformed into high-value, nutrient-dense fermented foods [9, 10]. This could improve local nutrition, preserve cultural food heritage, and create economic opportunities.

This review examines advanced fermentation technologies, compares them with current practices in Nigeria, and proposes scalable adaptations that balance technological feasibility with socio-cultural relevance. Our objective is to provide actionable insights fostering improved food security and public health without undermining traditional food systems.

2. Advanced Fermentation Technologies in Industrialized Settings

2.1. Precision Fermentation and Microbial Engineering

Precision fermentation leverages genetically engineered microorganisms, commonly yeasts or bacteria, to biosynthesize highly specific nutritional compounds, such as vitamins, probiotics, enzymes, and protein analogs. The technology has enabled the production of human milk oligosaccharides for infant formula and animal-free dairy proteins, supporting scalable, clean-label alternatives [11–13]. As an illustration, microbial expression systems have been optimized to produce "milk proteins" identical to those found naturally, with well-established bioreactor platforms enabling high yields and regulatory acceptance. These fermentation-derived products provide consistent nutritional content, allergen control, and sustainability advantages over traditional sourcing—a model with potential lessons for local biofortification efforts in African contexts [11,12].

2.2. Starter Culture Systems

Defined starter cultures have revolutionized fermentation quality control across sectors such as dairy (yogurts, cheeses), cereal (sourdough, fermented grain porridges), and beverages (kombucha, kefir) [14,15]. Using carefully selected microbial strains ensures product consistency, reduces batch failures, and standardizes sensory properties. Starter cultures can also be designed for specific functional outcomes, such as enhanced vitamin synthesis, lactic acid production to lower pH, or probiotic viability. Their application has diminished spoilage rates and improved consumer acceptance through predictable product traits.

2.3. Bioreactor and Process Control Systems

Bioreactors offer precisely regulated environments for fermentation, controlling parameters such as pH, temperature, oxygen levels, and agitation. Batch, fed-batch, or continuous fermentation modes are possible, supporting both consistency and scale. Fermented products like kombucha, tempeh, and industrial yogurts are standardized using these systems in commercial settings [16–18]. Bioreactor automation reduces labor, enables reproducibility, and streamlines quality management. Moreover, closed systems prevent contamination and facilitate hygiene control—critical for food safety.

2.4. Digital and AI-Assisted Monitoring

The integration of sensors (e.g., pH, temperature, gas sensors) with digital data platforms and AI analytics has further elevated fermentation control. Real-time monitoring enables early detection of deviations, predictive corrections, and optimization of nutrient yield and flavor development [19–21]. Machine learning algorithms can model fermentation trajectories and suggest parameter adjustments to prevent spoilage, reduce energy use, or shorten processing time. Such systems deliver commercially viable production with minimal human intervention, paving the way for high-throughput, low-risk fermented goods. The potential benefits of advanced fermentation technologies and their features. Table 1 summarizes these technology features and benefits.

Table 1 Advanced Fermentation Technologies: Features and Potential Benefits

Technology	Features	Benefits
Precision fermentation	Engineered microbes for target compound synthesis	High yield, specific nutrient fortification
Starter cultures	Defined microbial strains with desired traits	Consistency, safety, repeatability
Bioreactors	Controlled fermentation parameters (pH, temp, O_2)	Reproducibility, volume scalability
AI & sensor systems	Real-time monitoring and data-driven adjustments	Operational efficiency, reduced spoilage, quality

3. Fermentation Practices in Nigeria and Associated Challenges

Nigeria's fermented foods, including ogi (grains), fufu (tubers), kunu (millet-based beverage), and dawadawa (legume condiment), are produced through largely artisanal methods [22–24]. Typically, fermentation is spontaneous, driven by ambient microorganisms, with variability in container type, crop preparation, fermentation duration, and hygiene. Producers often rely on traditional knowledge to judge readiness based on smell, acidity, or texture.

