Fermentation: An Ancient Solution to Modern Challenges

sightandlife | Special Report

Imprint

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Acknowledgement
We would like to sincerely thank all the individuals and organizations who contributed to this Special Report. Our deepest appreciation goes to the technical team for their invaluable input throughout the process. We extend a special thank you to the Children's Investment Fund Foundation for their support in making this publication possible.

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ISSN 3079-7276

For citations, please use
Sight and Life. 2025. Fermentation: An ancient solution for modern challenges. Basel, Switzerland. DOI: https://doi.org/10.52439/HQMU7816

On the cover
Preparing injera in Burayu, Oromia, Ethiopia
Photograph: Bruktawit Legesse Soressa

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Glossary

Back-slopping
A fermentation technique that involves using a small amount of a previous batch is used to initiate the next fermentation.

Fermentation
A metabolic process where microorganisms, such as bacteria, yeast, or fungi, convert organic compounds (e.g., glucose) into alcohol, gases, or acids under anaerobic conditions.

Fermented foods
Foods or beverages produced through controlled microbial growth, and the conversion of food components through enzymatic action.

Foodomics
The application of omics technology to study the comprehensive components in food.

Lactic acid bacteria
Microorganisms that produce lactic acid by fermenting carbohydrates, often used as starter cultures and probiotics.

Prebiotics
Substrates, often soluble fibers, selectively utilized by host microorganisms, serving as 'food' for beneficial microbes and conferring health benefits.

Probiotics
Live microorganisms that, when consumed in sufficient amounts, provide health benefits.

Starter cultures
A carefully selected and characterized microbial inoculum composed of specific strains of bacteria, yeasts, or molds, used to initiate and control fermentation processes in food production.

Substrate
A raw material or substance that an organism, enzyme, or microorganism acts upon to produce a product, such as food.

Traditional fermentation
A natural metabolic process in which microorganisms, such as yeast and bacteria, convert sugars in food into alcohol, gases or acids under anaerobic conditions, improving their nutritional, shelf life, organoleptic, and health-promoting characteristics.

Spontaneous fermentation
Traditional fermented foods and beverages produced by spontaneous generation, where this is no control over the microbiota or the substrate used.

Foreword

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Technology, in its many forms, will very likely play a significant role in any sustainable solutions to the many challenges both human and planetary health are currently facing. We need to invest in emerging technologies while leveraging existing technologies for nutrition, applying them both responsibly and equitably. This Special Report is a good example of that.

No matter how far technology advances, there will always be a place for traditional wisdom—indeed, humanity's most ancient technology. This publication is proof of that. In these days of AI and other sophisticated tech, we are choosing to focus on an ancient craft that can be a solution for modern problems.

Many cultures have been using fermentation techniques in food preparation for centuries. People across Africa and South Asia consume fermented foods as part of their staple diets—for example injera in Ethiopia, gari in Nigeria, or dosa in India. For many, it's just a way of life, but it can also be a way to solve big nutrition challenges.

Once used primarily for food preservation and security, the world is now acknowledging and accepting a wider role for fermentation in improving malnutrition status, including hidden hunger. Fermentation techniques can enhance the nutritional value of foods, making minerals more bioavailable, proteins more digestible and, potentially, promoting gut health. They can also act to enhance flavor, as those who have eaten injera can attest.

Microbial biofortification is a technique, for instance, that uses microorganisms to enrich the vitamin content of food during fermentation and holds promise for enhancing and standardizing the vitamin B content of fermented foods. This might be a crucial step in arresting widespread deficiencies in B vitamins that pose a severe threat to vulnerable groups such as children and pregnant women. With its possibilities for small-scale production and low environmental footprint, microbial fortification might be the answer to the negative impact of the global food production system on both planetary and human health.

Why this Special Report now? The world is well poised to tap into the potential of fermentation. We see this technique as a vehicle to advance breakthroughs in malnutrition solutions, particularly in LMIC where many communities traditionally use fermentation. Novel yet simple interventions can have large-scale impacts on child malnutrition and other pressing nutritional challenges – for example, by incorporating fermented foods in school meal programs, or providing low-cost starter cultures and training for entrepreneurs to enhance food safety and standardization.

In this Report, we bring experiences from the field to illustrate how some of these interventions are being done and what more is possible. We also highlight challenges such as gaps in regulations and guidelines to ensure standardization, longevity and safety for fermented food products. We present evidence of the link between fermented foods and disease prevention: Several mechanisms in fermented food have been linked with the prevention of diseases such as obesity and diabetes, and reducing the risks of cardiovascular disease and even cancer. Fermented foods can support immune function and are a compelling component of a holistic approach to well-being.

In LMIC, solutions to protein diversification and food security could be achieved by establishing self-reliant biomanufacturing units. Read about how mycoprotein production derived from fungi is being produced in a climate-safe environment in Kenya using high-tech bioreactors, which will enable year-round production of essential proteins. We highlight methods across the value chain of fermented food production – from using non-toxic and natural metabolites to incorporating food-grade bacteriocins into coatings or packaging films to preserve the microbiological safety and sensory attributes of indigenous foods.

There is so much happening in the world of fermented foods that it's hard to keep up with the advancements and the incredible progress. This Special Report is an attempt to gather all knowledge in one place to enable further advancement and more impactful innovation.

New technology will never replace ancient wisdom, but it can build on it, improving and accelerating the benefits in myriad ways. As future-ready citizens we adopt and adapt technology to our advantage and, in this case, advance traditional wisdom.

We are proud that our work, and that of our partners, is powered by innovation. We are grateful for the efforts of many likeminded innovative thinkers trying to break new ground in nutrition solutions using ancient information and techniques. In adapting fermentation to more contemporary forms and methods, and leveraging technology to catalyze climate-smart solutions, we can build a healthier, more resilient and more equitable world for all.

Editorial

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The race toward sustainable solutions and innovative food systems has accelerated dramatically. Policy reforms, technological leaps (hello, AI!), community-driven initiatives, and bold themes of resilience have all joined the fray. And yet, polycrises – from the lingering effects of COVID-19 and escalating climate extremes to geopolitical conflicts and shifting economic policies – continue to challenge progress. Cuts to international aid, including reductions in U.S. support, further complicate the landscape, raising concerns that food crises may deepen in many vulnerable regions.

Globally, hunger has remained alarmingly high for three consecutive years. More than 800 million people – nearly 10% of the global population – are affected by malnutrition, and projections indicate that we are not on track to meet any of the seven World Health Assembly global nutrition targets by 2030. An estimated 35.4 percent of people in the world (2.83 billion) are unable to afford a healthy diet. By 2050, it is expected that no country in sub-Saharan Africa and only a few in Asia and the Pacific will meet the World Health Organization's minimum recommendation of 400 grams of fruits and vegetables per capita daily.

In the face of these mounting challenges, the idea of resilience evolves from a mere buzzword into the backbone of food and nutrition security – empowering our food, health, and social systems to weather shocks while safeguarding the nutrition of the most vulnerable. Now more than ever, resilience must drive policy, spark innovation, and catalyze action toward long-term, sustainable solutions.

Despite persistent global challenges, there are promising developments. Increased investment in school meals, enhanced efforts in large-scale food fortification, the promotion of whole grains, a focus on nature-based solutions, and a renewed emphasis on localized food systems are emerging as positive trends.

However, progress remains insufficient. Declining nutrient density in plant-based foods, largely driven by climate change, is concerning. A study by Tigchelaar and colleagues highlights a stark reality: By mid-century (2041–2060), climate extremes will significantly reduce global micronutrient availability. As much as 75% of calcium, 30% of folate, 39% of iron, 68% of vitamin A, and 79% of vitamin B12 in primary food products could be lost. These projections underscore the urgency of enhancing the nutritional quality of plant-based foods and strengthening food system resilience.

A critical question emerges: How can we maximize the nutritional value of our foods?

Enter the world of fermentation – a powerful yet often overlooked solution that seamlessly integrates nutrition, sustainability, localization and resilience. More than just a method for preservation and flavor enhancement, fermentation represents a vast, untapped frontier of innovation. It offers a climate-friendly, nature-based approach that can accelerate progress across multiple fronts – research and development, sustainable business models, scaling, and financing. Fermentation also plays a crucial role in counteracting the declining nutrient density of plant-based foods, a challenge exacerbated by climate change. Nutritionally, it enhances protein digestibility by breaking down complex proteins into smaller peptides and free amino acids while generating bioactive compounds with antioxidant, antihypertensive, and antimicrobial properties. It reduces antinutritional factors such as phytates and tannins, improving the bioavailability of key nutrients – particularly iron and zinc, two micronutrients in which deficiencies are widespread. Additionally, fermentation minimizes food waste and promotes dietary diversity. By strengthening localized food systems and reducing dependence on fragile supply chains, it provides a evidence-based, climate-resilient strategy for improving food security and nutrition.

So, without giving too much away, what are we most excited about in this Special Report? Unsurprisingly, nutrition remains front and center. As a 35-year-old think-do tank, we enjoy the flavors of fermented foods – but our real focus is on innovations that increase micronutrient bioavailability in plant-based diets and reduce malnutrition. While we are already deeply engaged in phytase research, we aim to move beyond traditional fortification. One promising innovation involves selecting functional strains or consortia with B vitamin–synthesizing capabilities to significantly increase the vitamin content in fermented foods. This microbial biofortification strategy offers a resilient, scalable solution – from small industrial setups to household levels – that may help address some of the supply challenges associated with conventional fortification.

We are also deeply intrigued by recent insights into fermentation, which provides a more granular look at the impact of fermentation on food composition. Although further research is needed, foodomics is already revealing that fermentation transforms foods at metabolomic and biochemical levels, creating new components with unique functions. Mapping the nutritional value of fermented foods could serve as a foundational step, aligning with Sight and Life's ongoing work and our innovative special reports that spotlight emerging opportunities in nutrition and food systems. Ultimately, we hope this research will uncover functional biomarkers that connect fermented foods with nutritional status – including micronutrient deficiencies, undernutrition, and overweight/obesity – and overall health.

Aligned with our helping people help themselves model, we strongly support initiatives that harness fermentation to improve community health, local economies, and food security. Across East Africa, fermentation is deeply rooted in food culture and holds immense potential for business opportunities. Programs that enable small-scale producers to use starter cultures for probiotic-rich fermented foods are driving local entrepreneurship, strengthening resilience, and enhancing both nutrition and economic empowerment. Today, such efforts have created jobs for many and increased access to nutritious fermented foods. In some cases, the integration of these foods into school meal programs is also improving diet quality for children, supporting better growth and cognitive development.

Finally, fermented foods are a testament to local ingenuity, bridging both high-tech innovation and indigenous dietary traditions. Fermentation is already deeply embedded in many cultures, offering immense potential to enhance nutrition while preserving local foodways. Traditional techniques –such as those used in preparing injera in Ethiopia, gari in Nigeria, or dosa in India – not only sustain indigenous microorganisms and cultural knowledge but also safeguard culinary traditions, biodiversity, and economic stability. These time-honored practices highlight the power of fermentation in maintaining food diversity and resilience. By embracing local solutions, communities build their resilience against global challenges by reducing dependence on external inputs while preserving a rich diversity of options.

In this report, we invite you on an engaging journey into the fascinating realm of fermentation, organized into five key sections:

1. The science underlying fermentation, including microbial processes and associated health and nutritional benefits.
2. The challenges that hinder the widespread adoption of fermentation and the opportunities to upscale its utilization.
3. Best practices supported by compelling evidence from the LMIC field
4. Novel advancements in fermentation within LMIC, extending beyond traditional methods.
5. A comprehensive framework of action.

We extend our profound appreciation to all those who have contributed to this Special Report. A special acknowledgment goes to the Children's Investment Fund Foundation (CIFF) for their vital support in making this publication possible. We also sincerely thank our exceptional report advisory technical team – Dr. Anna Greppi, Yamina de Bondt, Nieke Westerik, and Adewale Olesegun Obadina, for their invaluable guidance and meticulous review of the enclosed articles.

The Evidence Base

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Exploring Traditional Fermentation: An Introduction

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The history of fermented foods

The fermentation of foods and beverages is an age-old practice that has played a significant role in traditional human diets across every continent.[1] Ancient societies independently discovered that microorganisms, through fermentation, could preserve food, enhance its nutritional value, and improve its flavor and texture.[2] Historical records indicate that fermentation was indigenous to many regions of the world. The earliest archeological evidence dates back to around 6000 BCE, showcasing early instances of pottery used for fermenting wine.[3] Fermentation was part of several ancient civilizations, with soy sauce in East Asia, yogurt throughout Europe and the Middle East, beer in Babylonia, and vegetable preservation in China.[1,4]

The early 19th century marked a period of burgeoning interest in microbiology in Europe. Several independent chemists concluded that yeast is a living organism, a view met with strong opposition.[5] However, the work of the French chemist Louis Pasteur finally put an end to the criticism and led to an improved understanding of fermentation. Pasteur showed that lactic acid fermentation was caused by living organisms.[6]

> **"Traditional fermentation remains prevalent at the household or village level in numerous LMIC"**

Fundamentals of traditional fermentation

Since their first appearance, fermented products, defined as foods made through desired microbial growth and enzymatic conversions of food components,[7] have been produced through natural fermentation facilitated by indigenous microorganisms naturally present in the substrate or the processing environment.[8,9] Examples of such foods include sauerkraut, kimchi and some fermented soy products.[10]

Traditional fermentation practices

Traditional fermentation methods, passed down through gen erations, are typically practiced at the household, community or small-scale industrial level. The art of fermentation carries immense cultural and historical significance, shaping culinary traditions globally. Moreover, fermentation presents a significant economic opportunity, particularly for women. As custodians of food preparation and preservation knowledge, women utilize fermentation to earn income, improve food security, and support community livelihoods. While traditional fermentation remains prevalent at the household or village level in numerous low- and middle-income countries (LMIC), larger-scale industrial operations are relatively scarce.

> **"Fermentation presents a significant economic opportunity, particularly for women"**

Starter cultures

Via the addition of starter cultures - a process known as culture-dependent fermentation - resulting in products such as yogurt, kefir, kombucha, and natto.[10] During the fermentation process, microorganisms metabolize carbohydrates, proteins and other nutrients present in the substrate, producing various compounds, including organic acids, alcohols, gases and flavor-enhancing molecules.[11] Various types of fermentation are distinguished by the specific microorganisms involved and the resulting end products. Traditional fermentation can be categorized into lactic acid fermentation, fungal fermentation and alkaline fermentation.[11]

Fermented foods can be broadly categorized into two groups based on the presence or absence of live microorganisms. Examples of live microbe-containing fermented foods include yogurt, kefir, miso, kimchi, and tempeh. In contrast, non-live microbe-containing counterparts encompass bread, beer, wine and heat-treated or pasteurized fermented vegetables.[7]

> **"The earliest archeological evidence of fermentation dates back to around 6000 BCE"**

Typical Ethiopian stews and condiments served over injera, the fermented pancake-like staple. *Photo credit: Milonk/Shutterstock.com*

Health and nutrition benefits of traditionally fermented foods

Historically, food fermentation primarily served as a preservation method, leveraging the concentration of fermenting microorganisms, their byproducts, and the fluctuating pH of the substrate to inhibit the proliferation of pathogenic microorganisms.[8] Widely applied in LMIC, traditional fermentation of staple foods also can enhances the nutritional content of the raw product, increasing the bioavailability of minerals,[12-14] enhancing the digestibility of proteins,[14-16] and in some cases, removing allergens, reducing antinutrients as well as toxins.[17-21] Fermented foods have the potential to promote a healthy gut microbiome, strengthen the immune system, and reduce the risk of infections and illnesses.[14,22-25] While fermented foods are often touted for their health benefits, it is important to recognize the nuances involved. Much of the research suggesting potential benefits has been conducted in vitro, yet this does not necessarily translate into significant findings in vivo. What we know from the in vivo research is needed to understand the role of other dietary and environmental factors in affecting the health outcomes associated with traditional fermented foods.[26]

Fermented foods and beverages have long played a vital role in human culture, offering preservation, flavor enhancement and nutritional benefits. Traditional fermentation practices not only hold cultural significance but can also contribute to food security, support local food systems, and offer health benefits. Moving forward, it is crucial to promote and preserve traditional fermentation methods while exploring innovative approaches to enhance their scalability, accessibility, and sustainability for future generations.

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The Multifaceted Value of Fermentation

Fermentation, a time-honored method of food processing worldwide, harnesses the power of microorganisms to transform raw ingredients into nutritious, flavorful foods. It holds significant potential to support sustainable and equitable food systems, particularly across low- and middle-income countries.

Food safety and preservation

- Ensures food safety by creating conditions that suppress harmful pathogens
- Extends shelf-life by producing natural preservatives that prevent spoilage and reduce food loss and waste

Organoleptic properties

- Enhances sensory properties , enhancing flavors, aromas and textures

Nutritional value

- Increased protein digestibility: enhances breakdown of proteins
- Increased mineral bioavailability: improves calcium, zinc and iron absorption
- Vitamin bio-enrichment: increases vit. B2, B9 and B12 content
- Reduced anti-nutritional factors, allergens and toxins

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Staple foods + Microorganisms/ Starter culture

Environmental benefits

- Supports sustainable food systems by requiring less energy input compared to other preservation methods, reducing the carbon footprint
- Reduce need for long-distance transportation by promoting consumption of locally produced foods

Social impact

- Honors traditional practices: well-accepted and embedded in culture
- Valorization of local raw ingredients: promotes local flavors and traditions
- Empowerment of local, smallholder producers and workforce (especially women and youth)
- Income generation: creates economic opportunities

Potential health benefits

- Source of beneficial bacteria: supports gut health
- May have an impact on immunity and overall health

Fermentation: A Promising Approach for Enriching Food with Natural B Vitamins

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Key messages

- Deficiencies in B vitamins pose a severe threat to human health, leading to devastating and life-threatening conditions, especially in vulnerable groups such as children and pregnant women.
- Fermented foods provide an option for addressing a range of dietary deficiencies, but traditional fermentation methods have the disadvantage of producing final products with highly variable B vitamin content.
- Supplementation of functional microbial strains or consortia with vitamin B biosynthetic capabilities is a promising approach to enhance vitamin content during fermentation.
- With its possibilities for small-scale production and low environmental footprint, microbial biofortification has the potential to complement existing strategies aimed at combating B vitamin deficiencies.

Introduction

B vitamins such as riboflavin (vitamin B_2), folate (vitamin B_9) and cobalamin (vitamin B_{12}) are water-soluble vitamins that play key roles in human metabolism. They function mainly as cofactors, coenzymes, transcription control factors or antioxidants. Humans lack the ability to synthesize these vitamins, so they must be obtained from dietary sources. Unfortunately, deficiencies in folate and cobalamin are prevalent in many countries, particularly in low-income regions.[1] These deficiencies pose a severe threat to human health, leading to devastating and life-threatening conditions, especially in vulnerable groups such as children and pregnant women. Although riboflavin deficiency is less common, it can still cause significant health issues such as growth problems, anemia and inflammatory skin lesions.[2]

Globally, dietary diversification, fortification and supplementation are the main strategies to address vitamin deficiencies.[3] The first involves consuming a varied and nutritionally rich diet that includes both plant- and animal-based foods. Fortification refers to the enrichment of foods or crops with micronutrients to improve their nutritional value, while supplementation involves providing micronutrients in the form of capsules, tablets or drops. Despite their established effectiveness, these approaches remain inaccessible to a significant portion of the vulnerable population due to factors including but not limited to the unaffordability of a healthy diet, weak regulations and policies that hinder the implementation of fortification programs, and poor supply chain management, which can lead to frequent stockouts of essential micronutrients.[4]

Fermentation offers a promising alternative. It transforms raw materials into final fermented food products through the action of microorganisms. Fermented foods are widespread globally, and are estimated to constitute about one-third of all foods consumed worldwide.[5] Fermentation enhances foods' safety and shelf life and improves their nutritional, functional and organoleptic qualities. Spontaneous fermentation and back-slopping, which are non-controlled fermentation methods, are common around the world. However, these methods produce final products with highly variable B vitamin content, which may not always significantly help to meet vitamin requirements.[6-8] In contrast, selecting functional strains (**Table 1**) or consortia with B vitamin synthesizing capabilities to supplement the endogenous microbiota can increase the B vitamin content of fermented foods to the quantity desired. This microbial biofortification approach is a promising alternative for enhancing the vitamin content of fermented foods, being compatible with sustainable production at small industrial scales or household levels (**Figure 1**).[9-11]

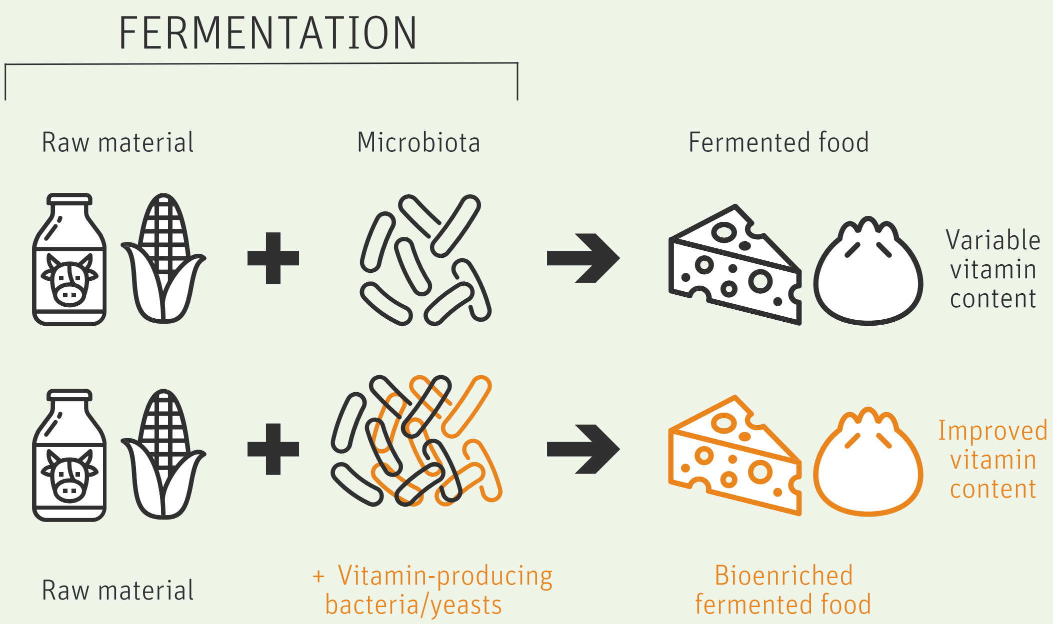
> **"Fermented foods are estimated to constitute about one-third of all foods consumed worldwide"**

TABLE 1: Examples of use of functional microbial strains applied for bioenrichment of vitamins B_2, B_9 and B_{12} in fermented foods

Vitamin	Food	Microbial species involved	Quantities of vitamin reported (fresh weight)	Estimated serving	Contribution to RDI
B_2*	Bread [18]	*Limosilactobacillus fermentum*	0.66 mg/100 g	100 g	40%
	Coconut beverage [44]	*Limosilactobacillus reuteri*	16 mg/L	100 mL	100%
	Gluten-free bread [47]	*Weissella cibaria*	0.35 mg/100 g	100 g	20%
B_9**	Yogurt [48]	*Lactobacillus amylovorus*	0.26 mg/L	225 mL	15%
	Soy milk [49]	*Streptococcus thermophilus*	1.8 mg/L	100 mL	45%
	Injera [9]	*Saccharomyces cerevisiae + L. plantarum*	53.5 µg/100 g	200 g	27%
B_{12}***	Bread [11]	*Propionibacterium freudenreichii*	8.9 µg/100 g	100 g	›100%

*B_2 Recommended Daily Intake (RDI) ~1.4 mg/day
**B_9 RDI ~400 µg/day
***B_{12} RDI ~2.5 µg/day

FIGURE 1: Use of fermentation to increase vitamin content of the final product, with and without vitamin-producing functional strains (in orange)



Source: Anna Greppi

Fermentation to increase vitamin B_2 (riboflavin) content

Vitamin B_2 is involved in essential reactions for life, and can only be synthesized by some plants and microorganisms. In general, a diverse diet provides the recommended daily intake (1.4 mg/day for pregnant women), and riboflavin deficiency is most common in LMIC in Asia and Africa.

Yeast and lactic acid bacteria (LAB), which are usually employed as microbial starters for most food fermentations, can synthesize vitamin B_2 in a species- or strain-specific way. Thus, the selection of strains that produce higher levels of this vitamin has been reported as a promising approach to enhance the riboflavin content during fermentation.[12] For example, genetic screening revealed that African millet–based fermented foods are a good source of B-group vitamin-producing microorganisms due to the occurrence of pathways for riboflavin and folate synthesis.[8,13] However, under physiological conditions, the microbial production of vitamin B_2 is generally low and inadequate for developing *in situ* biofortification strategies. In contrast, exposure to the selective pressure of roseoflavin, a toxic analog of riboflavin, is a valuable biotechnological tool to select riboflavin-overproducing strains due to impaired regulation of the *rib* operon, responsible for vitamin B_2 biosynthesis.[14,15] Interestingly, roseoflavin-resis tant strains can increase vitamin B_2 production from a few µg/L to several mg/L. In the last years, riboflavin-overproducing strains belonging to the species *Lactiplantibacillus plantarum*, *Limosilactobacillus fermentum*, *Leuconostoc mesenteroides*, *Lactococcus lactis*, *Weissella cibaria* and *Propionibacterium freudenreichii* have been selected and employed for the production of riboflavin-enriched fermented staple foods such as bread, dairy, soy and cereal-based products.[16-20]

Fermentation to increase vitamin B_9 (folate) content

Vitamin B_9 is a crucial vitamin involved in numerous physiological processes.[21] Folate biosynthesis primarily occurs in plants, bacteria and yeasts, while humans and animals cannot synthesize folate *de novo*. Folate vitamers exist in either oxidized form (such as folic acid, the synthetic form) or reduced form (such as natural folates like 5-methyltetrahydrofolate) and may contain substituents such as methyl or formyl groups.[22] Despite variations in stability and bioavailability among different folate vitamers, those synthesized by microorganisms are biologically active in humans.[23]

Good natural dietary sources of folate include organ meats (e.g., liver and kidney) and fresh green vegetables (e.g., spinach). Fermentation using folate-producing microorganisms has been proven several times to be effective to increase the folate content of foods. For example, folate-producing LAB were isolated from maize gruel, and the best candidates were used as starters to produce sorghum motoho with a final folate content up to eight times higher than the control, reaching about 20 µg/100 mL – adequate to cover young children's daily folate requirements.[24] Similarly, high-producing *L. plantarum* strains were selected from injera[6] and inoculated together with folate-producing yeast, using a traditional back-slopping process. This resulted in a concentration of 53.5 µg/100 g fresh material, providing up to 22% of the recommended nutrient intake for folate.[9] Similarly, a selected autochthonous yeast strain of *Pichia kudriavzevii* was proposed for co-fermentation with *L. fermentum* in a model of fermented pearl millet–based gruel, enhancing the folate content to 4 µg/100 g fresh matter.[25] Interestingly, the most productive folate-producing *L. plantarum* strain isolated from injera was able to reverse folate deficiency in a murine model, suggesting alternative solutions beyond consuming folate-rich foods to mitigate this vitamin deficiency.[26]

> **"Using microorganisms to produce active vitamin B_{12} offers a promising approach for fortifying plant-based products, boosting intake in those consuming few animal foods"**

Fermentation to increase vitamin B_{12} (cobalamin) content

Vitamin B_{12} is another key micronutrient playing a fundamental role in human nutrition.[27] However, its biosynthesis is limited to certain bacteria and archaea.[28] For food applications, a few LAB strains are known to encode a complete *de novo* biosynthetic pathway for cobalamin, including *Limosilactobacillus reuteri,*[29] *L. fermentum,*[30] *Furfurilactobacillus rossiae*[31] and *L. plantarum.*[32] However, the ability of LAB to synthesize active cobalamin is disputed, as they may produce corrinoid compounds (also known as pseudovitamins) that have a lower affinity for intestinal transporters, making them unavailable to humans.[33] On the other hand, active cobalamin synthesis by propionic acid bacteria is well known and can be exploited.

Cobalamin dietary sources for humans are almost exclusively foods of animal origin such as meat, fish, eggs and dairy products.[34] In these foods, the vitamin originates from the gut microbiota of the animals or from the soil. Cheese also contains vitamin B_{12}, thanks to the fermentation of milk by LAB or propionic bacterial strains.[35] Traditional African fermented dairy products, including nono, wara, fene, suusac, pendidam, gariss, nyamie, leben/lben and kulenaoto are also considered good sources of vitamin B_{12}.[36] Notably, vitamin B_{12} in dairy products is particularly beneficial for human nutrition due to its higher bioavailability compared to other animal-based foods.[37] Certain plant-based foods, such as tempeh, also contain vitamin B_{12}, primarily due to bacterial synthesis during fermentation.[38,39] Recent work in Ethiopia showed that fermentation of teff flour during the preparation of the staple food injera significantly increased the vitamin B_{12} content, leading to a final product with up to 5.7 µg/100 g, able to fully cover the recommended nutritional intake.[7] Nevertheless, all vitamin B_{12} from these samples was in the inactive form of pseudocobalamin.

The use of microorganisms producing the active form of vitamin B_{12} is a promising way to develop plant-based food products fortified with vitamin B_{12} as an alternative strategy to increase its intake in people who consume limited amounts of animal products.[38] Recent studies have explored the combination of *P. freudenreichii* in mixed fermentation with LAB by using cereals (i.e., wheat, oat, rice and rye bran, as well as millet and sorghum flours), pseudocereals (i.e., buckwheat bran, amaranth and quinoa flours), and legumes (i.e., soybean, faba bean and lupine flours) for cobalamin fortification.[40,41] Limited results have also been reported about the *in situ* cobalamin enrichment of fermented soy milk products by LAB.[42,43] Recently, a fermentation process was developed for bread applications, using a mixed fermentation method with strains of *P. freudenreichii* and *Weissella confusa*, which allows the concomitant production of dextran (a texture-enhancing agent) and vitamin B_{12} (*in situ* fortification). The authors estimated that consuming 100 g of this fortified bread would meet the recommended daily intake for B_{12}.[11]

Spontaneously maize-based fermented products (mawè and ogi) in Benin. *Photo credit: Dr Anna Greppi*

"Despite variations in stability and bioavailability among different folate vitamers, those synthesized by microorganisms are biologically active in humans"

"Yeast and lactic acid bacteria, which are usually employed as microbial starters for most food fermentations, can synthesize vitamin B2"

Conclusions and perspectives

The current global food production system is negatively impacting both planetary and human health, necessitating a swift transition to a sustainable and fair food system. Microorganisms could play a crucial role in this transition, as they can produce nutritionally rich and healthy microbial foods with low environmental footprints. One key recommendation for a sustainable transition is a shift towards plant-based diets, which are also beneficial from a health perspective due to their high content of healthy compounds, such as fibers and antioxidants. However, some essential micronutrients, like vitamin B_{12}, are absent in plant-based foods but can be provided through microbial fermentation. Moreover, it is worth mentioning that several B-vitamin-producing strains have also been characterized for their probiotic potential (survival in the digestive tract and the production of enzymes of nutritional interest, such as enzymes involved in the degradation of polyphenols).[44-46] When a fermented product is not cooked before consumption, these microorganisms may survive the digestive tract and exert their beneficial health effects, thus opening new perspectives for the formulation of functional foods tailored for specific targets of consumers.

The global impact of fermentation is significant, given the vast diversity of fermented foods worldwide, reflecting their immense traditional and cultural importance, as well as the variety of food substrates and resource utilization methods. Traditional fermented foods and their production practices are often deeply integrated into the economic and social structures of various human societies. Fermentation also drives innovation, as B vitamin–producing microorganisms can be successfully applied to different food matrices. However, the impact of fermentation on the taste and texture of foods should be systematically evaluated. Additionally, it is essential to assess the population-level impact of such strategies. Efforts should also focus on the local production of microorganisms, which can be a significant bottleneck. While fermentation is a relatively simple process, producing microorganisms requires specific skills and equipment, which may be scarce, particularly in areas with limited industrial infrastructure.

In conclusion, the development of B vitamin–enriched fermented foods through microbial fermentation represents a promising approach to address dietary deficiencies, especially in regions with limited access to diverse dietary sources of these essential vitamins. It could serve as a sustainable complementary approach to existing strategies aimed at combating B vitamin deficiencies.

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Microbial Food Safety and Preservation of Fermented Foods in Nigeria

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Key messages

- Fermented foods have a crucial role to play in the socio-economic advancement of Nigeria.
- The diverse microorganisms found in Nigerian fermented foods have also contributed to improved food security and enhanced nutrition outcomes.
- However, fermented foods have yet to achieve substantial commercial value on account of their food safety risks, short shelf life and the unacceptable packaging standards of the finished products.
- In recent decades, there has been an increasing interest in developing and applying rapid, non-toxic and natural metabolites to produce safe and available high-quality fermented foods for consumers.
- Incorporating food-grade bacteriocins into edible coatings or packaging films can preserve the microbiological safety and sensory attributes of the indigenous fermented foods; such bioactive packaging films are a promising solution to problems associated with post-processing contamination and pathogenic microorganisms.

Introduction

Fermented foods have a crucial role to play in the socio-economic advancement of Nigeria, serving as a significant dietary staple due to their nutritional benefits, digestibility and widespread availability.[1] However, they have yet to achieve substantial commercial value on account of their short shelf life and the unacceptable packaging standards of the finished products.[2]

Microbial safety concern of fermented foods

Contamination of fermented foods during processing, transportation and storage by food-borne pathogens such as *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli* and *Salmonella enteritica* can pose a significant food safety risk, even at low concentrations. In addition, spoilage microorganisms such as *Bacillus subtilis* reduce the shelf life quality and result in public rejection of these food products in Nigeria. The microbial quality of fermented foods from Nigeria, including emu (Palm wine), ogi (cereal-based staple food), and fufu (cassava-based staple food), was evaluated. These foods were found to have a high population and occurrence of bacterial species, including *Bacillus subtilis*, *Citrobacter freundii*, *Escherichia coli*, *Klebsiella oxytoca*, *Pseudomonas aeruginosa*, *Salmonella enteritis* and *Staphylococcus aureus*.[3-5] The presence of such bacterial species in fermented foods is often the result of poor hygiene and improper food handling on the part of food vendors. It has been associated with food spoilage and food-borne infections.

> **"Contamination of fermented foods by food-borne pathogens can pose a significant food safety risk, even at low concentrations"**

Preservation techniques for fermented foods

The non-regulation of the safety and quality of fermented foods could pose health risks to consumers. However, growing consumer awareness of food safety and quality has sparked a pressing need for research and development focusing on natural and biological preservatives in the Nigerian food industry.[6-7] This has led to a surge in research aimed at developing natural food-grade compounds as potential antimicrobials and biological preservatives, derived from natural antimicrobial substances found in plants, animals, marine algae and microorganisms, with the aim of reducing the use of synthetic additives in food.[8]

Scientific approaches to ensuring microbial safety and preservation of ethnic foods: a promising path forward

In addition, beneficial microorganisms, including probiotic strains, play a crucial role in food preservation. These microorganisms are of considerable economic significance because of their significant use as starter cultures in food fermentation processes and their ability to produce antimicrobial substances that have the potential to interfere with the growth of pathogenic microorganisms. The lactic acid bacteria (LAB) that are commonly found in Nigerian fermented foods, including *Lactobacillus plantarum*, *Lactobacillus*

Woman selling long plastic bags full of white cassava flour, called gari, near Dassa Zoume village, Les Collines region, Benin, West Africa. *Photo credit: BOULENGER Xavier/Shutterstock.com*

fermentum, *Lactococcus lactis*, *Pediococcus acidilactici* and *Enterococcus durans*, are recognized as good probiotics and are notably reported for their health promotion and production of antimicrobials peptides.[9,10] These LABs are also categorized as 'generally regarded as safe' and are typically used as a starter or adjunct culture for the fermentation of agricultural food products.[11] For instance, *Lactobacillus* species cultures were used in the fermentation and preservation of fermented condiments, including iru (*Pakia biglobosa*), ugba (*Pentaclethra macrophylla*) and ogiri (*Ricinnus cummunis*) in Nigeria. These LAB strains were reported to produce antimicrobial compounds that inhibited both pathogenic and spoilage microorganisms. Thus, the LAB strains were recommended to develop new antibiotic alternatives and biopreservatives to combat antimicrobial resistance (bacteria developing resistance to antibiotics) and food loss due to spoilage in the food industry.[12]

"There has been a surge in research aimed at developing natural food-grade compounds as potential antimicrobials and biological preservatives"

Furthermore, the metabolites from the microbiome and probiotics from Nigerian fermented foods such as palm wine (*Elaeis guineensis*), burukutu (*Sorghum bicolor*), ogi (*Zea mays* and *Sorghum bicolor* mixed gruel) have been reported to possess antibacterial and health-promoting benefits for consumers.[13] These comprise many volatile compounds produced by the metabolic activity of probiotic bacteria. These compounds play critical roles in regulating health and maintaining a healthy microbiome.

Challenges and future direction

Post-biotic compounds play a crucial role in regulating gastrointestinal health in humans. Previous studies have shown that probiotic bacteria isolated from Nigerian fermented foods produce numerous classes of postbiotic compounds, such as the short-chain fatty acids (SCFAs) serving an essential role in maintaining the gut balance and the antimicrobial peptides (AMPs) that inhibit the growth of gut pathogens in the microbiome.[14] In recent decades, there has been an increasing interest in developing and applying rapid, non-toxic and natural metabolites, primarily bacteriocin, to produce safe and available high-quality fermented foods for consumers. The diverse microorganisms found in Nigerian fermented foods have also contributed to improved food security and enhanced nutrition outcomes. However, conventional culture-based laboratory methods for detecting and quan

Fufu at the market
Photo credit: Paul D Smith/Shutterstock.com

tifying microorganisms in food are often inadequate, leading to insufficient information for preventing food spoilage and deterioration.[15] Bacteriocins have been shown to have antimicrobial effects with no adverse effect on human organs, blood circulation or metabolism, and they suppress the growth of numerous food-borne pathogens and spoilage microorganisms. Bacteriocins are antimicrobial peptides produced by bacteria to inhibit the growth of similar or closely related bacterial strains, often functioning as a defense mechanism. Recently, concerns about antibiotic resistance in food and in microorganisms found in livestock have grown globally, so much that there is an increasing interest in finding alternatives to antibiotics in both human and animal health from microbial metabolites.[16]

> **"Bacteriocins have antimicrobial effects and suppress the growth of numerous food-borne pathogens and spoilage microorganisms"**

Research was recently carried out to isolate probiotic strains and use their metabolites (bacteriocins) as potent antimicrobial alternatives. Food bacteriocins provided possible natural alternatives to antibiotics and potential preservatives to allow the production of foods of reliable quality and safety.[17] However, the application of packaging innovations and active packaging materials to preserve perishable fermented foods such as fish and meat has yet to be adequately harnessed in Nigeria.[18] A promising alternative involves incorporating food-grade bacteriocins into edible coatings or packaging films to preserve the microbiological safety and sensory attributes of the indigenous fermented foods. Antimicrobial packaging films infused with LAB significantly extend shelf life by maintaining continuous interaction with the food matrix. This interaction enhances the stability of LAB bacteriocins, gradually releasing antimicrobial peptides into the food.[19] Bioactive packaging films are a promising solution to problems associated with post-processing contamination and pathogenic microorganisms. These films have exhibited superior antimicrobial inhibition to several contemporary food packaging methods. Nisin – the approved bioactive packaging bacteriocin that is commercially available – effectively prevents infections and spoiled organisms in food, especially meat and cheese.[20]

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The Gut Microbiota as a Modulator of Health: What Role Can Fermented Foods Play?

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Key messages

- Incorporating fermented foods into the diet offers a promising strategy for modulating the gut microbiota composition and metabolic potential, which in turn can impact health and reduce the risk of various diseases.
- The beneficial effects of these foods can be diverse, including improvements in digestive health, metabolic regulation, immune function, mental well-being, and cardiovascular health.
- However, the category of fermented foods is very diverse and beneficial effects have been mainly investigated and observed for fermented dairy products.
- More clinical trials are needed to fully understand the complex relationship between the food microbiota, the gut microbiota and human health.
- Future research in this area may finally lead to the identification of specific starter cultures and fermentation processes that produce fermented foods with targeted positive impact on the gut microbiota and overall health.

The gut microbiota

It is becoming increasingly evident that the gut microbiota plays a crucial role in maintaining health and modulating disease risk. Among the factors influencing the composition and functionality of the gut microbiota, diet is particularly significant.[1] Specifically, fermented foods have gained attention for their potential health benefits through modulation of the gut microbiota. This article explores the relationship between food fermentations, the gut microbiota, and their interplay in human health and disease.

Scientists define microbiota as "the assemblage of microorganisms (including bacteria, archaea, eukaryotes, and viruses) present in a defined environment."[2] The human body's largest population of microorganisms resides in the intestine and is collectively called the gut microbiota. In adults, the human gut microbiota consists of more than 100 trillion microorganisms and weighs about 200 g.[2]

The gut microbiota plays an important role in the normal functioning of the host organism. Within the gut, these microorganisms harvest energy from foods, improve gut motility and function, reinforce the gut barrier, protect against pathogens, and synthesize bioactive molecules, such as vitamins and hormones. Additionally, the gut microbiota can metabolize dietary fibers into short-chain fatty acids (SCFAs), such as acetic, propionic and butyric acids, which offer benefits that extend beyond the gut.[3,4]

Disruption of the gut microbiota may lead to proliferation of opportunistic pathogens and harmful microbial activities. An imbalanced microbiota has been associated with diabetes, metabolic syndrome and obesity, allergies, colon cancer, and depression, among other things. However, it remains unclear whether an abnormal gut microbiota is a cause or a consequence of these conditions. Ongoing research is investigating whether improving the microbiota can lead to better health outcomes.[4,5]

> **"Probiotics, prebiotics, synbiotics and postbiotics are showing promise in restoring microbial imbalances"**

Gut microbiota modulation by probiotics, prebiotics, synbiotics and postbiotics

Different bioactives such as probiotics, prebiotics, synbiotics and postbiotics are showing promise in restoring microbial imbalance and supporting human health.[6]

Probiotics are live microorganisms that, when consumed in adequate amounts, confer health benefits. Although probiotics rarely establish long-term residence in the gut, they can create a more favorable environment for beneficial microbes or offer various other health advantages such as enhancing immune function or aiding digestion in generally healthy adult people.[7]

Prebiotics are substrates, often soluble fibers, that are selectively utilized by host microorganisms, conferring a health benefit. They serve as 'food' for beneficial microbes supporting gastrointestinal health, cardio-metabolic function, and mental well-being, while also playing a key role in reducing the risk of metabolic diseases.[6,8]

Prebiotics
Substrates, often soluble fibres, that are selectively utilized by host microorganisms, conferring a health benefit

Probiotics
Live microorganisms that confer health benefits when consumed in adequate amounts

Synbiotics
Contain both prebiotics and probiotics and can be complementary or synergistic

Postbiotics
Preparations of inanimate microorganisms and/or their components that confer a health benefit on the host

The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statements on defining prebiotics, probiotics, synbiotics and postbiotics

Synbiotics contain both a prebiotic and probiotic, and can be complementary (i.e., both components have not been designed to function cooperatively) or synergistic (the substrate has been selected to be utilized by the co-administered probiotic). Numerous randomized controlled trials (RCTs) in humans across a range of populations, from healthy individuals to those with acute and chronic diseases, have been conducted to examine the health benefits of putative synbiotics. Reported health outcomes include, for example, prevention of surgical infections, treatment of overweight or obesity, and treatment of inflammation. However, the appropriate dose, duration and composition of a synbiotic needed to confer a health benefit are likely to be specific to the context, including outcome and baseline host target site microbiota, as well as coexisting environmental factors.[9]

Postbiotics are preparations of inanimate microorganisms and/or their components that confer a health benefit on the host. Data from human studies are limited, but the efficacy of postbiotics has been demonstrated in the eradication of *Helicobacter pylori* infection, reduction of symptoms in patients with irritable bowel syndrome (IBS) and chronic unexplained diarrhea, and in the abrogation of the negative effects of stress.[10]

> **"An imbalanced microbiota is associated with diabetes, obesity, allergies, colon cancer"**

Gut microbiota modulation by fermented foods?

The potential of fermented foods (e.g., fermented dairy products and vegetables) to influence the gut microbiota has been investigated by various research groups, with varying levels of success. The observed changes typically involve broad shifts in microbial populations and do not always directly correspond to the microbial composition of the fermented foods themselves.[11] Fermented foods can impact the gut microbiota either by introducing their own microbiota or through the properties of the fermented food matrix.

Delivery of (live) microorganisms to the gastrointestinal tract by fermented foods

Fermented foods are frequently mistaken for probiotics. While they can serve as carriers for probiotics or other beneficial substances, specific criteria must be met for a fermented food to qualify as a 'biotic.' These criteria include documented health benefits, thorough product characterization (down to the strain level for probiotics), and rigorous testing.[12]

> **"While they can serve as carriers for probiotics or other beneficial substances, specific criteria must be met for a fermented food to qualify as a 'biotic"**

In a recent study, the dietary intake of live microbes in 9,338 foods was estimated by experts who relied on reported values in the literature or on known effects of food processing on microbial viability. They found that 96% of the foods examined are estimated to contain low amounts of microorganisms ($<10^4$ colony forming unit CFU/g). Fresh fruits and vegetables (3%) contained medium amounts of microorganisms and only 1%, identified as unheated fermented foods, contained high amounts of microorganisms ($>10^7$ CFU/g). The study indicated that 90% of the microbe-containing foods originate from fermented foods.[13]

A follow-up study found that consumption of foods with higher microbial concentrations is associated with lower systolic blood pressure, C-reactive protein, plasma glucose, plasma insulin, triglyceride, waist circumference and BMI levels. However, no causal relationship has been established. Therefore, further research is necessary to separate the benefits of the food itself from those provided by the microbes it contains.[14]

Altered food constituents and new bioactive compounds in fermented foods

The effect of fermented foods on the gut microbiota is not solely dependent on the microorganisms they introduce. During fermentation, food constituents are transformed, and new compounds are produced, which can then indirectly affect the gut microbiota.[15] For example, exopolysaccharides synthesized by lactic acid bacteria can act as potential prebiotics.[16] Fermentation can also increase polyphenol bioavailability, which has been demonstrated to impact the gut microbiota. Additionally, the production of SCFAs during fermentation can also create a more favorable environment for the growth of beneficial gut microbes or impact mucus concentration.[10] These are just a few examples, not an exhaustive list, of how fermentation can influence the gut microbiota.