Major challenges include:

- Microbial contamination: Food products are susceptible to pathogens such as *Bacillus cereus*, *Escherichia coli*, and molds generating mycotoxins [4, 25].
- Inconsistent fermentation: Variability leads to unpredictable acidity, flavor, and performance, hindering consumer confidence and safety [26, 27].
- Limited infrastructure: Producers often operate without refrigeration, temperature control, or sanitized vessels, increasing risk of spoilage [28].
- Economic loss: Imprecise fermentation and poor storage result in waste, undermining livelihoods.

As these challenges persist, there is a growing recognition of the need for affordable technologies that enhance safety and quality without erasing cultural authenticity.

4. Comparative Analysis: Bridging the Technological Divide

Industrial fermentation technologies offer a blueprint for efficiency, but adaptation respects resource constraints and cultural contexts. The following strategies propose how advanced methods can be tailored for Nigeria:

4.1. Starter Cultures from Indigenous Microbes

Isolation of beneficial lactic acid bacteria or yeast from existing fermented foods can yield starter cultures that are safe, adaptive to local substrates, and preservation-compatible. This approach preserves traditional microbial heritage while improving consistency and health benefits [29].

4.2. Low-Cost pH Monitoring Tools

Simple pH strips or affordable probes, possibly solar-powered or battery-operated, can provide semi-quantitative data during fermentation. This allows timely intervention, helping producers maintain target acidity and reduce spoilage [13].

4.3. Scaled-Down Bioreactor Models

Mini bioreactors built from food-grade drums or containers equipped with immersion heaters, stirrers, or water jackets can simulate large-scale fermentation control. These mobilizable systems suit small-scale enterprises, enabling more consistent outcomes without major capital investment [17].

4.4. Mobile Fermentation Monitoring via Smartphones

Smartphone-based apps can enable producers to log fermentation data (pH, temperature, time) and share this with supervisors or extension agents. Training modules integrated into apps would support ongoing capacity building and quality oversight.

4.5. Training and Extension Services

Farmer cooperatives and community food entrepreneurs would benefit from hands-on training in hygienic practices, fermentation hygiene, and the use of starter cultures or bioreactors. These programs can be supported by government or NGO partnerships. Table 2 presents fermentation technologies that can be adapted in Nigeria and are scalable.

Table 2 Scalable Fermentation Technology Adaptations for Nigeria

Advanced Technology	Adaptation for Local Context	Expected Outcome
Starter cultures	Locally sourced LAB strains for repeated use	Improved safety and product uniformity
Affordable pH monitoring	pH strips or low-cost electric probes	Better acid control and spoilage reduction
Low-tech bioreactors	Barrel-type vessels with controlled temperature/agitation	Consistency and increased volume
Mobile fermentation apps	Smartphone-based logging and training	Remote guidance and quality improvement

These interventions require cross-sector collaboration, local adaptation, and alignment with cultural preferences. Critical considerations include scalability, cost-effectiveness, acceptance among producers, and regulatory alignment.

5. Nutritional and Functional Impacts

Applying these adapted methods can elevate the nutritional and functional properties of fermented foods:

5.1. Enhanced Nutrient Bioavailability

Controlled fermentation can significantly reduce anti-nutrients such as phytates and cyanogens present in cereals and tubers, thus enhancing the bioavailability of minerals such as iron and zinc [30]. Fermented cereals or tuber flours have been shown to release more bioaccessible iron.

5.2. Mobilized Bioactive Compounds

Fermentation often increases phenolic compounds and antioxidant capacity in foods. For instance, ogi and fermented maize porridges demonstrate higher antioxidant potential than their raw counterparts, contributing to gut health and immune support [31].

5.3. Probiotic and Prebiotic Benefits

Starter-culture fermentation can enrich foods with beneficial lactic acid bacteria, supporting gut microbiota and delivering probiotic effects—something less reliable in spontaneous processes.

5.4. Targeted Biofortification

Through precision fermentation, it is conceivable to engineer starter strains that produce vitamins deficient in local diets, like B12 and D, and deliver them through staple fermented products, addressing micronutrient gaps [23].

5.5. Extended Shelf Life

Controlled acidification lowers pH faster and to reliable thresholds, thereby enhancing shelf stability, reducing spoilage, and improving food safety without the need for refrigeration [11]. These enhancements align with public health goals, particularly in areas with micronutrient deficiencies, increasing the nutritional quality of culturally accepted staple foods.