Conclusion

Incorporating fermented foods into the diet offers a promising strategy for modulating the gut microbiota composition and metabolic potential, which in turn can impact health and reduce the risk of various diseases. The beneficial effects of these foods can be diverse, including improvements in digestive health, metabolic regulation, immune function, mental well-being, and cardiovascular health. However, the category of fermented foods is very diverse and beneficial effects have been mainly investigated and observed for fermented dairy products. More clinical trials are needed to fully understand the complex relationship between the food microbiota, the gut microbiota, and human health as mechanisms behind possible health benefits are still mostly unknown. To help close this knowledge gap, in the European research project "HealthFerm" (www.healthferm.eu), five human intervention trials and several *in vitro* colon fermentation experiments are planned to further unravel the impact of plant-based fermented foods on the gut microbiota and human health. Future research in this area may finally lead to the identification of specific starter cultures and fermentation processes that produce fermented foods with a targeted positive impact on the gut microbiota and on overall health.

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Discovering Health-Promoting Effects of Fermented Foods: From Diabetes Prevention to Anti-Cancer Possibilities

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Key messages

- Several mechanisms in fermented foods have been linked with the prevention of diseases such as obesity, diabetes, cardiovascular disease and even anti-cancer properties.
- Fermented foods can positively impact the immune system.
- Fermented foods are a compelling component of a holistic approach to well-being.
- Consumption of fermented foods should be encouraged among all ages to promote good health.

Health-promoting benefits

Fermentation can be described as the intentional biochemical process that desirably transforms and modifies food substrates into different products through microbial action. This age-long process has numerous benefits on the final product, from enhanced sensorial quality to preservation, improving nutrient composition and bioavailability, among other factors. Furthermore, the microorganisms involved in the fermentation process have been reported to modulate the gut microbiota[1,2] and to be a source of probiotics (**Figure 1**). Such beneficial food-related microbiota complements the gut microbiota and benefits the host. Beyond these aspects, fermented foods are also considered to have several health-promoting benefits,[3] including i) reducing the risk of cardiovascular diseases, ii) obesity prevention, iii) diabetes prevention, and iv) anti-cancer properties, as described in detail below.

> **"Fermented foods are also considered to have several health-promoting benefits, including reducing the risk of cardiovascular diseases"**

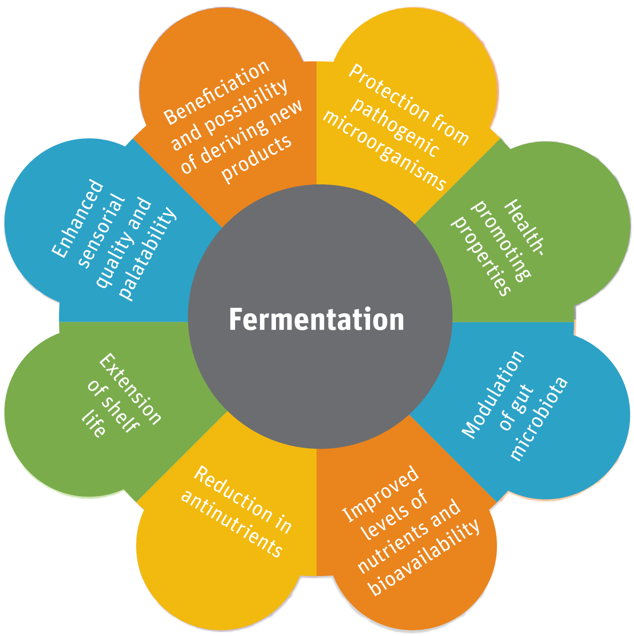

FIGURE 1: Overview of general benefits of fermentation and fermented foods. *Source: Oluwafemi Ayodeji Adebo*

Fermented foods and obesity

Obesity is a chronic complex disease defined by excessive fat deposits that can impair health. Obesity can lead to increased risk of type 2 diabetes and heart disease, affect bone health and reproduction, and increases the risk of certain cancers.[4] Consumption of fermented foods may prevent obesity through several mechanisms that go beyond their impact on the consumer's gut microbiota. Beneficial enzymes are produced by microorganisms during the fermentation process. These enzymes can aid in the digestion and absorption of nutrients, potentially increasing nutrient utilization.[5] Fermented foods with a low glycemic index, such as certain types of yogurt (kefir) and fermented vegetables (kimchi), may help regulate blood sugar levels.[6] A study by Sun et al.[7] reported that an instant fermented tea (IFT) exhibited an inhibitory effect on body weight gain and visceral fat weights (**Table 1**, page 32). Stable blood sugar levels can also reduce cravings for sugary or high-calorie foods, ultimately contributing to weight management and obesity prevention.[8] Likewise, fermented foods often have a rich flavor profile due to organic acids, aromatic compounds, and other metabolites produced during fermentation.[9] Consumption of flavorful foods can enhance satiety and satisfaction with meals, potentially reducing overall calorie intake and preventing excessive weight gain.[10]

The probiotics and bioactive compounds found in fermented foods can support immune function by promoting a balanced immune response and reducing inflammation. A healthy immune system is essential for maintaining metabolic health and preventing obesity-associated complications.[11] Some research suggests that bioactive compounds such as phytoestrogen, biogenic amines and isoflavones derived from fermented foods may also modulate gene expression related to metabolism and energy regulation.[12,13] Interestingly, bioactive compounds can prevent weight gain as observed in a study on obese rats, using fermented barley.[14] Certain compounds, such as acetyl-CoA carboxylate found in fermented foods like gochujang and sauerkraut, may activate lipid metabolism and thermogenic genes, increasing energy expenditure and reducing fat accumulation.[15] Fermented foods may contain bioactive compounds that inhibit lipogenesis, the process by which the body converts excess carbohydrates into fatty acids for storage. By suppressing lipogenesis, fermented foods can help prevent fat tissue accumulation and reduce the risk of obesity.[16] Lastly, fermented foods may influence the secretion and activity of gut hormones involved in appetite regulation, such as peptide YY (PYY) and glucagon-like peptide 1 (GLP-1). By promoting the release of satiety hormones and inhibiting hunger hormones, fermented foods can help regulate appetite and reduce the likelihood of overeating, thereby preventing obesity.[17]

Fermented foods and diabetes

Diabetes is a chronic metabolic disease characterized by elevated levels of blood glucose (or blood sugar), which leads over time to serious damage to the heart, blood vessels, eyes, kidneys and nerves.[18] Beyond the influence on gut microbiota, it has been demonstrated how fermented foods contribute to diabetes prevention by i) enhancing antioxidant status, ii) improving nutrient absorption, iii) regulating appetite, and iv) forming beneficial bioactive compounds.[19] These mechanisms collectively contribute to the metabolic health benefits of fermented foods, offering a multifaceted approach to diabetes prevention.

Fermented foods often have higher levels of antioxidants than non-fermented foods. These antioxidants can neutralize free radicals in the body, reducing oxidative stress, a known factor in developing insulin resistance and diabetes.[20] Another mechanism involved in the interplay between fermented foods and diabetes is through the improvement of dietary nutrient absorption. The fermentation process can break down food components, making it easier for the body to absorb essential minerals such as magnesium, zinc and iron. These minerals are crucial for insulin sensitivity and glucose metabolism, thereby playing a role in diabetes prevention.[21]

Fermented foods can also directly impact appetite regulation and satiety improvement. Some fermented products contain bioactive peptides, such as ghrelin, that can influence hormones involved in hunger regulation.[17] By modulating these hormones, fermented foods can help manage weight, significantly reducing the risk of developing type 2 diabetes.[6] Additionally, the fermentation process can lead to new bioactive compounds not present in the original food, such as isoflavones. These compounds can have various health benefits, including improved insulin action and reduced blood sugar levels. For instance, certain fermented soy products (e.g., douchi, tempeh and gochujang) contain isoflavones with potential anti-diabetic properties.[22]

> **"Fermented foods can help regulate appetite and reduce the likelihood of overeating, thereby preventing obesity"**

Fermented foods and cardiovascular disorders

Cardiovascular diseases (CVDs) are a group of disorders of the heart and blood vessels. They include coronary heart disease, cerebrovascular disease and rheumatic heart disease. Fermented foods can significantly prevent cardiovascular disorders through various mechanisms beyond their effects on gut microbiota. Such mechanisms include i) enhancing antioxidant status, ii) improving blood lipid profiles, iii) reducing blood pressure, and iv) inhibiting platelet aggregation. As mentioned above, fermented foods contain high levels of antioxidants such as vitamin C, carotenoids and phenolic compounds that can help neutralize free radicals in the body, thus reducing oxidative stress that can trigger cardiovascular disorders.[23] Oxidative stress is a key factor in the development of CVDs, as it can lead to the oxidation of low-density lipoprotein (LDL) cholesterol. This process is critical in the formation of atherosclerotic plaques. By reducing oxidative stress, fermented foods can help prevent the development and progression of atherosclerosis.[24]

Another way fermented foods contribute to cardiovascular health is by improving the lipid profile in the blood.[25] Some studies have shown that consuming certain fermented dairy products can decrease total cholesterol and LDL cholesterol levels while possibly increasing HDL cholesterol levels[26,27] (**Table 1**, page 32). This effect is partly attributed to the action of specific strains of probiotics present in these foods, which can metabolize cholesterol in the gut, thus reducing its absorption into the bloodstream.[28] Fermented foods can also have antihypertensive effects, which contribute to the prevention of cardiovascular disease. Bioactive peptides produced during fermentation have been shown to in hibit the angiotensin-converting enzyme (ACE), similar to how ACE inhibitor drugs work.[29]

ACE inhibitor drugs work.[29] This inhibition can lead to reduced blood pressure levels, decreasing the risk of hypertension and its associated cardiovascular complications. Also, some fermented foods (such as fermented milk) can inhibit platelet aggregation, which is a contributing factor to thrombosis and subsequent cardiovascular events such as heart attacks and strokes.[30] Certain bioactive compounds, such as isoflavones, biogenic amines and phytoestrogen, formed during fermentation, can prevent platelets from clumping together, thus reducing the risk of clot formation.[31] The above mechanisms, combined with the beneficial effects on gut microbiota, position fermented foods as a potentially valuable component of a diet aimed at ameliorating CVDs.

Fermented foods and anti-cancer properties

Cancer is a generic term for a large group of diseases that can affect any part of the body. Other terms used are malignant tumors and neoplasms.[32] Fermented foods may play a role in cancer prevention through several mechanisms, including enhancing antioxidant defense, modulating the immune system, and producing anti-carcinogenic compounds during fermentation. Firstly, the development of antioxidants in foods during fermentation makes fermented food a good candidate for scavenging free radicals in the body. Free radicals are unstable molecules that can cause cell damage, leading to mutations and potentially cancer.[33] By reducing oxidative stress produced by free radicals, the antioxidants in fermented foods can help protect DNA from damage, thereby reducing the risk of cancer development.[34]

Natto, fermented soybeans, a healthy traditional Japanese food.
Photo credit: kai keisuke/Shutterstock.com

Further, fermented foods can positively impact the immune system, and a well-functioning immune system is crucial for identifying and eliminating cancer cells. The process of fermentation produces beneficial probiotics, live microorganisms that confer health benefits to the host.[35] These probiotics can help balance the gut microbiota, promoting an environment that supports immune health. They can stimulate the activity of immune cells such as macrophages, natural killer cells, and lymphocytes, thereby enhancing the body's immune response to pathogens.[36] Fermented foods are also rich in vitamins and minerals essential for immune function, including vitamin C, vitamin D, zinc and selenium. The fermentation process can increase the bioavailability of these nutrients, making them more accessible to the body.[5]

Lastly, the fermentation process itself can lead to the formation of anti-carcinogenic compounds. For instance, certain fermented soy products (miso soup and natto) contain isoflavones, which have been associated with a lower risk of cancers such as breast and prostate cancer.[37] These compounds can function in various ways, such as inhibiting tumor growth and inducing apoptosis (programmed cell death) in cancer cells.[38]

> **"By reducing oxidative stress, fermented foods can help prevent the development and progression of atherosclerosis"**

Conclusions

Fermented foods are consumed worldwide and can provide health-beneficial properties for consumers. Besides effects such as nutritional improvement and modulation of gut microbiota, several mechanisms have been linked with the prevention of diseases such as obesity, diabetes, cardiovascular disease and even cancer. Indeed, several underlying mechanisms overlap because fermented food is produced by similar processes, which, when consumed, prevent diseases. Fermented foods stand out as a compelling component of a holistic approach to well-being. Consumption of fermented foods should be encouraged among all ages to promote good health. Future research will undoubtedly continue to illuminate their vast potential, guiding their application in healthcare and disease prevention strategies.

TABLE 1: Some studies that have demonstrated the health benefits of consuming fermented foods in vivo

Fermented product	Study group	Reported health benefit	Ref
Fermented foods and obesity			
Instant fermented teas (IFT)	Mice	According to the authors, visceral fat and body weight gain were inhibited by IFT. In addition, IFT reduced leptin and raised the low-density lipoprotein cholesterol (LDL-C) and high-density lipoprotein cholesterol (HDL-C) in the blood. When compared to the control group, IFT dramatically raised the serum's albumin-to-globin (A/G) ratio while decreasing the plasma levels of alanine aminotransferase (ALT) and aspartate aminotransferase (AST). The liver's malondialdehyde (MDA) level was lowered with IFT therapy. They also presented histomorphology, which showed that the injection of IFT had effectively conserved the architecture of the liver tissue. Additionally, IFT was able to modulate the expression of genes linked to obesity more successfully than instant Pu-erh teas (PET).	7
Fermented barley	Obese rats	The fermentation of barley by *Lactobacillus plantarum dy-1* prevented the rats from gaining weight and becoming fatter. A study found that the fermented barley extract's beta-glucan, ferulic acid and vanillic acid impeded weight gain in rats.	14
Vegetable juice fermented with lactic acid	Obese mice	Fermented vegetable juice (VJ) and two lactic acid bacteria (LAB) (*Compani lactobacillus allii* WiKim39 and *Lactococcus lactis* WiKim0124) controlled the in vitro antibody array. Researchers concluded that giving mice supplements containing fermented vegetable juice reduced their weight increase, blood biochemical markers, and liver fat buildup.	39
Fermented foods and diabetes			
Fermented soya flour and alfalfa meal	Zucker diabetic fatty (ZDF) rats	The authors found that by altering the intestinal microbiome of ZDF rats, fermented soy flour and lucerne meal reduced type 2 diabetes.	40
Fermented milk enriched with finger millet	Sprague-Dawley rats	Low-density lipoprotein and very low-density lipoprotein levels significantly decreased, while high-density lipoprotein levels insignificantly increased, when probiotic fermented milk enhanced with finger millet was added. Additionally, researchers observed that enriched fermented milk reduced inflammation and mildly altered the liver structure, preventing more drastic modifications in the acinar cells.	41
Fermented milk	Mice	Lower cholesterol levels, triglycerides, glycosylated hemoglobin, and fasting blood glucose were observed in mouse groups administered probiotic-fermented milk. Researchers added that the mice's oxidative stress had lessened.	42
Fermented foods and cardiovascular disorders			
Chili sauce, NianMianZi and spicy cabbage	Male mice	The diets were fermented by *L. plantarum* H6, which led to a significant decrease in serum cholesterol levels in C57BL/6 mice given a hypercholesterolemia diet. By blocking the farnesoid X receptor pathway and enhancing the intestinal microbial community structure of C57BL/6 mice, the diets primarily induced the expression of the CYP7A1 gene by increasing the in vivo synthesis of bile acids and bacterial flora with bile salt hydrolase activity.	43
Fermented milk	Spontaneous hypertensive rats	There were very noticeable effects on blood pressure; milk fermented with the two strains of *L. helveticus* caused a greater drop in blood pressure than in the control group. With one of the strains, there were notable variations in heart-rate effects.	44
Dietary Maillard reaction products and their fermented products	Institute of Cancer Research (ICR) mouse and rats	The high-cholesterol group's protection from cMRP (Maillard-reacted sodium caseinate) and F-cMRP (fermented Maillard-reacted sodium caseinate) may have been due to an antioxidative defense system controlling cholesterol synthesis and metabolism. Consequently, F-cMRP and cMRP may have therapeutic and preventative uses in treating cardiovascular disease.	45
Fermented foods and anti-cancer properties			
Fermented milk	Rats	The authors reported a significantly lowered aberrant crypt (AC) count in the rats fed with the three highest doses (1, 1.5 and 2 ml). In contrast, those supplemented with 1.5- and 2-ml finger millet significantly lowered aberrant crypt foci (ACF) count.	46
Fermented brown rice	Transgenic rat for adenocarcinoma of prostate (TRAP) rats	Fermented brown rice (FBRA) inhibited the growth of prostate carcinogenesis and reduced the incidence of adenocarcinoma in the lateral prostate. When TRAP rats were administered FBRA, their histologically high-grade prostatic intraepithelial neoplasias exhibited increased apoptosis, reducing cell proliferation. FBRA has the potential to prevent prostate cancer in humans by activating pathways that respond to energy restriction, which in turn limits the growth of tumors.	47
Fermented germinated brown rice	Rats	Fermented germinated brown rice (FGBR) and germinated brown rice (GBR) both lowered TNF-α, IL-6, and IL-1β levels, in addition to decreasing the primary aberrant crypt foci (ACF) count. At the 2.5% level, FGBR boosted Bax expression while decreasing the amount of sialomucin-producing ACF (SIM-ACF).	48

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Challenges and Potential Solutions

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Unstandardized Production Techniques, Spontaneous Fermentation, Food Safety Risks and Processing Obstacles

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Key messages

- Without proper control, spontaneous fermentation can lead to contamination by harmful microorganisms or the production of undesirable flavors.
- The absence of standardized production practices in the creation of fermented foods poses a high risk for food safety, and is a special concern in low- and middle-income countries (LMIC).
- There is a need to educate small-scale producers to strictly adhere to good manufacturing and hygiene practices, hazard analysis and critical control points (HACCP) systems, and the adequate design of food processing plants.

The importance of fermented foods

Being a traditional and highly affordable food processing technique, fermentation has led to the creation of a wide range of foods that have sustained livelihoods and positively contributed to the development of the human diet.[1] Fermentation is therefore a 'go-to' processing technique for the transformation of raw food materials. It transforms food by bringing about a 'pre-digestion' of food substrates to increase the bioavailability of associated nutrients and even, in some instances, to remove allergens (including 2S albumin proteins, profilins, cupins, and prolamins), antinutritional compounds (such as phytate, tannins, lectins, protease inhibitors, saponins, alkaloids and oxalate), and toxins (such as cyanogenic glycosides, bacterial toxins, mycotoxins and biogenic amines). Above and beyond this, fermentation also creates variety, improves shelf life, and helps modify foods into organoleptically satisfying products.[2-4]

> **"Fermentation transforms food by bringing about a 'pre-digestion' of food substrates to increase the bioavailability of nutrients"**

Fermentation is a biotechnological process that makes use of the metabolic activities of microflora and their enzymes to break down food substrates into a desired end product.[5] This method, used globally since ancient times to produce preserved foods and beverages, continues to serve the same purpose today.

Despite their many nutritional and health benefits, fermented foods are also associated with the presence of pathogenic microbes and their associated toxins, thus posing a major food safety risk. Since the majority of indigenous fermented foods are based on spontaneous fermentation and unstandardized production techniques, the likelihood of contamination via utensils and contact surfaces is common in LMIC. We can therefore categorically affirm that the use of poor-quality ingredients, in combination with inadequate hygiene conditions during production processes and insufficient safety and hygiene control standards, has led to the failure of food safety systems implementation, especially in LMIC and/or for small-scale products (at household level, in villages and small-scale cottage industries).

Unstandardized production techniques

The processing of fermented foods originated by a process of trial and error, and has evolved into an art that has been passed down through generations.[6] Typically, this process is carried out within households under varying, often unpredictable, environments. The equipment used, such as calabash, earthenware, leaves, baskets and cloths, is often rudimentary and not thoroughly disinfected after each use. Due to differences in the individual production process, microbial communities, raw materials and regional practices, sensory characteristics and nutritional qualities of fermented foods can vary significantly.[7]

The unstandardized production methods and techniques vary from one production batch to another, making the quality and safety of fermented food inconsistent. Given production standards that have not been optimized beyond the conventional methods of processing, there is little or no consideration for good manufacturing practices and sanitation.[8] The lack of standardized food fermentation production techniques also has an impact on the raw materials used. For example, the quality of the water used in producing some fermented foods cannot be guaranteed because processors often fetch water from streams owing to the absence of potable water. Consequently, the safety of the water used is uncertain. Additionally, the temperature and humidity conditions of individual processing environments differ from each other, making it impossible to have uniformity in the final product.

Moreover, each geographical area has a different cultural background, which will vary depending on ethnic groups and customs, and this diversity is reflected in the techniques used to produce fermented foods. Each ethnic group uses different preparation and storage techniques, resulting in the production of fermented foods with high levels of inconsistency. Standardization of the techniques used during fermented food preparation is therefore crucial to ensure uniformity, quality, consistency and safety. Without standardization, there is a risk of variations in product quality, which can impact consumer satisfaction and safety.

The process of producing fermented foods involves several steps such as cleaning, peeling, cutting, soaking/pressing, and packaging, among others. Obstacles in processing arise as a result of limited equipment, inadequate facilities and lack of technical expertise. These obstacles eventually lead to problems of scaling-up, consistency, texture and flavor development, irregularities in quality control and regulatory compliance, microbial contamination and stability, or compromised shelf life of the fermented food.[25]

"Each ethnic group uses different preparation and storage techniques, resulting in fermented foods with inconsistency"

Spontaneous fermentation

The process of producing fermented foods normally involves the use of living organisms or enzymes such as bacteria, yeast or molds to produce a specific product. In LMIC, most fermented foods are obtained by means of traditional fermentation, i.e., through spontaneous fermentation. This type of fermentation depends largely on chance inoculation involving mixed cultures.[8] The microbiota involved in this method derive from the raw materials, utensils, and the environment in which these foods are processed. The quality of the final products is therefore difficult to predict or control, resulting in short shelf life and quality diversity of the final fermented foods.[8]

This method of fermentation makes it difficult to produce fermented foods with consistent flavor, aroma and other characteristics because of the shift in the microbial flora of the raw materials.[9] Moreover, this method makes food highly prone to the outbreak of foodborne diseases since it harbors opportunities for the growth of other undesirable microorganisms associated with the raw materials. Safety issues regarding fermented foods have been raised, emphasizing the potential failure of spontaneous fermentation, which can create significant health hazards.

Fermented locust beans, a West African condiment also known as dawadawa, iru and netetou. *Photo credit: Abimbola Olayiwola/Shutterstock.com*

Despite this risk, most small-scale fermentations in LMIC, as well as some technically well-controlled industrial processes, continue to rely on spontaneous processes.[9] Spontaneous fermentation represents a low-cost technology, which is very advantageous in LMIC for the purposes of avoiding food spoilage.[10] The lack of specific scientific protocols for food processing operations, such as the length of fermentation period, the quality and quantity of water to be used, the fermenting temperature, the quality and quantity of substrate, and the length or degree of heating, makes it impossible to control and maintain the production process. This lack of standardization creates problems in maintaining the quality of such undefined multi-strain cultures.[11]

> **"Spontaneous fermentation makes food highly prone to the outbreak of foodborne diseases since it harbors opportunities for the growth of undesirable microorganisms"**

Fermentation of different classes of foods from the tropics has been largely practiced traditionally. These fermentation processes are broadly effective as they proceed spontaneously, relying on the availability of favorable conditions for the growth of the natural microflora of food, water, and the processing environment. These native organisms also include pathogenic microorganisms such as bacteria and fungi, which also thrive considerably in the fermenting lot and produce metabolites that are harmful to consumers of such fermented foods. Also, the activities of fermented food processors often bring about cross-contamination and the introduction of pathogens to fermented foods.

Furthermore, spontaneous fermentation processes used routinely allow the participation of diverse microorganisms.[11] Therefore, the involvement of pathogenic and spoilage microorganisms during production cannot be ruled out, especially during fermentation under very poor hygiene conditions, which is commonly the case in LMIC. These traditional fermentation methods are still used today, primarily in home-based local food production, or in small-scale production.[12] While spontaneous fermentation can result in unique and flavorful food products such as wines, *ogi*, and bread, it can also introduce variability and engender potential risks. Climatic factors regulate the structure and metabolism of the microbiota in spontaneous food fermentations.[13,14] For example, concentrations of several organic acids,[15] nitrogen compounds and alcohol[16] increased in wine with the increase in air temperature. The profile of the microbiota and flavor compounds varied with the variation of daily average temperature in Chinese liquor fermentation.[17]

Food safety risks

Food safety is a critical concern in fermented food production, and risks can arise from various sources, including microbial contamination, chemical hazards, and physical hazards. Factors such as inadequate sanitation, improper storage, and inadequate temperature control can increase the risk of foodborne illnesses.[11,12] Mitigating these risks requires implementing appropriate food safety measures, including good manufacturing practices (GMPs), good hygienic practices (GHPs), hazard analysis and critical control points (HACCP), as well as regular inspections.

Food processing in an unhygienic environment using rudimentary equipment without consideration for GMP may subject the product to contamination, creating grievous health hazards.[18] Although fermentation is meant to produce foods of high nutritional quality and safety standards, more is needed to solve the problems of contaminated raw materials, uncontrolled fermentation processes, post-processing contamination, water supply, and inadequate sanitation and hygiene. There is a need to incorporate low-technology methods for inactivating microorganisms during traditional food production and to encourage the implementation of control measures that will tremendously enhance the safety and quality of traditional foods in LMIC.[18]

How safe are most traditional fermented foods? Studies have shown that foodborne pathogens can survive in lactic fermented cereal foods with acidic pH, consumed as complementary infant food in West Africa.[18,19] The survival of *Shigella* and the occurrence of pathogenic strains of *Escherichia coli* in traditional fermented *ogi, akasa* and *kenkey* have been reported.[19] For instance, Oguntoyinbo[20] isolated *Bacillus cereus* from tested traditional alkaline fermented protein meals in Nigeria. This bacterium produces diarrhea toxin and contributes to many self-limiting diarrhea incidences in LMIC. It thus appears that microbial safety of fermented foods could not be adequately achieved by fermentation metabolites such as acidity and alkalinity alone. GMP and improvement in the mechanization of the processes involved in production will be essential to ensure safety standards.[21]

The food safety risk of a contaminated fermented product increases when low-quality ingredients are used for its production that may initially contain a high number of bacteria, fungi, or toxins produced by these. Moreover, crops of low quality and standard are often used by households or in small-scale food production, resulting in products with inappropriate microbiological standards.[22,23] Ideally, the water used in the dilution stage or in the fermentation itself should also be free from microbiological contamination. Unfortunately, limited access to water in some regions, especially in rural areas, and the use of potentially contaminated water from streams or rivers for production increases the risk of pathogens in traditional fermented foods.[24] Generally, in LMIC, the lack of GMPs has a major impact on the safety of traditional, homemade, or cottage-made foods.[20] This is compounded by the sale of such foods in unsanitary conditions without the use of protective coverings, such as gloves, which is also a public health risk. Moreover, in LMIC, due to poverty and low consumer awareness, fermented foods sold locally are usually packaged in non-sterile utensils such as used jute bags or paper (e.g., newspaper), as well as gourds or leaves. The inability to buy adequate packaging materials to limit microbial spoilage, even with a properly executed production process, poses a significant additional risk of contamination.[20]

Addressing these challenges in food fermentation typically involves a combination of proper training, investment in infrastructure and equipment, the implementation of quality control measures, and adherence to food safety regulations and standards. Additionally, fostering collaboration and knowledge-sharing within the fermented food production community can help overcome these challenges more effectively.

> **"Studies have shown that foodborne pathogens can survive in lactic fermented cereal foods with acidic pH consumed as complementary infant food in West Africa"**

Processing obstacles

Overcoming processing obstacles is essential for maintaining product quality and safety throughout the production process. This can be achieved by means of the following:

1. **Improving safety and consistency**
   - *Starter cultures*: The use of identified and controlled strains of fermenting microbes helps minimize the risk of microbial contamination caused by spontaneous fermentation.
   - *Controlled environments:* Having precise temperature and humidity controls during the production of fermented foods is crucial. These prevent the growth of undesired microorganisms and create conditions that favor the growth of desired microbes while discouraging unwanted ones, leading to a more consistent product.
   - *Standardized ingredients:* Using consistent ingredients such as vegetables, milk or grains minimizes variations in the final product's flavor, texture and nutritional value, irrespective of ethnic groups and regions.[26]
2. **Quality maintenance**
   - *Strict sanitation:* Contamination and harmful bacteria can be prevented by the application of rigorous hygiene practices throughout the process.
   - *Monitoring of fermentations:* There is a need for close monitoring of the fermentation process to ensure that it progresses as expected – i.e., within a controlled environment for the processes involved.
   - *Standardized testing:* Regular final product testing is encouraged to ensure that the product meets safety and quality standards for flavor, texture and nutritional content.[27]
3. **Balancing tradition and efficiency**
   - A balance must be struck between the traditional processing of fermented foods and the biotechnological processes to improve the final product's safety and consistency.[25]

Conclusion

In conclusion, despite all the benefits and advantages of fermented foods, the absence of good, standardized production practices poses a high risk to food safety. This is a particular concern in LMIC, since there are no systems in place in these countries to monitor the relevant processes. Thus, there is a need to educate small-scale producers to strictly adhere to good manufacturing and hygiene practices, HACCP systems, and the adequate design of food processing plants. Controlling the fermentation process is essential for ensuring product safety and consistency. Without proper control, spontaneous fermentation can lead to contamination by harmful microorganisms or the production of undesirable flavors.

This is, therefore, a wake-up call for all stakeholders to delve into the relevance of standardized fermentation techniques by giving more attention and priority to cottage producers in LMIC. Moreover, there should be effective collaboration with the developed countries on how to reduce the associated safety risks.

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Regulatory Frameworks for Fermented Foods: Status Quo, Challenges and Future Outlook

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Key messages

- A renewed focus on traditional fermented foods (FFs) is driving innovation and commercialization of FFs, which in turn brings forth a need for novel regulations.
- The recent emergence of a significant diversity of non-native / traditional and emerging commercial FFs has shown that the current regulatory frameworks for FFs are not developed to an adequate extent.
- As a prerequisite to harmonized FF regulations it is important to establish food standards for FFs.
- The challenge vis-à-vis developing harmonized regulatory for FFs involves creating standards for specific FFs and using these to create relevant FF regulations.
- Harmonization of regulations for FFs can be achieved through the development of up-to-date FF standards through the Codex Alimentarius Commission of the United Nations Food and Agriculture Organization.

Introduction

In recent years, there has been a global resurgence of interest in fermented foods (FFs).[1,2] This is mostly attributed to their purported nutritional and health benefits,[3] an interest in new sensorial experiences, and a growing focus on food conservation and sustainability, whereby fermentative processes can be implemented to improve food preservation and reduce food waste. Notably, a renewed focus on traditional FFs from around the world is driving innovation and commercialization of FFs, which in turn brings forth a need for novel regulations. Traditionally, such regulatory legislations are influenced by political, cultural and geographical priorities and reflect an integrated academic and political approach with engagement of a variety of stakeholders involving assimilation of evidence from dietary patterns and scientific understanding, among others. While a holistic overview of FF regulations is not possible here, we present some salient features of FF regulations observed around the world, along with anticipated challenges and future outlook. For more in-depth reading, readers can refer to Mukherjee *et al*[4] and Chilton *et al*.[2]

Brief overview of status quo

Nations and organizations have adopted different approaches to regulate FFs. In some cases, regulations are specifically focused on FFs, while in other instances, FFs and their microorganisms are governed by broader regulations intended for specific food categories, such as yogurt for dairy.[4] Regulations for FFs have traditionally focused on aspects of safety, without considering the unique nature of FFs compared to other foods. Taken together, these have contributed to fragmented laws governing the production, safety, communications and other aspects of FFs.

The recent emergence of a significant diversity of non-native / traditional and emerging commercial FFs in global markets has further shown that the current regulatory frameworks for FFs are not developed to an adequate extent to regulate the large variety of FFs. For example, regulations for kombucha, which is now largely available in Europe but was originally an eastern Asian fermented drink, are not as developed as those for yogurt-like FFs that are traditional to Europe. This is partly offset by several recently developed legislations that aim to govern 'novel' or 'non-traditional' foods. According to the European Union (EU) Novel Foods regulation,[5] any food without a "significant" history of consumption in the EU before 15 May 1997 may be considered a novel food. In Australia and New Zealand, novel foods are described similarly as non-traditional foods which, in turn, are defined as a food, food-derived substance or source material that have no history of human consumption in these countries (Standard 1.5.1 [version: F2017C00324]). These laws are relevant for enterprises involved in research and development of functional FFs (i.e., FFs with claimed health benefits) as well as introducing and marketing traditional FFs from other parts of the world in the corresponding legislative areas. In the EU, for traditional FFs originating from non-EU, third countries, an alternate route for authorization and access to the European single market is also offered through Article 14 of the Novel Foods regulation, which accepts safe consumption of a traditional FF by a significant population in a country outside of the EU for at least 25 years as evidence of safety.

> **"Specific regulations for specific fermented foods remain largely absent, with legislative efforts being largely reactive"**

Specific regulations for specific FFs, however, remain largely absent, with legislative efforts being largely reactive with a lack of cohesion at international, federal or even regional levels. These issues have arguably been precipitated due to several factors, with the primary reason being a lack of accurate scientific data (discussed below in brief in conjunction with future outlook). Overall, at the moment, there does not seem to be a common framework that nations and organizations follow to develop and implement legislations pertinent to FFs. Below we have provided some representative snapshots of the global FF regulatory regime that further our understanding of the status quo.

A fragmented regulatory space

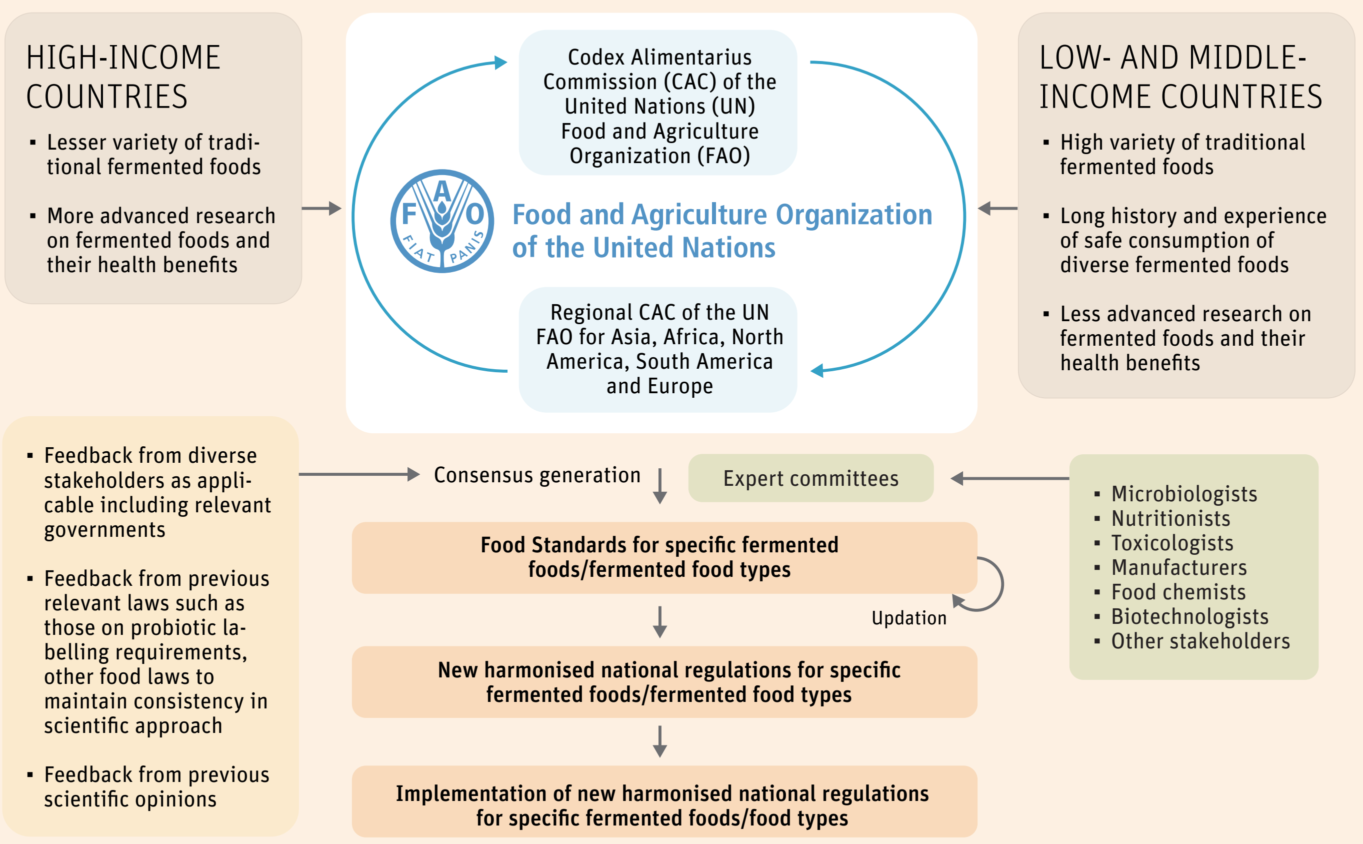
The regulatory regime in Europe provides a good example of the fragmented regulatory atmosphere vis-à-vis FFs usually observed. In the EU, FF microorganisms are considered as ingredients and termed as 'food cultures', which are not defined in EU legislation and are covered by the General Food Law. Microbes used in producing FFs eligible as 'novel foods' (see below for details regarding novel foods) are, however, subject to the Novel Foods Regulation.[5] Notably, no new microorganisms used as live food cultures have been evaluated and authorized under the EU novel foods directive since 1997. Labelling and communications regarding the nutritional and health effects of FFs, particularly of functional FFs, are further regulated by the Nutrition and Health Claims Regulation 1924/2006 (NHCR).[6] For example, labelling an FF as 'probiotic' is prohibited by the NHCR unless a proven health benefit is associated with the product. However, due to the non-binding nature of the legislation, some EU member states have allowed the generic use of the term 'probiotic'. These products are in turn sold in some EU member states that have implemented the legislation (under the "principle of mutual recognition" established in the EU Treaty [Regulation EU 2019/515]), to the detriment of local producers of FFs.[4] Consequently, Spain along with a few other countries have recently started to allow, or are in the process of allowing, the 'probiotic' labelling without necessarily associated health claims in order to protect domestic markets from similar products originating in other EU countries.[7] Evidently non-harmonised, reactive and lagging regulations, complicated by selective application and commercial interests, are creating a further fragmented and convoluted regulatory ecosystem for FFs in the EU.

Making kombucha at home has caught on as a food trend.
Photo credit: ViJpeg/Shutterstock.com

Fermented foods regulation in the USA: cottage foods

While specific laws exist in the USA for regulation of foods such as yogurt,[8] the cottage food or homemade foods legislations represent a unique approach taken by the US that is relevant to FFs. In the United States, cottage foods are described as potentially non-hazardous foods made in a personal kitchen that do not require time or temperature regulation for safety. Preparation of these foods, which include various locally produced FFs, is regulated by the Homemade Foods or Cottage Foods legislations, which represent a somewhat different approach to FF regulation than seen elsewhere globally. All states in the US except New Jersey have some sort of cottage foods legislation[7] that allows home-based food enterprises to sell their products commercially and provide guidelines for best practices in the preparation of such foodstuffs. Notably, several US states are in the process of expanding the range of cottage foods included in these legislations, including those produced through microbial fermentation. For example, in 2019, Texas amended its Cottage Food Law to include fermented vegetables with a pH of less than 4.6. Some states, such as Wyoming, North Dakota and Utah, additionally have Food Freedom Laws that allow residents to sell almost any kind of homemade foods excepting meats, including FFs such as kefir, sauerkraut and kombucha. Unlike the Cottage Foods legislations, Food Freedom laws do not limit sale, permissions, licensing and inspection requirements, thereby being comparatively more lenient – with one important consideration being that the products must be sold to "informed end-consumers". Alaska, Mississippi and a few other US states are also considering similar laws. These legislative reforms have proven successful. Driven by increasing

FIGURE 1: Proposed framework for global harmonization of fermented food regulations



Potentially better harmonization of regulations for fermented foods can be achieved through the development of up-to-date fermented food standards through the Codex Alimentarius Commission of the United Nations Food and Agriculture Organization. This will include consultation with scientific experts along with other relevant stakeholders from both developed and developing countries to formulate new, harmonized fermented food-specific legislations. **Source:** Arghya Mukherjee

consumer interest, the US cottage food sector—comprising locally made, organic FFs—has grown significantly, increasing in value from US$5 billion in 2008 to nearly US$20 billion in 2016.

> **"Codex Standards provide standards for microbial loads, preservatives and additives, contaminants, analytical methods and recommendations for hygiene and labelling"**

The Codex Alimentarius and fermented food standards

As a prerequisite to harmonized FF regulations, primarily at the national level, it is important to establish food standards for FFs. Some Food Standards for FFs are available through the Codex Alimentarius, which is a collection of Standards, guidelines and codes of practice adopted by the Codex Alimentarius Commission (CAC) of the United Nations (UN) Food and Agriculture Organization (FAO). These Codex Standards (similar to usual Food Standards) provide standards for microbial loads, preservatives and additives, contaminants (heavy metals, molds), analytical methods and recommendations for hygiene and labelling, among others. These are extensively used by different countries globally (for example, Argentina) to draft their national food regulatory frameworks, including for FFs. Currently, the CAC has made Codex Standards for fermented milks (a category that includes kefir, kumys and yogurt), cheeses and kimchi available through the Codex Alimentarius.[9-28] The vast diversity of FFs globally, particularly the historical prevalence of FFs in Asia and Africa, has, however, precipitated the development of Codex Standards for other FFs by Regional CACs. For example, Codex Standards for fermented cooked cassava products are now available from Africa, and doogh, fermented soybean, gochujang and tempeh are now available from Asia.[29-33] Notably, no Regional Codex Standards for FFs are available for the North American, European and South American CACs; no Codex Standard is available yet for kombucha.

Beyond the Codex Alimentarius, some level of harmonization and integration of FF Food Standards and FF regulations is observed in the regulatory regimes of South Korea and India. Indeed, Standards for a diverse range of Korean traditional FFs are covered in the Food Code and controlled under the Food Sanitation Act. These include FFs such as kimchi, jeotkal, gochujang, meju and doenjang, among others. In India, the Food Standards for certain FFs such as fermented milks and cheeses, among others, are attached to the relevant regulatory legislation, i.e., the Food Safety and Standards Act.

Future outlook

Moving forward, the challenge vis-à-vis developing harmonized regulatory for FFs is primarily twofold:

1. Development of FF standards for specific FFs involving relevant, robust, up-to-date and accurate scientific knowledge.
2. Using these FF standards to create relevant FF regulations, while taking into account commitments made in previous relevant legislations (**Figure 1**).

The primary bottleneck in relation to the former is the general lack of accurate scientific data to understand the ideal FF compositions and their health benefits/risks. This is important, as Food Standards, which often form the basis of Food legislations, are developed through consultative consensus between experts from various relevant disciplines including microbiology, food chemistry, manufacturing, toxicology and others, and depend on accurate, cutting-edge scientific data. This issue is particularly acute for low- and middle-income countries, particularly in Asia and Africa, that often have a rich history of FF consumption but are unable to carry out holistic research on these foods due to a paucity of funds. Understandably, a lot of the scientific advances, even for traditional FFs from Asia/Africa/South America are currently coming out of developed countries. Codex Alimentarius Commission (CAC) of the FAO along with the respective Regional CACs as mentioned above can provide assistance in this regard, with UN-funded development of FF standards. These standards can then in turn be used to frame national Food Standards and FF specific regulatory frameworks where guidelines for composition, safety, communication and distribution, among others, will be addressed (**Figure 1**). This can potentially provide an actionable blueprint for the development and implementation of harmonized FF regulation, since most regional FF clusters are based on specific use of ingredients and microorganisms that are inherited traditionally in specific geographical regions.

Additional considerations include:

1. Simpler and potentially faster procedures for regulatory approval.
2. Availability of clear, concise and extensive guidance documents.
3. Availability of well controlled clinical studies and meta-analyse for FFs (this pertains to the health benefits/claims for regulation of FFs and functional FFs).
4. Continual updating of FF standards.
5. Conscious reduction in the lag time between generation of new scientific insights and translation to Food Standards.

Notably, while a comprehensive study on the potential enablers and barriers to development and implementation of FF standards and regulations has not been carried out, this will shortly be addressed in the strategic roadmap for FF research and development to be developed by the EU-COST Action project PIMENTO.[34] Ultimately, harmonization of FF regulations and Standards provides a stepping-stone for the possible recommended daily allowance of FFs in the future. Indeed, it would contribute to ease of doing business and would encourage innovation and consumer confidence, which in turn will catalyze economic progress , particularly in LMIC with a rich tradition of FFs.

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Upscaling Small-Scale Fermented Food Production to Support Nutrition Security And Livelihoods

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Key messages

- Fermentation can reduce food losses, and support food and nutrition security, livelihoods and business development.
- Formal development and upscaling of traditional and local food production is an underutilized avenue for responsible sustainable development and food security.
- Upscaling small-scale fermented food processing activities significantly supports the food and nutrition security of individual households.
- Continuous collecting of feedback on what does or does not work and refining the approach is essential to ensure sustainable and successful upscaling.
- Upscaling of small-scale fermented food processing also stimulates economic development in rural areas and has significant social influence in empowering women.

The potential for upscaling fermented foods

The process of fermentation transforms raw materials into culturally important foods with an improved shelf life, taste, nutritional composition, digestibility and commercial value.[1] Fermentation can thereby reduce food losses and support food and nutrition security, livelihoods and business development.[2]

In this contribution, we discuss the economic, societal and business potential for upscaling fermented foods in LMIC using two specific cases that exemplify a wide range of fermented foods in Africa: mabisi, derived from spontaneously fermented raw milk and representing traditional fermented foods,[3] and probiotic yogurt, made by adding a controlled starter culture to pasteurized milk and representing modern analogues of traditional fermented foods.[4] Both are produced by numerous small- and medium-scale entrepreneurs in Africa.

> **"Upscaling small-scale fermented food processing activities supports the food and nutrition security of individual households"**

To produce mabisi, raw milk is transferred to calabashes or plastic buckets. After a two-day incubation, a semi-solid fermented milk product is formed. Mabisi is consumed at the household level and sold at local informal markets in Zambia, while similar foods exist across Southern Africa.[3] As such, it is an archetypical example of how traditional fermented foods impact the development of small businesses in rural areas.[2]

Similarly, probiotic yogurt is produced by pasteurizing raw milk, cooling it to 45°C and adding a controlled starter culture. The product is kept warm for about 6–12 hours, depending on the type of starter culture and the temperature of incubation, after which it is ready for consumption.[5] The yogurt can be sweetened and/or flavored according to the consumer's wishes and is an example of how small-scale milk processing can be implemented. The Yoba for Life Foundation has stimulated and supported the production of probiotic yogurt among over 350 small- and medium-scale enterprises across East Africa. For more information, see page 65

To further capitalize on the potential of fermented foods, we argue that upscaling is necessary, while prioritizing the needs of current local processors and consumers; below, we discuss six factors critical for successful upscaling.