6. Socio-Economic and Policy Considerations

Success in transitioning to modernized fermentation depends on context-sensitive socio-economic and policy strategies:

6.1. Capacity Building

Training programs tailored for local producers, such as rural women's cooperatives, are essential. These would cover hygiene, starter culture use, fermentation tracking, and use of simple bioreactors.

6.2. Regulatory Framework Development

Authorities like NAFDAC should develop regulations that recognize small-scale fermentation innovations, create quality assurance protocols, and ensure safety without burdening informal food systems [23].

6.3. Public–Private Partnerships and Investment

Collaboration among academia, food industries, and development organizations can fund pilot projects, subsidy models for starter culture distribution, and micro-loans for semi-mechanized fermenters.

6.4. Market Acceptance and Cultural Relevance

Fermented products must align with local sensory preferences—taste, texture, aroma. Packaging and branding using culturally meaningful designs may increase consumer trust and willingness to adopt modernized versions [24].

6.5. Economic Incentives

Producers applying enhanced fermentation should access formal markets, microcredit support, and certification that equates quality with premiums, encouraging widespread adoption and better livelihoods.

Cross-cutting these elements ensures that technological innovations are sustainable, equitable, and culturally integrated—rather than imposed—thus fostering successful transformation of traditional food systems.

7. Future Directions and Recommendations

To enable effective adoption of advanced fermentation techniques in developing contexts, the following strategic actions are proposed:

7.1. Pilot Projects with Indigenous Starter Cultures

Initiate pilot-scale collaborations with local food producers using starter cultures derived from native fermented products. These pilots would compare outcome consistency, safety, and nutritional profiles versus traditional fermentation.

7.2. Field-Deployable Fermenter Prototypes

Design and test low-cost fermenter prototypes in rural and peri-urban settings - such as insulated barrels or solar - heated vessels - to assess performance, usability, and adoption barrier feedback.

7.3. Nutritional and Metabolomic Assessment

Use analytical tools such as NMR, HPLC, or metabolomics to quantify nutrient and bioactive changes in traditional versus enhanced fermented foods - providing data-driven evidence of benefits.

7.4. Policy and Standards Development

Partner with food safety agencies to define tiered regulatory frameworks for traditional fermented products, clarifying hygiene guidelines, starter culture certification, and minimum safety thresholds.

7.5. Training and Extension Infrastructure

Develop training modules and dissemination platforms, such as mobile apps or short courses, targeted at small-scale food entrepreneurs and cooperative members.

7.6. Public–Private–Academic Consortia

Build multi-stakeholder consortia to coordinate innovation, funding, and policy advocacy, with goals of scaling demonstrations and supporting market entry of improved fermented products.

7.7. Consumer Acceptance Studies

Conduct sensory and behavioral studies to understand adoption drivers for modernized fermented foods—balancing technological advantages with cultural and taste preferences.

Together, these actions can help scale the modernization of fermentation with cultural sensitivity and economic viability, ultimately improving nutrition, safety, and livelihoods across Sub-Saharan Africa.

8. Conclusion

Advanced fermentation technologies from precision fermentation to AI-enabled monitoring represent powerful innovations for producing safer, more nutritious, and scalable fermented foods. However, successful adoption in a context such as Nigeria requires adaptations sensitive to local resources, infrastructure, culture, and economic realities. Starter cultures derived from indigenous strains, low-cost fermentation vessels, mobile monitoring tools, and supportive policy frameworks offer a practical path forward. Enhanced nutritional outcomes, shelf-life stability, and food safety can be achieved without compromising traditional food heritage.

By leveraging these modern tools within culturally grounded frameworks, stakeholders, including producers, governments, and development partners, can foster resilient food systems, promote public health, and empower rural economies. This review highlights that the future of fermentation in developing regions lies not in wholesale technology importation, but in co-creating innovations that align with local realities while building on advances pioneered by industrialized nations.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares that no known competing interests exist in this paper.

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