Build on the local context

Scaling up requires interest and demand for the product in question, which may arise from tradition and cultural heritage (e.g., the demand for mabisi) or from changing lifestyles and health awareness (e.g., the demand for probiotic yogurt).

First of all, the availability of raw materials will impact which product to produce and where. Especially in the case of perishable products such as milk, logistical considerations define which product (e.g., locations where milk is or is not accessible) can be produced and marketed in which area (e.g., locations where refrigeration is or is not available). Moreover, as consumer preferences differ widely, there is no one-size-fits-all. Thus, the choice as to which product can best be scaled up depends on the intended sales market.

We noticed that the entry of fermented milk products into the market increased the overall demand for milk products, thus offering an additional market for dairy farmers to buy their raw milk. Opportunities to boost incomes and become more food-secure are thus created for farmers, processors and other actors along the milk value chain. Similarly, increasing consumption improves the nutritional status of consumers, as these fermented dairy products contain essential micro- and macro-nutrients.

Develop partnerships with existing women producers

Current producers of fermented milk products need to be put in the driving seat of the upscaling process (**Figure 1**). Through training, they can be empowered to act as an example and can, in turn, support other interested potential producers.

As illustrated by the case of home-scale production of mabisi and probiotic yogurt, traditionally women are center stage in the production of food for families and communities.[2] However, a high potential for scaling up (and increased profits) will attract the attention of male entrepreneurs. For women not to be left behind, new support programs should build on the specific needs and challenges that women face.[6,7] While upscaling is impossible without the active involvement of the producer community, strong partnerships – for example, with international NGOs or research organizations such as Yoba for Life, the Netherlands Development Organization (SNV) and universities – can boost the upscaling process thanks to the expertise and finances that these organizations can provide.

Consider technological scalability

Especially in the LMIC context, income-generating activities that start with minimal investments and gradually grow along with profits have the best chances of enabling entrepreneurs at the bottom of the pyramid to set up successful businesses.[2] For example, both mabisi and probiotic yogurt can be produced at the household level, then grow to 50 L production, e.g., in a separate shed in the back garden, and subsequently into a business unit producing 500 L per day with minimal technological requirements. For yogurt, pasteurization is often done in milk cans that are placed in water baths on top of specifically constructed firewood-saving stoves. When producing 500 L, 10 milk cans of 50 L can be used. This flexibility of basing the upscaling on existing equipment,

Scaling up yogurt production from home-kitchen production to 50 L capacity in a production unit.
Photo credit: J van Loon and N Westerik, Yoba for Life

which allows for gradual expansion, is a key success factor in the upscaling process.

Align with government policies

Commercially sold food products must be certified by a national certification body. This certification for ensuring that producers meet government standards for safety, allowing them to market their products widely. Currently, no formal standards exist for traditionally processed mabisi. This lack of standards prevents traditional processors from engaging in formal sales and hampers the upscaling of their production.

Recently, research has scientifically validated how ecological selection shapes existing natural bacterial communities into predictable composition and functionality, eliminating the need for preselected strain bacteria and raw materials in mabisi.[8] This breakthrough has defined key processing parameters that can now enable the formalization and standardization of the traditional processing of mabisi. Consequently, the Zambia Bureau of Standards (ZABS) has introduced a new method to legalize (traditional) processing, namely by implementing a code of practice that describes and sets boundaries for critical processing parameters. Such parameters include the pH value after 24 hours of fermentation and the viscosity of the final product.

> **"Upscaling of traditional and local food production is an underutilized avenue for sustainable development"**

Enhance profitability and entrepreneurial skills

The production of fermented foods obviously needs to be profitable to make upscaling feasible. However, ensuring income generation depends not only on the ability to technically produce the product but also on the business skills of the business owner.[9] Partly, these are entrepreneurial soft skills related to promoting and selling a product, and identifying opportunities or creative ways to produce and/or sell it. However, other skills need to be learned, such as proper bookkeeping to gain insight into the incurred costs and the minimum sales price, and how to analyze ways to reduce costs and increase profits. The work of Yoba for Life has shown that support in these areas can greatly boost the turnover and profitability of SMEs, thereby supporting upscaling as further elaborated in (see page 65).

Improve continuously

Continuous collection of feedback on what does or does not work and refining the approach is essential for ensuring sustainable and successful upscaling. This may concern production methods at different scales of operation, individual business and marketing strategies, or knowledge-sharing and upscaling strategies, or knowledge-sharing and upscaling strategies. Within the Yoba for Life Foundation, applying these principles has led to working with over 350 small-scale processors in very different contexts throughout East Africa.

Conclusion

Formal development and upscaling of traditional and local food production has been recognized as an underutilized avenue for responsible sustainable development and food security.[2,10] Upscaling small-scale fermented food processing activities significantly supports the food and nutrition security of individual households. More broadly, this also stimulates economic development in rural areas and has significant social influence in empowering women to contribute to the market and secure household income.[11,12]

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Starter Culture Development for Safer, More Nutritious, and Controlled Fermentation

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Key messages

- One of the key factors influencing the safety and quality of fermented foods is the microbial community responsible for driving the fermentation process.
- In recent years, advancements in microbiology, molecular biology and bioinformatics have revolutionized the field of starter culture development.
- Despite the importance of starter cultures in improving food quality and nutritional properties, developing effective starter cultures poses several challenges.
- Recent advancements in molecular biology, genomics and bioinformatics hold immense promise for enhancing the efficiency, sustainability and diversity of fermented food production, paving the way for a new era of innovation in fermentation.

Drivers for the use of starter cultures

Fermented food products are widely recognized globally and are occasionally classified as 'functional foods' because of their suggested health advantages.[1] Fermentation has long been recognized as a vital process in food production, contributing to the preservation, flavor enhancement, and nutritional enrichment of a diverse range of food products. From ancient civilizations to modern food industries, fermentation has played a central role in the transformation of raw ingredients into safe, palatable, and nutritious foods.[2,3]

However, despite its long-standing history and widespread application, fermentation is not without its challenges, particularly in terms of ensuring safety, consistency and nutritional quality. One of the key factors influencing the safety and quality of fermented foods is the microbial community responsible for driving the fermentation process.[4,5] These microorganisms are autochthonous (i.e., native to the host environment) and are used as starters in fermented products, enhancing the fermented products with health benefits which include the potential to modulate gut microbiota and the immune system, and to improve the functional and nutritional status.[6]

"Advancements in microbiology, molecular biology and bioinformatics have revolutionized the field of starter culture development"

Traditionally, fermentation relied on naturally occurring microorganisms present in the environment or on the surface of raw ingredients. While this approach can yield delicious and culturally significant products, it also poses risks in terms of microbial contamination and variability in fermentation outcomes.[4] There is an increased pressure to produce more food with a higher nutritional content without the risk of foodborne infections and with greater control of the fermentation process. To address these challenges, there has been a growing interest in the development of starter cultures.

A starter culture, in the context of food microbiology, refers to a carefully selected and characterized microbial inoculum composed of specific strains of bacteria, yeasts, or molds, used to initiate and control fermentation processes in food production. Starter cultures offer several advantages over spontaneous fermentation that is carried out at small or household scale and is characterized using simple, non-sterile equipment, random or natural inoculums, unregulated conditions, sensory fluctuations, and poor durability. These include enhanced microbial stability, improved control over fermentation parameters, and greater consistency of product quality.[6] More importantly, starter cultures can be tailored to produce specific sensory attributes and nutritional profiles, making them invaluable tools for modern food producers seeking to meet consumer demands for safe, nutritious, and high-quality foods.[7]

In recent years, advancements in microbiology, molecular biology and bioinformatics have revolutionized the field of starter culture development. High-throughput sequencing techniques have enabled researchers to rapidly identify and characterize microbial strains with desirable fermentation traits, such as rapid growth, acid tolerance, and production of flavor-enhancing metabolites.[8] Furthermore, bioinformatics tools have facilitated the analysis of microbial communities and the prediction of their functional properties, allowing for the rational design and optimization of starter cultures for specific fermentation applications.[9]

Benefits and challenges of starter cultures in fermentation

Starter cultures play a critical role in fermentation by inoculating the raw substrate with specific microorganisms that drive the desired fermentation reactions. However, despite their importance in improving food quality and nutritional properties, developing effective starter cultures poses several challenges. Below are the benefits and challenges of starter cultures during fermentation (**Table 1**).

TABLE 1: Benefits and challenges of starter cultures

Benefits

Consistent quality and flavor

- **Predictability:** The uniformity of product quality and flavor can be provided by starter cultures with a consistent and predictable fermentation process.
- **Control:** Fermentation parameters can be controlled through the starter cultures, thereby reducing variability in the end product.

Safety enhancement[10]

- **Pathogen inhibition:** Antimicrobial substances such as bacteriocins and organic acids are produced by starter cultures that inhibit the growth of pathogenic microorganisms and enhance food safety.
- **pH control:** A less favorable environment is created through the acidification process of low pH, which is less favorable for harmful bacteria.

Improved shelf life

- **Preservation:** The use of starter cultures in fermentation increases the shelf life of products by reducing spoilage due to microbial activity.

Nutritional enhancement[11]

- **Bioavailability:** The bioavailability of nutrients in foods can be enhanced by fermentation, making them easier for the body to absorb.
- **Probiotics:** Probiotics are produced by some starter cultures, which can contribute to gut health.

Texture and functional properties[12]

- **Texture development:** Starter cultures play a crucial role in developing desirable textures in products such as cheese and yogurt.
- **Functional ingredients:** To improve the functional properties of food, starter cultures produce enzymes and other compounds.

Challenges

Strain selection and maintenance[13]

- **Specificity:** There is a need for extensive research to select the right strain for a specific product.
- **Stability:** It is difficult to maintain the viability and activity of starter cultures during storage.

Contamination risks

- **Cross-contamination:** Unwanted microorganisms pose a risk, and can eventually spoil the product or cause off-flavors.
- **Aseptic conditions:** To prevent contamination, strict aseptic conditions are needed, which requires careful handling and infrastructure.

Cost considerations

- **Production costs:** It is costly to keep up the production and maintenance of high-quality starter cultures.
- **Process adaptation:** Additional investment in equipment and training may be required when integrating starter cultures into existing fermentation production processes.

Regulatory and quality control

- **Compliance:** Compliance involves rigorous testing and documentation to ensure that starter cultures comply with food safety regulations and standards.
- **Quality assurance:** To ensure the effectiveness and consistency of the starter cultures, there is a need for continuous quality control measures.

Sensory and consumer acceptance

- **Flavor profile:** It is challenging for starter cultures to help achieve the desired flavor profile that meets consumer preferences.
- **Texture and appearance:** Consumers do not always accept changes in texture and appearance that are due to fermentation.

Environmental factors

- **Variability:** The performance of starter cultures can be affected by environmental factors such as temperature, humidity and oxygen, and this requires careful monitoring and control.

Future directions of starter cultures

Recent advancements in molecular biology, genomics and bioinformatics have revolutionized the field of starter culture development. High-throughput sequencing techniques allow for the rapid identification and characterization of microbial strains with desired fermentation attributes. Furthermore, bioinformatics tools enable researchers to predict the functional properties of microbial communities and optimize their composition for specific fermentation applications. These advances hold immense promise for enhancing the efficiency, sustainability and diversity of fermented food production, paving the way for a new era of innovation in fermentation.

The development of starter cultures for safer, more nutritious, and controlled fermentation represents a promising avenue for innovation in the food industry. By harnessing the power of molecular biology, bioinformatics, and traditional fermentation practices, researchers can optimize microbial communities to meet the evolving needs of consumers and producers alike. Continued investment in research and development, such as strain selection and improvement, functional properties, fermentation optimization, and innovative applications such as novel fermented products and biopreservation, are essential to position fermentation as a sustainable and nutritious food processing technology.

> **"Starter cultures can be tailored to produce specific sensory attributes and nutritional profiles"**

Conclusion

With the increased pressure to produce more food with a higher nutritional content without the risk of foodborne infections and with control of the fermentation process, the use of a selection of autochthonous microbial strains used as starter cultures can contribute to the predictable and reproducible improvement of the safety, and nutritional, organoleptic and functional quality of fermented foods, paving the way for a more sustainable and resilient food system.

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Fermented Foods in Food-Based Dietary Guidelines

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Key messages

- Food-Based Dietary Guidelines (FBDGs) indirectly influence millions of citizens' daily food choices.
- Nutrition and health professionals as well as policy makers need to be made aware of the health and sustainability benefits of non-animal-based fermented foods.
- Fermentation-enabled biomass has the potential to be used as a dry protein source.
- FBDGs should include more traditional non-animal-based fermented foods and should help identify which novel fermented foods can be part of a sustainable healthy diet for the target population.

Food-Based Dietary Guidelines

Food-Based Dietary Guidelines (FBDGs) illustrate what foods make up a healthy diet considering context-specific principles to provide the required nutrients and prevent chronic diseases.[2] They form the basis for the development of official food policies as well as nutrition and health programs. Moreover, they serve as an information source for health professionals and are used for catering recommendations in institutions such as daycare centers, schools, primary healthcare and hospitals. In other words, they indirectly influence millions of citizens' daily food choices.[1] This is why FBDGs are recommended by the FAO, WHO and IPCC as powerful, top-level tools to achieve health and climate goals.[2-4] However, a large-scale evaluation of FBDGs by Klapp and co-authors demonstrated that these documents lag in protein diversification messages and do not provide sufficient information for healthy and sustainable food choices.[5] This seems to affect fermented foods too.

Traditionally fermented foods included in FBDGs

Animal-based fermented foods such as yogurt and cheese are included in many FBDGs worldwide. However, given the high ecological footprints of animal-source foods (ASFs), including milk and dairy products, there is an urgent need to reduce the consumption of ASFs. To still benefit from the positive health effects of fermentation, FBDGs should recognize the wide range of fermented foods of non-animal origin.[5,6]

While certain types of cereal-based fermented foods such as bread are more frequently integrated into FBDGs, other plant-based fermented foods such as kombucha, kimchi, sauerkraut and other fermented vegetables are less common.[7] The South African FBDG provides a rare example, mentioning tshiunza, a traditional maize- or roots-based fermented food commonly consumed as porridge.[8] A particularly interesting example of fermented plant-based alternative to ASFs is tempeh. Tempeh is typically made from soybeans, but it can also be made of many other beans and legumes. A recently published review by Teoh and co-authors concluded that tempeh is a highly nutritious and sustainable source of plant-based protein. It is rich in essential amino acids, and the fermentation process improves the protein digestibility.[9] Tempeh can be found in several FBDGs worldwide as part of the protein group, for example in Australia, Malaysia, and the USA. The Australian FBDG states that "lentils, tofu and tempeh provide a valuable and cost-efficient source of protein, iron, some essential fatty acids, soluble and insoluble dietary fiber, and micronutrients. They are valuable inclusions in any diet and are especially useful for people who consume plant-based meals."[10] The Malaysian FBDG recommends consuming a portion of legumes in the form of dhal, tempeh and tauhu as part of the daily protein intake.[11]

> **"FBDGs should recognize the wide range of fermented foods of non-animal origin"**

Novel fermented foods included in FBDGs: the example of mycoprotein

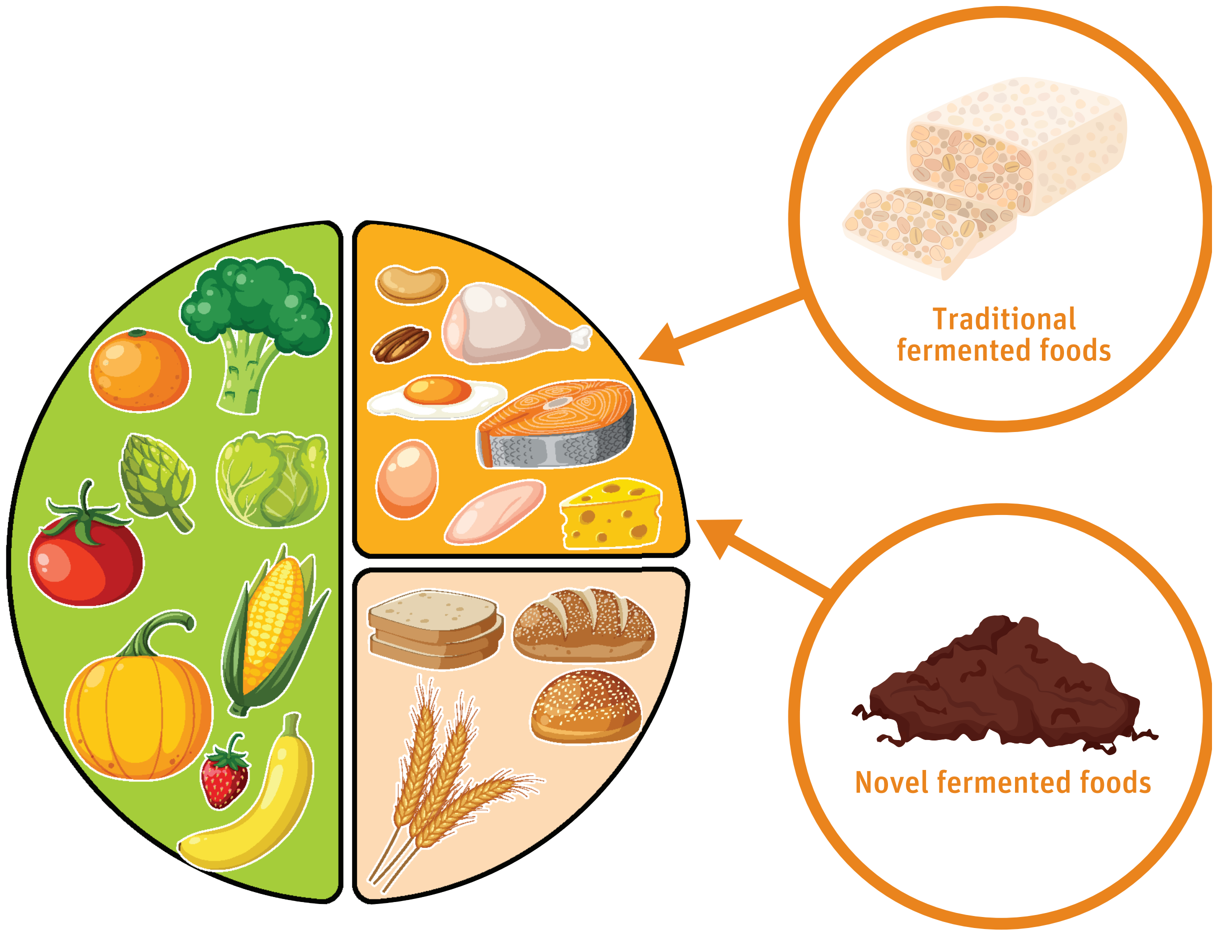
Over recent decades, fermentation technologies have been harnessed to produce novel foods, enabling the cultivation of alternative proteins. This has expanded the repertoire of fermented foods to include fermented biomass. Fermented biomass, also known as fermentation-enabled biomass, refers to food produced using fungi, bacteria, or algae that have been cultivated on a large scale. This differs from the classical metabolic fermentation, which uses microorganisms as actors of the fermentation process. Harvested biomass is typically processed to produce different meat and dairy analogues such as alternatives to beef mince, chicken fillets or yogurt.[12] However, fermentation-enabled biomass has the potential to be used as a food in other ways, including in its unprocessed form, as a dry protein source in ambient soups or stews.

Mycoprotein is the most widely known example of a fermented biomass, available in the UK since 1985.[13] The term mycoprotein was coined by UK regulators during novel food approval to describe pure fungal biomass, with an RNA content of no more than 2%, derived from filamentous fungi, such as *Fusarium venenatum*. As it is solely a fungal biomass, mycoprotein is a whole food ingredient, rich in both high-quality protein and fiber. Moreover, mycoprotein typically also provides a range of micronutrients (such as riboflavin, folic acid, manganese, choline and zinc, but these can vary depending on the fungal species used) and is low in saturated fat and phytic acid.[14,15] Fermented biomass of algae (microalgae and macroalgae) and bacteria (such as cyanobacteria) are less widely available, with production at present limited to start-ups,[16] but the availability of foods made from these forms of biomass is likely to increase in coming years.[17] A recently published study by Perez-Cueto and co-authors revealed that the European consumers have a significant interest in non-animal fermented foods and identified a strong market potential.[18]

Food made from fermented biomass in the form of mycoprotein. *Photo credit: Marlow Foots Ltd.*

As a source of high-quality protein, fermented biomass would naturally sit within the protein food group of FBDGs (**Figure 1**). However, since it is a relatively new food, the presence of fermented biomass is limited in FBDGs around the world, reflecting both availability and awareness. The sale of mycoprotein is currently limited to around 20 countries worldwide, with most consumption in the UK, Europe and North America as well as Aus

Figure 1: Protein diversification through fermented foods of non-animal origin in food-based dietary guidelines
Graphics credit: iStockphoto/colematt, 7romawka7, Kolesnyk Yevheniia.



tralia. So far, only mycoproteins are reflected in FBDGs. Within Europe, mycoprotein features in the accompanying guidance of the UK's EatWell Guide,[19] while in the Swiss Food Pyramid's portion size guidance, mycoprotein is referenced under the leading brand name (Quorn).[20] More recently, the Nordic Nutrition Recommendations recognized fungi, in the form of mycoprotein, as a source of protein in addition to plant and animal foods.[21]

Emerging trends and opportunities for FBDGs

With its Planetary Health Diet (PHD) published in 2019, the EAT-Lancet Commission emphasizes the urgent need to shift to more plant-rich diets to improve the health of people and the planet.[22] However, like many FBDGs, the PHD also neglects non-animal based fermented foods, both traditional and novel. Considering the nutritional benefits linked to fermentation, such as the reduction of antinutritional factors and the improvement in protein digestibility of legumes and cereals, this is a missed opportunity.[23,24] A best-practice example can be found in the Kenyan FBDG, which refers to this benefit and points out that "processing techniques such as fermentation enhance the bioavailability of micronutrients in plant-based diets, and fortification or enrichment add important nutrients to foods." This is also true for novel fermented foods.

While novel fermented foods such as mycoprotein are typically available as meat analogues in high-income countries, they are likely to be less relevant in low- and middle-income countries (LMIC). However, biomass has the potential to produce a variety of different foods to address citizen needs. But the appropriateness of novel fermented foods needs to be further considered in terms of nutrition adequacy, production, and appeal. Since non-animal foods lack vitamin B_{12}, fortification of novel fermented foods provides a means of ensuring that these nutrients are provided in the diet. Fungal biomass, on the other hand, is low in phytic acid, and thus mineral bioavailability should be less of a concern.

Lastly, as sustainability becomes increasingly important in FBDGs, it is worth noting that the wide range of fermented protein-rich foods of non-animal origin boasts a beneficial environmental footprint in comparison to more traditional sources of protein in the form of livestock. Such novel fermented foods require less land and thus minimize deforestation and biodiversity loss, using less water and generating fewer greenhouse gas emissions.[26,27] While traditional plant-based fermented foods can be a cost-efficient nutrient-rich option for LMIC, novel fermented foods may provide a realistic alternative to ASFs in the Global North, where intakes have increased substantially over recent decades.

Conclusion

Nutrition and health professionals as well as policymakers need to be made aware of the health and sustainability benefits of non-animal-based fermented foods. As the primary source of public education on food choices, FBDGs should include more traditional non-animal-based fermented foods and help identify which novel fermented foods can be part of a sustainable healthy diet for the target population.

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Fermentation: A Neglected Technology to Combat Child Food Poverty and Malnutrition in Africa

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Key messages

- Promoting the fermentation of indigenous foods is not just about preserving a cultural tradition; it is a crucial step towards achieving food security, improving public health, and reducing malnutrition.
- Leveraging the power of this ancient technology can contribute to creating sustainable, cost-effective and nutritionally rich solutions that benefit communities across Africa.
- It is essential to recognize the value of traditional knowledge and practices and to integrate them into modern nutrition programming and policy frameworks.
- This has the potential to ensure that future generations have access to the nutritious foods they need to thrive while preserving the rich cultural heritage that defines our communities.

The potential of probiotics

Fermentation, a time-honored culinary tradition, has been used for centuries to safely preserve food, enhance flavor, and boost nutritional value in Africa.[1] Fermented foods are essential components of diets of children of complementary feeding age (6 to 23 months), pregnant and breastfeeding mothers, and adults alike across the continent. Through the action of probiotics –micro-organisms (bacteria, yeasts and mycelial fungi) and their enzymes, fermentation pre-digests food, making nutrients more bioavailable, and often generates additional nutrients such as vitamins while removing anti-nutrients or toxins. Foods fermented with live cultures – such as lactic acid-producing bacteria – support digestive health, immune function, and general well-being. Fermentation saves fuel by reducing cooking times and enables foods to remain stable at ambient temperatures without refrigeration.[2] The potential of probiotics in the prevention and treatment of child malnutrition in Africa is documented.[3] Probiotics prevent diarrhea – one of the main direct causes of malnutrition, increase nutrient absorption, and boost immunity among children.[4]

Despite its numerous benefits, fermentation remains underutilized and undervalued in nutrition programming and policies in Africa. This is concerning, given the escalating issues of hunger and malnutrition that plague many communities across the continent.[5] As a practitioner deeply involved in community health and nutrition in Africa for the past 15 years, it is disheartening for me to witness the dire consequences of this oversight. I have witnessed first-hand the devastating effects of malnutrition: children succumbing to hunger, women facing severe health complications, and communities struggling to thrive. Meanwhile, the cost-effective, culturally appropriate, and nutritionally rich practice of fermentation of foods for children and women remains largely underutilized.[6] The popular alternatives promoted by nutrition programs are frequently expensive and inaccessible to the poor, exacerbating the very issues they aim to solve.

> **"Despite its numerous benefits, fermentation remains underutilized and undervalued"**

Utilizing fermentation to combat child food poverty and malnutrition in Africa

Fermentation is a powerful technology in addressing child malnutrition. It transforms basic ingredients into nutrient-dense foods, improving their digestibility and bioavailability. Fermented products – for example, tuber products known as 'agbelima' in Ghana and 'myiodo' in Cameroon – are used for food security.[7] These foods are particularly beneficial for young children, who need balanced and easily digestible diets to support their growth and development. The technology could reduce the proportion of children who are faced with wasting, stunting and anemia due to inadequate dietary intake, poor absorption, and frequent childhood illnesses. There is scientific evidence of the value of probiotics in the prevention and treatment of diarrhea in children in Africa.[4] Diarrhea remains a key direct cause of child wasting in this continent due to poor water, hygiene and sanitation facilities and practices.

The need for bold and innovative approaches

In a world where one in four children (27%) live in severe child food poverty,[8] bold and innovative approaches are urgently needed to improve the diets of children.

needed to improve the diets of children. About 59 million of the 181 million children (33%) living in severe food poverty are in sub-Saharan Africa, second only to South Asia (38%). Eleven African countries, including Côte d'Ivoire, the Democratic Republic of the Congo, Egypt, Ethiopia, Ghana, the Niger, Nigeria, Somalia, South Africa, Uganda and the United Republic of Tanzania, form the majority of the 20 countries contributing to 65% of the number of children living in severe poverty worldwide.[8] Overall, East and Southern Africa have the highest proportion of children experiencing severe or moderate food poverty (79%).[8] With most of these children consuming grains, roots, tubers and plantains (43%), as well as dairy products (23%), the safe use of fermentation has the potential to improve the nutrient value and nutrient absorption of these diets. Consequently, this could sustain optimal growth and development in early childhood and beyond. Moreover, the two regions in Africa with the highest child food poverty also have a high concentration of traditionally fermented foods.

> **"Fermentation is a powerful technique in addressing child malnutrition"**

To mention but a few, Côte d'Ivoire has a fermented cassava dish known as 'attieke', which is rich in carbohydrates and dietary fiber.[9] The Democratic Republic of the Congo has a peanut butter stew known as 'maafe', often fermented with tomatoes and chilies. It is a good source of protein and healthy fats. Egypt has a fermented milk product called 'kishta', which is rich in probiotics and can improve gut health and immunity.[10] Ethiopia has 'injera' a fermented teff flour for spongy flatbread, rich in iron, calcium and protein.[11] Ghana has a fermented cornmeal dough known as 'kenkey', rich in carbohydrates.[12] Niger also has a fermented milk product called 'nono', which is rich in calcium and protein. Nigeria has a fermented corn or millet pap known as 'ogi', rich in carbohydrates and essential vitamins.[13] Somalia has a fermented milk beverage known as 'suusac', which is rich in probiotics and calcium.[14] South Africa has a fermented milk product known as 'amasi', which is rich in protein, calcium and probiotics. East Africa has non-alcoholic fermented millet, sorghum and maize beverages and foods. These include 'bushera' and 'ebibisi' in Uganda, 'kati' in Tanzania, and 'kinaa' and 'ucuru wa kugagatia' in Kenya. South Sudan has several traditionally fermented millet and sorghum foods, including, 'asida', 'nyiri', 'togboa', 'shira' and several others. The region also boasts fermented milk products such as 'bongo' in Uganda, 'maziwa lala' in Kenya, and 'rob' in South Sudan. Beyond these grains and milk, there are several other traditionally fermented foods that are not documented in East Africa.

Significant nutritional benefits

In my literature search on fermented millet, sorghum, maize flour, and their composites – the common substrates used in making local brews among the Itesots, Karamojong, and other tribes in Uganda – I discovered that these traditional processes have also provided significant nutritional benefits to children in these communities. What many may not realize is that children from these backgrounds have thrived on the beneficial elements derived from the fermentation process used in brewing.

For instance, the product known as 'akiria' or 'amure' in Teso and Karamoja, respectively, can be utilized directly from the fermentation pot to prepare a nutritious and flavorful porridge for children. It can also be roasted and consumed directly, or reconstituted with water. Another method involves drying the fermented product, which can then be mixed with hot water to create a puree for children. This drying process serves as a means of preservation.

Another product, 'ebibisi,' which is the sweet product of dried 'akiria' combined with water and local yeast during the initial 2–3 days, is traditionally reserved for feeding children and women. In the past, caregivers would dry 'ebibisi' for later reconstitution with hot water as a healthy snack for children. Unfortunately, due to food insecurity and the commercialization of food, children in Karamoja are now often fed only the dregs or residues of the actual local brew, merely to fill their stomachs.[15,16] I first encountered this concerning reality while conducting formative research in Karamoja about 16 years ago.

Improving children's diets through scientifically validated fermentation processes

When I began working with UNICEF in Karamoja in 2016, I encouraged my colleagues to promote the local fermentation of grains and legumes as a means to enhance the nutritional quality of children's diets. However, there was reluctance due to various issues, including safety concerns. Undeterred, I continued conducting small-scale, informal research among the Karamojong and Itesots on the fermentation of these foods. My findings highlighted a need for more scientific exploration to address the hesitancy surrounding the promotion of fermented foods for children. I have been involved in the development of fermented composite complementary foods – millet, sorghum, maize and powdered milk – at the Food Processing Technology and Incubation Plant of the National Agricultural Research Organization (NARO) in Kawanda, Kampala.[17] This initiative aims to improve the quality of children's diets through scientifically validated and safe fermentation processes.

Through my own research, programming experience, and ongoing scientific trials with the fermentation of complementary foods, I am convinced that such products, rich in probiotics, carbohydrates, protein, calcium and essential nutrients, are ideal for children's developing gut health. These fermented foods deserve a place in modern nutritional programming.

Promoting fermentation techniques on a large scale can ensure that these nutritious products are accessible and widely available. This approach can play a crucial role in combating child food poverty and malnutrition in sub-Saharan Africa and beyond.

This is urgent, given that four out of five children living in severe child food poverty (80%) consume only breastmilk, dairy, or a starchy staple.[3] Only 17% are given nutrient-dense foods such as eggs, animal-source foods, fruits, vegetables and pulses, either alone or in combination with breast milk, dairy products and starchy staples.[3] This presents an opportunity to utilize fermentation to enhance the nutrient value of local foods.[18] A diet of fermented legumes and cereals would significantly improve the nutritional status of children under two years, who are the most affected in Africa. Incorporating fermented legumes, cereals, milk and other staples in the diet of children, can contribute to their healthy growth and development as several nutritional deficiencies can be filled.

Moreover, fermented foods play a crucial role in the diets of pregnant and breastfeeding women. These foods provide essential nutrients, including vitamins and minerals vital for maternal health and fetal development. There is evidence that suggests the consumption of fermented foods during pregnancy may improve neonatal and infant health.[19] The consumption of fermented foods, those that contain probiotics, by breastfeeding mothers could improve the health and nutrition of children, including those born prematurely or with low birth weight. Like young children, pregnant and breastfeeding mothers often live in areas with food insecurity and do not receive the required quality of diets to meet their nutritional needs. Countries such as Uganda, South Sudan, Somalia, Ethiopia and Nigeria, which face climatic and security challenges, bear the greatest burden. Fermentation also helps preserve seasonal produce, ensuring a steady supply of nutritious foods throughout the year. Such produce is highly perishable and prone to spoilage, and therefore its nutritional values may be missed. This is especially important in regions where food insecurity is prevalent and access to fresh produce is limited. Regions facing food insecurity can utilize fermentation to ensure a steady supply of nutritious products throughout the year.

> **"Fermented legumes and cereals would significantly improve the nutritional nutritional status of African children under two"**

Key challenges hampering fermentation in Africa

Despite the numerous benefits of fermentation to the most at-risk groups – children and women – several challenges hinder its widespread adoption in Africa. One key challenge is the prioritization of Western dietary solutions in nutrition programming, which often overlooks the potential of indigenous technologies such as fermentation. These programs frequently promote food found in Western diets, alienating communities from their cultural practices and failing to sustainably address the root causes of malnutrition.

Another significant barrier is the lack of supportive policies and programs that recognize the value of fermentation in improving maternal and child diets. Policymakers and program managers tend to focus on introducing new technologies and interventions without considering the value of traditional methods and indigenous foods. Cumbersome and restrictive regulatory frameworks also deter small-scale producers from engaging in fermentation practices.

There is a disconnect between the research and development that takes place in academic institutions and actual nutrition programs. These institutions ought to generate scalable and affordable technologies which address the real nutrition and food-related challenges among the most vulnerable groups. Unfortunately, this is not the case, as researchers and innovators are mostly stuck in the confines of their buildings. Imagine what Uganda could achieve in improving processing of nutrient-dense and safe children's foods if the NARO Food Processing Technology and Incubation Plant in Kampala were to be established in Karamoja and other areas hit hardest by malnutrition! What if other innovation centers in cities such as University Responsiveness to Agribusiness Development Ltd (CURAD) in Uganda and others elsewhere followed suit by taking the technologies where they are most needed?

Furthermore, there is a significant gap in education and awareness regarding the benefits of fermented complementary foods. Many communities lack the knowledge and skills needed to safely and effectively ferment complementary foods.

A coordinated effort to promote fermentation of women and children's foods in Africa

To address these challenges and harness the full potential of fermentation, Africa needs a coordinated effort involving multiple stakeholders, including policymakers, program managers, community leaders and educational institutions. Here are some key steps to promote fermentation and reduce the burden of maternal and child malnutrition in Africa.

- Governments and policymakers should recognize the value of fermentation as a viable solution to malnutrition. This recognition should be reflected in national nutrition policies and strategies, which should include specific provisions for promoting and supporting fermentation practices. Advocacy efforts should also focus on raising awareness among policymakers about the benefits of fermented foods and the importance of integrating these into public health and nutrition programs.

- Simplifying regulatory processes and providing clear guidelines for the production and sale of fermented foods will encourage more people to engage in fermentation. Regulatory authorities should work closely with local producers to ensure that fermented foods meet safety standards while also being accessible and affordable for consumers.
- Education is key to promoting fermentation and ensuring its widespread adoption. Schools, community centers and healthcare facilities are useful platforms for educational programs that teach people about the benefits of fermented foods and how to safely prepare them. Community engagement activities, such as cooking demonstrations and cultural festivals, have the potential to raise awareness and build support for fermentation practices.
- Investing in research and development is crucial for enhancing fermentation techniques and expanding their application, particularly at the household and community levels. Research institutions and universities should focus on studying the nutritional benefits of fermented composite staples and exploring innovative methods to improve fermentation processes. This research can inform policy decisions, guide program implementation, and provide evidence-based recommendations for promoting the safe fermentation of indigenous foods in Africa. It is important that this research and development adopt a human-centered design approach, involving affected communities to ensure that the solutions meet their specific needs. For example, how can women in Karamoja and other pastoralist communities be supported with appropriate technologies to extend the shelf life of locally fermented milk for feeding their children? I have also heard about a local herb used by the Pokot people in Amudat, Karamoja, which helps preserve fermented or even fresh milk for up to a year. Scientists could collaborate with indigenous communities to scale up such practices, addressing the scarcity of milk among young children left behind in manyattas (groups of small houses enclosed by a fence) without adequate food.
- Reports such as the 'Milk Matters' report[20] and various IPC analyses, food and nutrition security assessments[21] have consistently highlighted inadequate milk supply and care for children as significant contributors to malnutrition in Karamoja. Thus, by working closely with these communities, researchers and technology developers have the potential to develop sustainable solutions to improve nutrition and food security in these regions.
- Providing economic incentives and support for local producers and small-scale entrepreneurs can boost the production and distribution of fermented foods particularly for children and women. This support could be in the form of grants, low-interest loans, technical assistance, and market access initiatives. By creating an enabling environment for fermentation-based enterprises, African governments and partners can stimulate local economies and improve food security.
- National nutrition and food guidelines, along with food guides, should include recommendations for the consumption of fermented foods by pregnant women and children of complementary feeding age. This inclusion will help ensure that fermented foods are recognized not merely as sustenance for the economically disadvantaged, but as valuable components of a healthy diet for all, promoting the healthy growth of children and better health for women.

"By creating an enabling environment for fermentation, African governments and partners can stimulate local economies and improve food security"

Conclusion

Promoting the fermentation of indigenous foods is not just about preserving a cultural tradition; it is a crucial step towards achieving food security, improving public health, and reducing malnutrition. Leveraging the power of this ancient technology, can contribute to creating sustainable, cost-effective, and nutritionally rich solutions that benefit communities across Africa. As we move forward, it is essential to recognize the value of traditional knowledge and practices and to integrate them into modern nutrition programming and policy frameworks. This has the potential to ensure that future generations have access to the nutritious foods they need to thrive while preserving the rich cultural heritage that defines our communities. Embracing fermentation can build a healthier, more resilient and equitable food system for all.

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Experience from the Field

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Yoba for Life Foundation: Locally Produced Probiotic Yogurt for Health and Wealth

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Key messages

- The Yoba for Life Foundation is dedicated to community economic development, school feeding programs, and preventive healthcare in East Africa through the promotion of locally produced fermented foods.
- The *Lactocaseibacillus rhamnosus* GG (LGG) in Yoba probiotic yogurt contributes to the achievement of food safety through the reduction of aflatoxins in fermented foods.
- Besides supporting the production side, interventions have been successfully implemented to promote the consumption of probiotic yogurt in (pre-)primary schools as part of the school menu in Uganda and Ethiopia.
- Today, 28,000 children in Uganda and 9,000 children in Ethiopia consume probiotic yogurt at school, as paid for by their parents in a fully sustainable manner. At the same time, this program has tremendously boosted the businesses of the local yogurt producers.

About the Yoba for Life Foundation

The Yoba for Life Foundation, established in the Netherlands in 2009, is dedicated to community economic development, school feeding programs and preventive healthcare in East Africa through the promotion of locally produced fermented foods. By empowering smallholder farmer cooperatives, women's groups, farmers and entrepreneurs to enhance their livelihoods through the fermentation of primary produce – particularly milk – with probiotic bacteria, Yoba for Life Foundation addresses poverty at its core while concurrently improving community nutrition.

Specifically, the Foundation helps marginalized people in resource-poor countries to produce and sell their own probiotic yogurt, which has proven health benefits.[2-6] The Yoba for Life Foundation has made a unique invention in the form of a probiotic yogurt starter culture, tailor-made to enable small- and medium-scale production of probiotic fermented food in rural areas. The Yoba starter culture contains a generic variant of *Lactocaseibacillus rhamnosus* GG (LGG), the world's most researched probiotic bacterium.[2] Since the expiry of the LGG patent in 2009, the Yoba for Life Foundation has made the bacterium available to people who can benefit most – those living in resource-poor countries who commonly face serious health risks that the bacterium can mitigate. The starter culture is produced in Europe, from where it is imported at cost price to various African countries. Local retail agents from all over the country buy the culture from the importer and sell it with a small mark-up to the Yoba yogurt producers in their region.

Yoba starter culture for the production of 100 L of probiotic yogurt. *Photo credit: Jeroen van Loon*

> **"The foundation helps marginalized people in resource-poor countries to produce and sell their own probiotic yogurt"**

Health benefits and reduction of aflatoxins

Research has shown that LGG inhibits a wide range of harmful bacteria and boosts the immune system; it prevents and reduces diarrhea,[3] respiratory tract infections,[4] and ulcers.[5] Yoba for Life and Vrije Universiteit Amsterdam have confirmed increased immune responses and a subsequent trend towards reduced respiratory tract infections in Ugandan school children.[6] Furthermore, the LGG starter culture contributes to the achievement of food safety through the reduction of aflatoxins in fermented foods.

Aflatoxin is a harmful toxin produced by some molds, commonly by *Aspergillus flavus* and *Aspergillus parasiticus*. Aflatoxins have been found in common African food products including maize, peanuts, oil seeds, dry fish and milk, among other things.[7,8] Consumption of foods contaminated with high doses of aflatoxins can cause acute aflatoxicosis and death. Long-term exposure to small amounts of aflatoxin leads to immunosuppression, stunted growth, and liver damage (liver cancer).[9]

The Yoba starter culture was found to remove 100% of aflatoxin from maize porridge contaminated with 120 ppb aflatoxin within 24 hours, with 90% of the toxin being eliminated in the first 12 hours of fermentation.[10] Also, in milk, LGG has shown to have the ability to bind aflatoxin M1.[11] Moreover, LGG has been shown to reduce aflatoxin in the gut, thus boosting the gut microbial flora.[12] In addition, fermentation with Yoba starter culture improves the nutritional value and digestibility of foods,[13,14] and inhibits the growth of aflatoxin-producing molds.[15,16]

Promoting entrepreneurship and income generation

The Foundation's expertise is in training interested groups and individuals to use a low-tech production protocol with widely proven applicability in the African context to produce and sell its own yogurt using the starter culture.[17] Secondly, the Foundation provides specialized training materials tailored to individuals with lower levels of education, focusing on running a small-scale yogurt business. This includes advice on sourcing inputs, marketing, bookkeeping and financial management. Economically disadvantaged groups and individuals are empowered to market their own health-promoting products while earning an income.[18,19] When introducing the concept in a new country or region, the entry point is usually dairy farmer cooperatives, whereby either the cooperative or individual members may decide to engage in the yogurt business. However, once the concept has been picked up by the early adopters and becomes more widely known, the demand for training from Yoba for Life sometimes becomes overwhelming, and active recruitment of potential processors is no longer being undertaken. Across East Africa, Yoba for Life works with more than 340 small and medium-scale entrepreneurs (51% female-owned) with approximately 1,200 employees, who produce 97,000 liters of probiotic yogurt per week on average.

Kashaka Women Entrepreneurs, *Photo credit: Jeroen van Loon/Shutterstock.com*

Yogurt programs in schools

Besides supporting the production side, interventions have been successfully implemented to promote the consumption of probiotic yogurt in (pre-)primary schools as part of the school menu in Uganda and Ethiopia, such that children at the bottom of the pyramid can reap the benefits of this health-promoting product. Good health is an essential component of inclusive education, as it ensures that students can participate fully in learning activities, since good nutrition can help improve concentration, memory and overall academic performance.[20] The program showed that school yoghurt contributes to increased attendance among students.[21] Indeed, when children know that they will receive yogurt at school, they are more likely to attend, which can help reduce absenteeism and increase student engagement.

Parents are asked to pay for the yogurt as a top-up on their termly school fees.[22] To implement the program, an individualized approach was initially required. Yoba staff members moved from school to school to convince the school management and subsequently talk directly to the parents during gatherings about the program's benefits and to provide them with a sample. Later, it became easier, and this was reinforced by a media campaign. Endorsement by local governments played an important role in acceptance by the schools and parents.[18]

Also, for this intervention, it took relatively more effort to convince a first group of early adopters, after which the program became more well known, which made it increasingly easy for more schools to join the program, reinforced by a campaign on local television and direct outreach by the yogurt producers themselves. The price of milk in Uganda lies (far) below the world market price for milk, and therefore producers can offer a package of 125 ml yogurt for the equivalent of US$ 0.13 in an economically viable and sustainable manner. Unfortunately, in Ethiopia the opposite is true, because the price of milk lies above the world market price. This makes the uptake of school yogurt more complicated and often (partly) reliant on existing school feeding funding from the government or development partners.[18]

> **"28,000 children in Uganda and 9,000 children in Ethiopia consume probiotic yogurt at school"**

Today, 28,000 children in Uganda and 9,000 children in Ethiopia consume probiotic yogurt at school, as paid for by their parents in a fully sustainable manner. At the same time, this program has tremendously boosted the businesses of the local yogurt producers linked to their neighboring schools. These producers are now in the driving seat to approach more schools and continuously expand the reach of the program.

The work of the Yoba for Life Foundation and its technical feasibility, economic, social and health impact have been scientifically studied and the findings published in peer-reviewed journals. For more information, please visit our website, www.yoba4life.org.

Children enjoying yogurt at school
Photo credits: Jeroen van Loon

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The Gut Microbiota in Women and Children in Zambia and the Relation to Diets and Fermented Food Consumption in LMIC

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Key messages

- For the gut microbiome to support health, it must be compositionally and functionally diverse and stable, ensuring the host is in a state of eubiosis.
- The gut microbiota is dynamic in its composition; various environmental factors have been linked to shifts between eubiosis and dysbiosis.
- In LMIC, differences in gut microbiota for people residing in urban or rural areas may be expected. To understand this better, we conducted cross-sectional studies in the Southern Province of Zambia, focusing on women of reproductive age.
- Our analysis suggests that location impacts gut microbiota composition of study participants, implying that location-specific environmental conditions exist that impact human gut microbiota.

The influence of environmental factors on gut microbiota

It is well known that diets, as well as the surrounding environment, influence the gut microbiota composition of humans throughout life.[1,2] Certain influences are beneficial, but others are not and can, for example, increase the risk of non-communicable diseases (NCDs).[3] Most research on how the environment impacts gut microbiota is done in high-income countries, leaving a gap in our understanding of gut microbiota composition in LMIC. Little is known about whether and how environmental factors influence gut microbiota in these settings. Here, we explore the gut microbiota composition of women and children in Zambia in an area where fermented food consumption is prominent.

> **"Most research on how the environment impacts gut microbiota is done in high-income countries, leaving a gap in our understanding"**

The contribution of gut microbiota to essential functions

The human gut microbiota consists of microorganisms including bacteria, fungi, archaea, and viruses/phages that reside in the gastrointestinal tract of humans.[3] Over a thousand different bacterial species have been detected. The gut microbiota contributes to essential functions such as digestion, nutrient absorption, synthesis of vitamins, and suppression of pathogens, and it plays a major role in modulating the immune system.[4,5] For the gut microbiome to support health, it must be compositionally and functionally diverse and stable, ensuring the host is in a state of eubiosis.[4,6] The Bacteroidetes and Firmicutes phyla dominate a healthy microbiota, with less than 10% being composed of the Proteobacteria, Verrucomicrobia and Actinobacteria phyla in most individuals.[4] When the gut exhibits a persistent imbalance in the proportion of gut microbes, both qualitatively and quantitatively, this is known as dysbiosis.[5,7]

The gut microbiota is dynamic in its composition, which is influenced by host-specific as well as environmental factors that alter its composition throughout life.[7] Several determinants that influence these dynamics are well known, and these include age, physical activity and ethnicity, as well as several environmental conditions, including diets and conditions associated with geographical location, such as sanitation.[7] Various environmental factors have been linked to shifts between eubiosis and dysbiosis.

Recent advances in high-throughput DNA sequencing have enabled studies that draw associations between environmental factors and gut microbiota composition without the need for traditional culturing methods. [8] Here, all bacterial DNA is extracted from a given sample (such as stool), and one specific common bacterial gene coding for 16S ribosomal DNA is sequenced. This yields profiles of relative abundance of bacterial taxa in a given sample.[8, 9] This new and relatively cheap method has enabled numerous cross-sectional studies that have used the stool microbiota as a proxy for the gut microbiota.[9] Researchers can collect information on various factors that may influence gut microbiota composition through questionnaires, open-ended interviews, and observations. These factors include sanitation levels, living conditions, household income, diet, health parameters, and stool samples as a proxy for the gut microbiota.

> **"The advent of high-throughput DNA sequencing technology has enabled numerous cross-sectional studies"**

Analysis of gut microbiota profiles

For analysis of gut microbiota profiles, diversity metrices from community ecology that help describe species communities are commonly used.[10] Alpha diversity metrics describe how diversity is distributed within a species community and are increasingly recognized as biomarkers for gut health; high diversity representing mature gut microbiota characterized by a stable and resilient community. Beta diversity compares species composition and their relative abundance between different species communities. Beta diversity analysis is used to assess if a certain characteristic (for instance, age group, diet quality score or sanitation status) impacts gut microbiota composition – for instance, through altered relative abundance of key bacterial taxa as function of that characteristic.[10]

Environmental conditions, such as living conditions, levels of sanitation and diets, differ significantly in LMIC compared to well-studied high-income settings, and their effect on gut microbiota remains understudied.[11,12] As a specific example, in LMIC differences in gut microbiota for people residing in urban or rural areas may be expected.[13-15] For instance, levels of sanitation, household income, access to healthcare, and prevalence of NCDs may be different between urban and rural areas. Consumption of whole grains and unsaturated fats is more prevalent in rural areas than in urban areas.[15] Further, non-alcoholic traditional fermented foods are of special interest in the context of LMIC. Fermented foods are foods in which raw materials are converted into a food product by the activity of microbes such as lactic acid bacteria and yeast. These are bacterial genera that are generically known for their probiotic effect in modulating the gut microbiota towards a healthy composition.[16] While most standardized or globalized fermented foods are based on a microbial consortium of up to three strains, traditional fermented foods commonly found in LMIC harbor a diverse community of microbes,[17] including various genera that are known for their probiotic effects.[18]

> **"Fermented foods commonly found in LMIC harbor a diverse community of microbes, including various genera known for their probiotic effects"**

To understand this better, we conducted cross-sectional studies in the Southern Province of Zambia, focusing on women of reproductive age. We obtained stool samples and documented information from over 350 study participants describing characteristics such as age, health status, living conditions, and diets. In particular, we targeted two study areas, each with an urban and a rural section – hypothesizing that overall living conditions would differ between these urban and rural areas, with a detectable impact on gut microbiota composition as determined using stool samples.

Our analysis on association between gut microbiota and location (**Figure 1**) suggests that location impacts gut microbiota composition of study participants, implying that location-specific environmental conditions exist that impact human gut microbiota. Our study was cross-sectional, not demonstrating any causation. However, our results using a large sample size do clearly support the notion that environmental factors associated with differences between urban and rural conditions impact gut microbiota. Exactly which environmental factors may explain gut microbiota composition and by what mechanism should be the focus of more focused studies. This notion was further supported by an explorative study in children, in which we examined the gut microbiota of 88 children aged 6 to 48 months in rural Zambia, targeting one urban area. In a similar cross-sectional approach of documenting various population characteristics and profiling gut microbiota using stool samples, we found that breast-feeding, use of

Clockwise from top left: Briefing of study participants on how data will be collected from their homes, homes at study sites in Choma and Mazabuka, located in the Southern Province of Zambia, cereal-based fermented beverages in shop, and the collection of information regarding the intake of traditional cereal-based fermented beverages. *Photo credit: Elise F. Talsma*

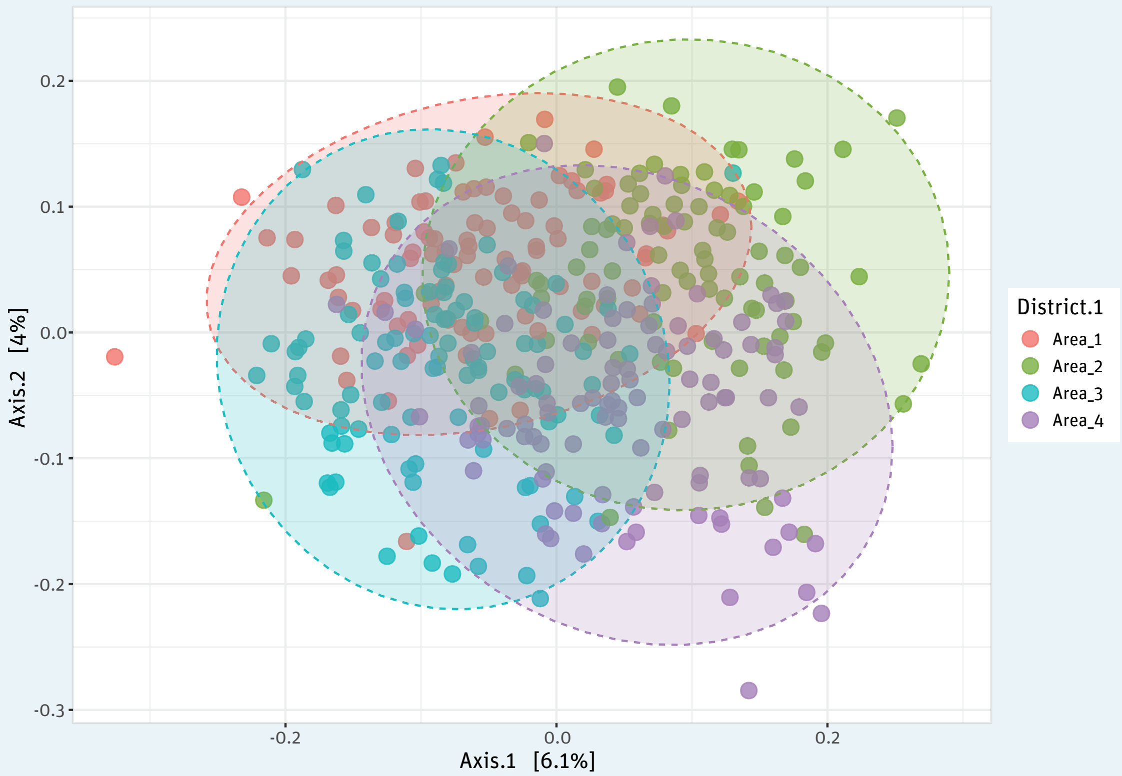
antibiotics, and the consumption of cereal-based and milk-based non-alcoholic traditional fermented foods impacted gut microbiota.

The exact way in which environmental factors contribute to modulating gut microbiota, and their relative importance, remains subject to further study. We are currently exploring the diets as an obvious candidate, since variations in diets have generally been shown to influence gut microbes,[5,6] and these might differ per location. Together with other factors, they can have an impact on individual's health outcomes, and therefore require Careful consideration and possible interventions. Our study has the potential to inform future research in several ways, both at our study sites as well as more generally in LMIC. These would include exploring the role of gut microbes in the relationship between NCDs and diet quality, and examining the impact of urbanization on diet quality, gut microbiota and disease outcomes. Further intervention studies on the effect of fermentation and diet quality on gut microbiota and subsequent health outcomes in various contexts can be inspired by our work.

"Our research may inform research on role of gut microbes in linking diet quality, urbanization, and NCDs"

For instance, both in-vitro and longitudinal studies could examine bacterial taxa and their combined metabolism's positive effect on microbiota.[18] More generally, beyond fermented foods, these studies should be designed to identify specific microbes that are affected by environmental factors, thereby informing further research on best practices to promote shifts in specific taxa within the gut microbiota to promote eubiosis in the gut. In this way, LMIC-specific strategies could be designed to optimize gut microbiota for optimal health.

Figure 1: Principle component analysis of beta diversity of gut microbiota profiles from 380 study participants per location



Area 1 and area 3 are urban areas; area 2 and 4 are urban areas. The percentage in brackets shows the amount of variation explained at each axis. The four differently coloured ellipses depict 95% confidence intervals. Beta diversity analysis reveals whether differences in gut microbiota composition exist at the level of bacterial taxa. Overall, on average study participants from each of the four locations had a gut microbiota species composition that is distinctly different from the other locations. The relatively low fraction of explained variation (of 10% in total) suggests that apart from location, other determinants impact gut microbiota – these remain to be explored.

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Fermented Foods in School Meals: Upgrading Traditional Processing of Mahewu

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South African drink of fermented maize or pap called mahewu
Photo credit: Aninka Bongers-Sutherland/Shutterstock.com

Key messages

- Schools meals serve as an important vehicle through which communities, governments and humanitarian organizations reduce the prevalence of hunger, encourage school attendance, and promote positive health and nutrition outcomes.
- However, many countries in sub-Saharan Africa often face challenges in providing nutritionally balanced meals due to financial constraints.
- Presenting traditional cereals to pupils in fermented form would add minimally to meal costs but significantly enhance their health and nutrition benefits for the students.
- Important considerations for the selection of foods for use in school meals include affordability, consumer acceptance, satisfaction of hunger, ease of preparation, and post-preparation shelf life; many locally available cereals meet these criteria.
- Integrating mahewu and similar beverages into school meals is a cost-effective way to boost nutrition, enhance health, and promote sustainable diets that are based on naturally processed local foods.

Introduction

Traditionally fermented cereal foods and beverages, made mostly from maize, sorghum and millets, have been a significant part of diets in sub-Saharan Africa for ages, contributing to food security, nutrition and incomes.[1] They are primarily produced through spontaneous fermentation. This is a low-cost food processing technology that depends on endogenous microbial communities of lactic acid bacteria and yeasts in the processing environment to enhance the shelf life, safety and sensory qualities of food.[2-4]

Interest in traditionally fermented cereals, particularly non-alcoholic beverages, has risen in recent years due to their perceived health benefits.[5,6] This article argues for their incorporation into school meals, particularly in low-income countries, as a means of enhancing the nutritional profile and health benefits of school meals.

Importance of mahewu in school meals

The importance of school meals for improving children's education, health and nutrition cannot be overemphasized.[7,8] Schools meals serve as an important vehicle through which communities, governments and humanitarian organizations reduce the prevalence of hunger, encourage school attendance, and promote positive health and nutrition outcomes.[9,10] School meal programs are among the largest social protection initiatives worldwide, reaching an estimated 420 million children annually.[11] Of these, 66 million are from the 54 African countries.[7]

> **"The importance of school meals for improving children's education, health and nutrition is undeniable"**

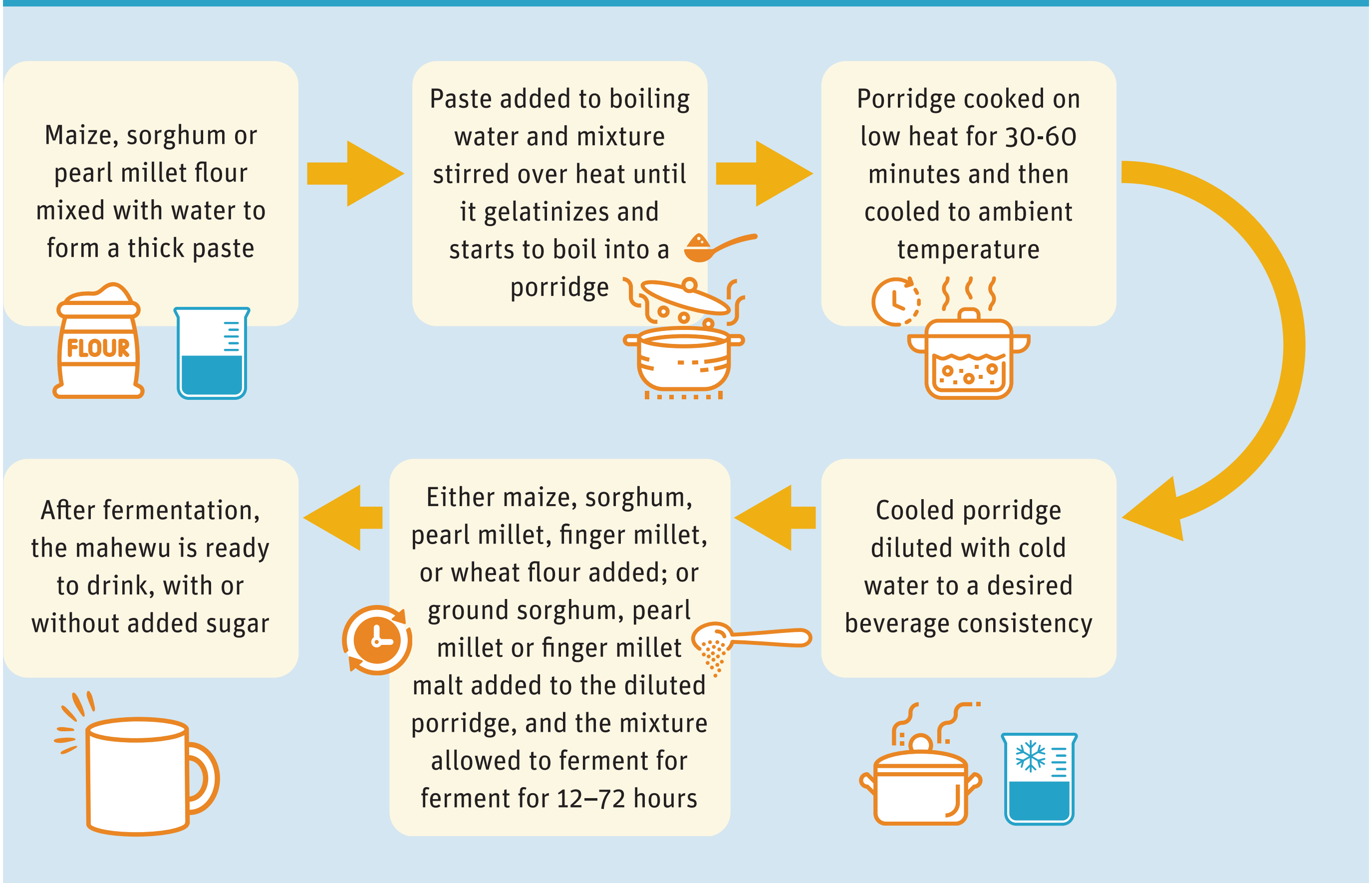
The effectiveness of school meals as a source of balanced nutrition, however, depends on the quality of the meals served. Many countries in sub-Saharan Africa often face challenges in providing nutritionally balanced meals due to financial constraints.[12] In sub-Saharan Africa, cereals are the main component of school meals, and also the most important source of calories and nutrients.[13] Fermenting these cereals before serving them to pupils would add minimally to meal costs but significantly enhance their health and nutrition benefits for the students.

> **"School meal programs are among the largest social protection initiatives worldwide"**

Fermentation of cereals breaks down complex proteins, carbohydrates and phytates, thereby releasing nutrients and enhancing their bioavailability.[14,15] Further, fermented cereal-based foods have been shown to enhance diet quality, and to help achieve recommended daily intake of various essential nutrients including the B-vitamins niacin, thiamine and riboflavin and micronutrients such as iron and zinc.[16,17] A recent study by Chileshe et al.[18] used Optifood modelling to assess the impact of adding traditionally fermented foods to diets composed of locally available foods in Zambia. It demonstrated that the addition of mabisi, a traditionally fermented milk product, and munkoyo, a traditionally fermented non-alcoholic cereal beverage, achieved nutrient adequacy for certain micronutrients. Additionally, traditionally fermented cereals are a rich repository of beneficial bacteria that support a healthy gut microbiome. This is linked to better digestion, stronger immune function, and improved mood and cognitive function.[19-21]

Important considerations for the selection of foods for use in school meals include affordability, consumer acceptance, satisfaction of hunger, ease of preparation, and post-preparation shelf life.[22,23] Fermented cereals that meet these criteria include a variety of non-alcoholic fermented maize, sorghum or millet beverages, such as mahewu in Zimbabwe, whose analogues include togwa in Tanzania, chibwantu and munkoyo in Zambia, mageu

FIGURE 1: Overview of processes to make mahewu in Zimbabwe.[31]



and amahewu in South Africa, motsena in Botswana, emahewu in Swaziland, obushera in Uganda, and maxau in Namibia.[6,24-30] These are all local foods that are deeply embedded in the culture of local populations and widely accepted.[1,30] They are popular for their refreshing sweet-sour taste and their energy-boosting and hunger-stilling properties.[6,31-33] Additionally, they are easy to prepare and can be stored under ambient conditions for up to 48 hours.

> **"Integrating mahewu and similar beverages into school meals is a cost-effective way to boost nutrition"**

Mahewu processing

The preparation of mahewu, as described by Pswarayi and Gänzle[35] as well as Kudita et al.[31] involves i) stirring maize, sorghum or millet flour into water and cooking the mixture into a thin gelatinized porridge, ii) allowing the porridge to cool to ambient temperature, iii) mixing in either ground sorghum, pearl millet or finger millet malt or uncooked maize, sorghum, pearl millet, finger millet, or wheat flour to the cooled porridge to start the fermentation, then iv) allowing the mixture to ferment at room temperature for 12–72 hours (**Figure 1**).

Outlook

In light of the well-established nutritional, economic and cultural benefits of traditionally fermented cereals, governments, schools, parents, and community organizations across sub-Saharan Africa should consider harnessing their full potential to improve the quality of school meals. Integrating mahewu and similar beverages into school meals is a cost-effective way to boost nutrition, enhance health and promote sustainable diets that are based on naturally processed local foods. Additionally, it could pave the way for upgrading traditional mahewu processing by village-level, small-scale producers, most of whom are women, for sale to schools, thereby improving livelihood opportunities for rural communities.

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Gari as a Vehicle for Vitamin A Delivery across West Africa

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"Although gari has a low nutrient density, it is an ideal vehicle for delivering micronutrients to vulnerable populations if fortified"

Key messages

- Gari is a cassava-based, fermented food product typically consumed in West Africa.
- The consumption of staple foods with a low nutrient density, such as gari, contributes to a high prevalence of micronutrient deficiencies in West Africa, with vitamin A as a major problem in Ghana.
- Fortifying gari with red palm oil is regarded as the most promising fortification strategy to deliver provitamin A.
- Consumers accepted the fortified gari based on sensory attributes.

Introduction

Gari is a cassava-based, fermented food product typically consumed in West Africa. The gari production process consists of grinding, fermenting and roasting cassava, which results in a coarse, granular product or grits.

Gari is a relatively cheap product consumed in diverse ways. It can be consumed with sauce or beans, or by soaking gari in water with sugar and powdered milk. Gari also serves as an intermediate product for the preparation of a dough called 'eba'.[1,2]

The fermentation process applied for gari production is a spontaneous fermentation, whereby lactic acid bacteria present in the environment are the main microorganisms. Fermentation is either done after dewatering the cassava mash or simultaneously with dewatering.

For fermentation, the cassava mash is placed in polypropylene bags or sacks (**Figure 1**). The fermentation time usually ranges between one and five days and is influenced by the sociocultural use and taste. Small variations in the gari production process, including the duration of the fermentation time, exist depending on the location where the gari is produced, resulting in region-specific differences in the quality and sensory properties of the gari.[3] In addition, the desired level of sourness, which is influenced by the fermentation time, depends on the gari-based dish in which the gari is to be incorporated.[2,4,5]

Converting cassava into gari, also called 'garification', has several advantages, as it increases the shelf life of the highly perishable cassava roots and decreases the content of toxic cyanogenic glycosides.[6,7] The latter mainly takes place during the grinding and fermentation step, whereby cyanogenic glycosides are enzymatically broken down.[8] In addition, the fermentation step is crucial for obtaining the desired sour taste and swelling index.[9]

Iron, iodine and vitamin A are the most prevalent micronutrient deficiencies worldwide and are highly prevalent in West Africa.[10] In Ghana, vitamin A deficiency is a severe health problem as it is estimated that one-fifth of the preschool children suffer from vitamin A deficiency.[11] As vitamin A plays an essential role in vision and immune response, its deficiency can lead to blindness and an increased risk of illness and mortality from severe infections.[12-15] The consumption of staple foods with a low nutrient density, such as gari, in combination with minimal consumption of fruit, vegetables and animal products, contributes to a high prevalence of micronutrient deficiencies in West Africa.[10,16,17]

Although gari is low in these micronutrients, it can be an ideal vehicle for delivering them to vulnerable population groups if fortified with one or more micronutrients.[7,16,18] Food fortification has been proven an effective strategy for preventing micronutrient deficiencies.[19,20] However, in order to have effective food fortification, the chosen food product should be affordable and widely consumed by all population groups, especially those at high risk of micronutrient deficiency.[21] Gari fulfils these requirements, and a few studies have investigated the fortification of gari with vitamin A.[22-24]

Left: Simultaneous dewatering and spontaneous fermentation of cassava mash in polypropylene bags or sacks to make gari.
Right: Sieving and roasting of cassava grits. *photo credits: Eline Van Wayenbergh*

"Consumers are willing to pay an additional 5-15% for red palm oil-fortified, yellow gari compared to the regular, white gari"

Fortification of gari for vitamin A delivery

In a recent study, the fortification of gari with vitamin A was investigated by exploring three vitamin A fortification strategies. These strategies included the addition of a chemically synthesized vitamin A form (vitamin A palmitate), the addition of red palm oil, and the use of biofortified yellow cassava. The latter two ingredients are naturally rich in β-carotene, a provitamin A carotenoid.[22]

A big challenge in fortifying food products with vitamin A is the low stability of vitamin A. Vitamin A is rapidly degraded under the influence of light, oxygen and high temperature – all factors which are difficult to control during gari storage.[25,26] Given the long shelf life of gari, which can go up to more than one year (depending on the moisture content of the gari and the storage conditions), high vitamin A stability during storage is important. Therefore, the stability of vitamin A was monitored during accelerated storage for the three above-mentioned fortification strategies (**Figure 2**).

It should be noted that the vitamin A content is expressed in retinol equivalents (REeq) using a conversion factor of 6:1 for converting β-carotene to REeq. However, in the literature, different conversion factors are reported, which might lead to different calculations of the vitamin A content.[20,27,28] Unlike vitamin A content, vitamin A retention is independent of the conversion factor used and was shown to be the highest for red palm oil-fortified gari. About 23% of vitamin A was retained after eight weeks of accelerated storage (60°C, 70% relative humidity), whereas the vitamin A retention was around 5% for the other two fortification strategies after eight weeks. The high vitamin A retention of the red palm oil-fortified gari can presumably be attributed to the presence of natural antioxidants in the palm oil and the protective effect of the oil matrix on β-carotene.[29]

Consumer perceptions of fortified gari

Next to the stability of vitamin A, the consumer acceptability of fortified gari is also important. To assess this, a sensory analysis and a focus group discussion were carried out in Ghana. In these analyses, regular unfortified gari, red palm oil-fortified gari and biofortified yellow cassava gari were included. Participants were asked to add an amount of water to the gari as they would to prepare gari with beans, a typical gari-based dish. Then, they were asked to score the gari on different attributes: color, smell, mouthfeel, taste and sourness. Consumer acceptability is mainly determined by the organoleptic properties of gari. These are primarily influenced by the fermentation step in the gari production process and the fortification strategy used.

As only one fermentation time and method were used in this study, the focus was on investigating the effect of fortification on the gari's sensory properties. Overall, the fortified gari samples scored slightly lower on all attributes, including color, smell, mouthfeel, taste and sourness (**Table 1**). These differences were, however, not always significant. In addition, the focus group discussion with seven gari producers revealed that they would be more willing to buy the fortified gari if they were informed that the fortified, yellow, gari is healthier. This demonstrated the importance of consumer education and consumer awareness. The outcome of the focus group discussion corroborated the study of Bechoff et al.,[30] who stated that consumers with previous knowledge of fortification tend to associate the yellow color of fortified gari with health benefits such as a positive influence on eyesight.

> **"Consumer acceptability is mainly determined by the organoleptic properties of gari"**

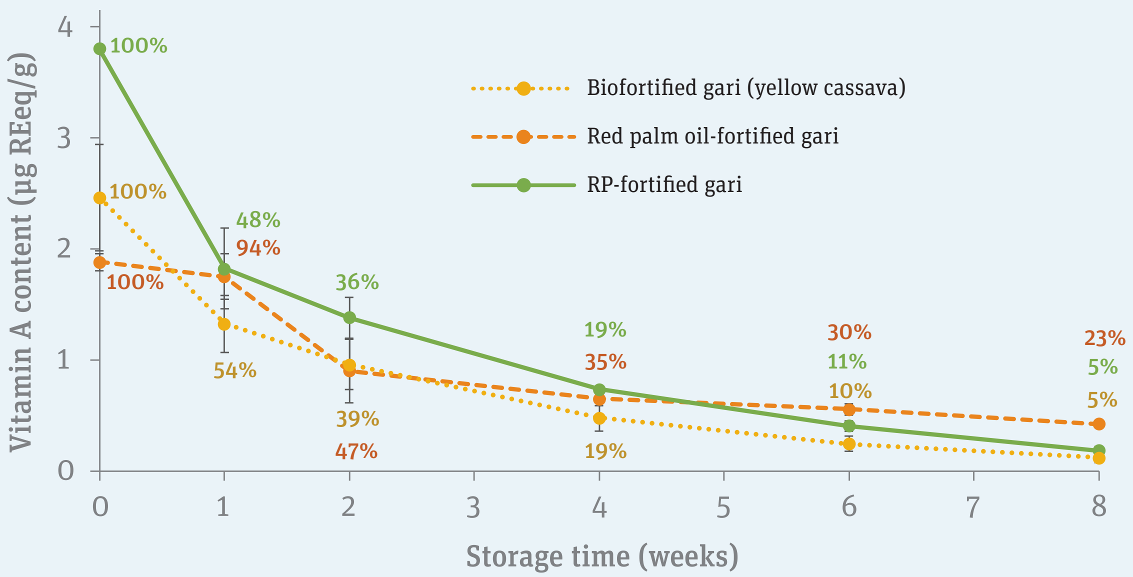
Guidelines for gari producers

Overall, fortifying gari with red palm oil is regarded as the most promising fortification strategy, given its good vitamin A stability during storage and limited effect on sensory aspects. Moreover, red palm oil, which is locally produced in West Africa, is a natural source of vitamin A. This makes it easy for small-scale local producers to apply gari fortification.

While fortification on an industrial level is common practice, this is not the case for fortification on a local level. However, the efforts of NGOs, government agencies and universities to promote the use of vitamin A-rich ingredients, such as red palm oil, have increased fortification at a local level.[9,31,32]

In Ghana, red palm oil is traditionally used for the production of yellow gari. Fortification at the local level is driven by both the processors and the consumers. In a pilot study, a gari processor in the Ashanti Region, Ghana, indicated that consumers are willing

Figure 1: The vitamin A content monitored during eight weeks of accelerated storage



The vitamin A content (expressed as μg retinol equivalents [REeq] per gram gari) monitored during eight weeks of accelerated storage (60°C, 70% relative humidity) of gari fortified with retinyl palmitate (RP), gari fortified with red palm oil and biofortified gari made with yellow cassava.

For the last two fortification strategies, the chemical form of vitamin A is β-carotene, naturally occurring in red palm oil and yellow cassava. To convert the RP content to RE eq, a conversion factor of 1.83:1 was used. For β-carotene, a conversion factor of 6:1 was used.

The vitamin A retention (vitamin A content at time t/vitamin A content at time 0) (%) is indicated on the graph for each sample and each time point in the corresponding color. Gari production was done in duplicate and RP analysis was also done in duplicate, resulting in a 2x2 setup. Error bars represent standard deviations of duplicate gari production followed by accelerated storage.

TABLE 1: Average scores (mean ± standard deviation) of three different gari samples (regular gari, gari with red palm oil and yellow cassava gari) given by an untrained panel of 77 participants

Attribute	Regular gari	Red palm oil-fortified gari	Biofortified gari (yellow cassava)
Color	7.8 ± 1.9 [a]	7.2 ± 2.1 [a,b]	6.3 ± 2.3 [b]
Smell	7.3 ± 1.6 [a]	6.3 ± 2.2 [b]	6.0 ± 2.4 [b]
Mouthfeel	7.1 ± 1.6 [a]	6.2 ± 2.0 [a]	6.2 ± 2.1 [a]
Taste	7.4 ± 1.6 [a]	6.3 ± 2.2 [b]	6.2 ± 2.1 [b]
Sourness	6.9 ± 1.9 [a]	6.1 ± 2.2 [a]	5.9 ± 2.2 [a]

Five different attributes were scored (color, smell, mouthfeel, taste, and sourness) according to a 9-point hedonic scale. Hereby, 1 is the lowest score and 9 the highest. Scores within the same row with a different letter are significantly different ($p < 0.05$).

to pay an additional 5-15% for red palm oil-fortified, yellow gari compared to the regular, white gari. This preference is driven by the perceived quality, taste, and sometimes the nutritional benefits (provitamin A) attributed to the palm oil.

The willingness to pay a price premium is consistent with other gari products where enhanced characteristics, such as flavor and color, derived from additional ingredients lead to higher consumer demand and market value (personal communication Managing Director of Christaa Agric Ventures, Ashanti Region, Ghana, February 2023). Given that adding red palm oil to gari improves the latter's nutritional value and can increase its market value, small-scale gari producers are advised to fortify gari with red palm oil. Red palm oil should be added towards the end of roasting to minimize vitamin A degradation during processing.

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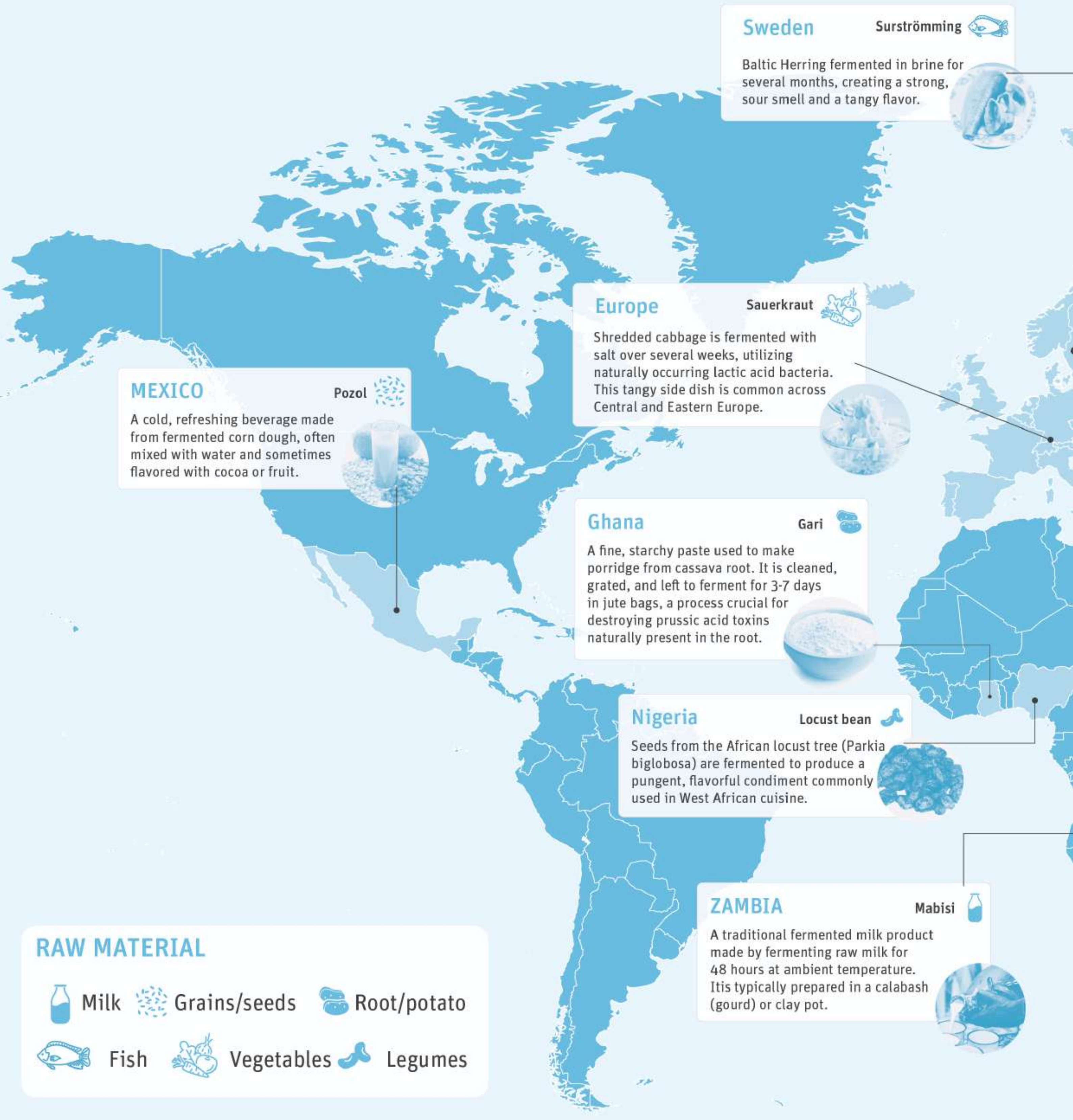
Exploring the World of Fermented Foods



Turkey

A fermented milk
prepared by mixin
and salt, which un
fermentation to be
cent drink. It is po
East, Central Asia,

Sweden

Surströmming

Baltic Herring fermented in brine for several months, creating a strong, sour smell and a tangy flavor.

Europe

Sauerkraut

Shredded cabbage is fermented with salt over several weeks, utilizing naturally occurring lactic acid bacteria. This tangy side dish is common across Central and Eastern Europe.

MEXICO

Pozol

A cold, refreshing beverage made from fermented corn dough, often mixed with water and sometimes flavored with cocoa or fruit.

Ghana

Gari

A fine, starchy paste used to make porridge from cassava root. It is cleaned, grated, and left to ferment for 3-7 days in jute bags, a process crucial for destroying prussic acid toxins naturally present in the root.

Nigeria

Locust bean

Seeds from the African locust tree (Parkia biglobosa) are fermented to produce a pungent, flavorful condiment commonly used in West African cuisine.

ZAMBIA

Mabisi

A traditional fermented milk product made by fermenting raw milk for 48 hours at ambient temperature. Itis typically prepared in a calabash (gourd) or clay pot.

RAW MATERIAL

Milk · Grains/seeds · Root/potato · Fish · Vegetables · Legumes

Ayran

drink, traditionally
g yoghurt with water
dergoes lactic acid
ecome a mildly efferves-
opular across the Middle
, and Caucasus region.

China

Soy sauce

A salty liquid seasoning created by fermenting soybeans and wheat with mold, yeast, and bacteria over many months. It is ubiquitous in Southeast and East Asian cuisines.

India

Dosa

A thin, crispy, savoury crepe made from a fermented batter of rice and lentils.

Japan

Natto

A traditional delicacy made from steamed or boiled soybeans fermented with Bacillus subtilis, resulting in a dish with a slimy texture after a 24-hour fermentation process.

Korea

Kimchi

A spicy, fermented Korean side dish made from napa cabbage and radishes, flavored with garlic, ginger, chili peppers, and fish sauce.

Vietnam

Fish Sauce

A fermented salty condiment made by combining fish or krill with salt and allowing it to ferment for up to two years. This is a staple ingredient in many Southeast Asian and East Asian countries.

Ethiopia

Injera

A sour, spongy flatbread made from teff flour, fermented for several days with ersho (starter). Served as a base for stews, curries and salads.

INDONESIA

Tempeh

A traditional fermented soy product made by culturing cooked soybeans with a fungus, typically Rhizopus oligosporus. It has a firm texture and nutty flavor, often used as a plantbased protein source in various dishes.

ZIMBABWE

Mahewu

A popular non-alcoholic, fermented sour beverage across Southern Africa, made through the lactic fermentation of cereal grains like maize, sorghum, and pearl millet.

Way Forward

Photo credit: Sarmiko.id/Shutterstock.com

Characterizing Fermented Food Composition for More Informed Sustainability Solutions

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Key messages

- Evidence suggests that fermented foods mitigate diet-related chronic disease through modulating the gut microbiome.
- Foodomics, the application of omics technology to study the comprehensive components in food, offers a powerful scientific approach to enhance our knowledge of food quality.
- Foodomics can provide valuable knowledge on how fermentation transforms food quality through metabolomic and biochemical processes into new components with their own functional attributes.
- This knowledge can be translated to inform sustainability solutions, from revitalizing local food systems to more precise formulation for improving the quality of fermented foods.
- The following research and translation efforts are recommended: map the quality of fermented foods; scale evidence on fermented food and health linkages; and translate knowledge for impact through training and other capacity-strengthening efforts.

Fermentation's compelling contribution to diets

The ancient practice of fermentation offers a compelling contribution to diets through transforming raw foods with new qualities including enhancing food preservation, nutrient bioavailability, palatability, digestibility, safety, and health attributes.[1,2] Evidence suggests that fermented foods mitigate diet-related chronic disease through modulating the gut microbiome,[3,4] improving human immune status,[4] mental health,[1,5] glycemic control,[6] and gastrointestinal health,[7] and reducing allergic response[8] and inflammation.[9,10] Further, fermented foods conserve place-based biodiversity of microorganisms as well as cultural knowledge associated with fermentation.[11,12]

Increasingly, fermented foods are being promoted as climate solutions for the global protein transition and for reducing food waste.[13] The protein transition has been called for to reduce greenhouse gas emissions linked to the production and consumption of protein-rich foods sourced from intensive animal agriculture to plant, animal, microbial, and fungal cell culture alternatives, including those produced through fermentation.[13-16] Fermentation offers a food waste solution from farm to household for preventing spoilage and, at an industrial scale, through converting food scraps to biofuel.[2,17]

While fermented foods are championed as sustainability solutions for both people and the planet, there remain knowledge gaps that limit their conservation and scaling in food systems, including the ability to address the following:

What is the composition of fermented foods?

1. How does fermentation enhance food quality based on composition?
2. How do variables across food systems impact the composition of fermented foods? For example, how does the diversity of microorganisms impact composition?
3. How does the quality of place-based fermented foods compare to industrial fermentation?
4. How do fermented foods contribute to human and planetary health?

Tempeh is a common fermented Indonesian dish. *Photo credit: wahdwp/Shutterstock.com*

Foodomics, the application of omics technology to study the comprehensive components in food,[18] offers a powerful scientific approach to enhance our knowledge of food quality. As applied to fermentation, foodomics characterizes the composition of fermented foods to complement other ways of knowing. This know-ledge can be translated for the conservation and promotion of fermented foods in diets. It can further be applied for more precise formulation of fermented foods – at the household, community, and enterprise levels – for achieving desired attributes.[19]

> **"Increasingly, fermented foods are being promoted as climate solutions for the global protein transition and for reducing food waste"**

Application of foodomics to fermentation

Fermentation involves metabolomic and biochemical processes whereby microorganisms consume substrates, excrete and/or produce enzymes that break down complex biomolecules into simpler components,[20] or undergo configuration changes.[21] The components of fermented foods are generally a mixture of biomolecules including macronutrients (carbohydrates, proteins, and lipids), micronutrients (minerals and vitamins), and specialized metabolites.[1] Many specialized metabolites such as flavan-3-ols are recognized as bioactive components in the body that may promote health.[22]

The newly formed components from fermentation modify food attributes, such as by improving nutrient bioavailability, enhancing flavor, and imparting pre- and probiotic properties.[1,23,24] In some cases, microorganisms generate enzymes that degrade macromolecules and specific undesirable or anti-nutritive food components, such as phytates, allergens, and fermentable oligosaccharides, disaccharides, monosaccharides and polyols (FODMAPS).[1,25]

Foodomics can build knowledge about fermentation by comprehensively characterizing food quality based on the biomolecular composition, including components intrinsic to a food and those transformed by microorganisms. Advances in foodomics have been enabled by technological developments in chemical separation techniques, including high-resolution mass spectrometry as well as data processing innovations such as the computational power of machine learning.[18]

Applying foodomics to fermentation provides knowledge regarding the impact of fermentation on food composition. Further, foodomics can uncover how food composition varies based on diverse variables, including fermentation temperature, duration, salinity, pH, aerobic or anaerobic environment, substrate, and specific types of microorganisms, be it a spontaneous inoculation, a starter culture or a bioengineered inoculum.[1,26,27] Ultimately, knowledge about the composition of fermented foods can be leveraged for informing solutions for the conservation of place-based fermented foods and associated biocultural diversity. Additionally, this knowledge can be translated to inform more precise fermentation at the household, community, and enterprise levels for enhancing food quality – including yielding desirable food components and decreasing undesirable components such as microbial toxins, pesticides and plasticizers.

> **"Advances in foodomics have been enabled by technological developments in chemical separation techniques"**

The Periodic Table of Food Initiative's mapping of fermented foods

While tremendous progress has been made in foodomics over the past decade, the lack of standardized tools has been a limiting factor in comparing data across studies and scaling applications for informing food system solutions. The Periodic Table of Food Initiative (PTFI) is a global science-to-action effort that has tackled the challenges of standardization in foodomics. An initiative of the Rockefeller Foundation, the PTFI, which is co-managed by the American Heart Association and Alliance of Bioversity CIAT, has collaborated with Verso Biosciences and a range of partners to create and distribute standardized multi-omics tools to map the food quality of the planet's edible biodiversity based on biomolecular composition. The PTFI is taking a globally coordinated approach to empower an ecosystem of partners around the world to apply its standardized foodomics tools along with existing protocols to characterize food quality.

The PTFI ecosystem comprises Centers of Excellence on each continent as well as national labs, including those located in low- and middle-income countries (LMIC). PTFI takes a systems approach of capturing metadata on food system attributes to provide contextual richness associated with each food. The resulting food composition data and metadata are made available as a global public resource on open-access data platforms including Marker Lab (https://ptfi.versobio.com/markerlab/) and the American Heart Association's Precision Medicine Platform (https://precision.heart.org). In some cases, data is shared privately with community partners following data sovereignty protocols.

Application of the PTFI's standardized foodomics tools to fermented foods enables the comparison of data between studies worldwide in order to characterize components of place-based fermented foods as well as identify fermentation variables that improve food quality. Currently, there are 38 fermented foods in the PTFI database of its first 500 foods. These fermented foods include diverse cheese types, chocolate, yogurt, skyr, labneh, sauerkraut, sourdough, tempeh and kimchi. Over 100 additional fermented food samples from LMIC are being analyzed using PTFI foodomics tools by global partners. Among these partners is the Bokulich Lab of the Institute of Food, Nutrition and Health, ETH Zurich, which leads FermDB, the largest interoperable database and map of fermented foods (https://bokulich-lab.github.io/FermDB/).[12]

> **"Currently, there are 38 fermented foods in the PTFI database of its first 500 foods"**

Figure 1 and **Figure 2** show variation in the components of foods from soybean, *Glycine max*, a plant native to East Asia with fermentation and other processing. Specifically, we see variation in composition between raw soybean (edamame), processed ufermented tofu (raw and cooked), and fermented tempeh (uncooked and cooked), a traditional Indonesian food.

From left to right in **Figure 1**, we see: (i) raw edamame; (ii) raw tofu (unfermented); (iii) cooked tofu (unfermented); (iv) raw tempeh (fermented); and (v) cooked tempeh (fermented). This figure demonstrates variation of the biomolecular composition of raw plant materials through processing, including fermentation and cooking. The variation of color in this heatmap compares the differing abundances of each component, with blue representing lower abundance and red representing higher abundance. The scale is based on data that were standardized by scaling each variable to have a mean 0 and standard deviation of 1, ensuring that that values are expressed in terms of the relative deviations from the mean (ex: 1 is one standard deviation above mean). All values are reported per 100g of wet weight of food. Note, the relative content of water in different foods may impact each comparison.

As shown in **Figure 1**, essential amino acid concentrations are enriched in the fermented soybean (tempeh) compared to the raw soybean (edamame) and the unfermented but processed soybean food (tofu). Conversely, the raw soybean has a variety of fibers that are more highly enriched compared to the uncooked and cooked tofu and fermented tempeh. Of note is the enrichment of fibers in the raw soybean composed primarily of glucose and galactose. There are lower amounts of all sugars in the tofu samples. In the tempeh samples, there are higher amounts of less common sugars, including xylose, mannose and arabinose. These findings are consistent with the physiological process of fermentation, whereby microorganisms break down and consume fibers – often with a strong preference for glucose – for their propagation, while enriching food in proteins and fats.

Figure 2 highlights the striking differences in the metabolites and other small molecules among all soy-based foods, underscoring the effects of processing. Some noteworthy components in higher abundance in the fermented tempeh are isoflavones. An additional striking observation is the higher concentration of amino acids, sugars and lipids in the cooked tempeh compared to the uncooked tempeh. These findings are consistent with the thermal process catalyzing the hydrolysis and release of these nutrients from their polymeric sources (e.g., proteins, starches, fibers, and triglycerides). Collectively, these findings highlight the biomolecular diversity and variation of food composition based on processing, pointing to the importance of dietary diversity of consuming diverse food types with diverse preparation, including unprocessed, cooked and fermented.

Figure 2 shows a heatmap of specialized metabolites and other small molecules measured in the soybean (*Glycine max*) food samples utilizing the PTFI's standardized untargeted metabolomics platform. From left to right we see: (i) raw edamame; (ii) raw tofu (unfermented); (iii) cooked tofu (unfermented); (iv) raw tempeh (fermented); and (v) cooked tempeh (fermented).

Figure 1: A heatmap comparison of components found in foods from soybean (*Glycine max*) generated through a foodomics approach

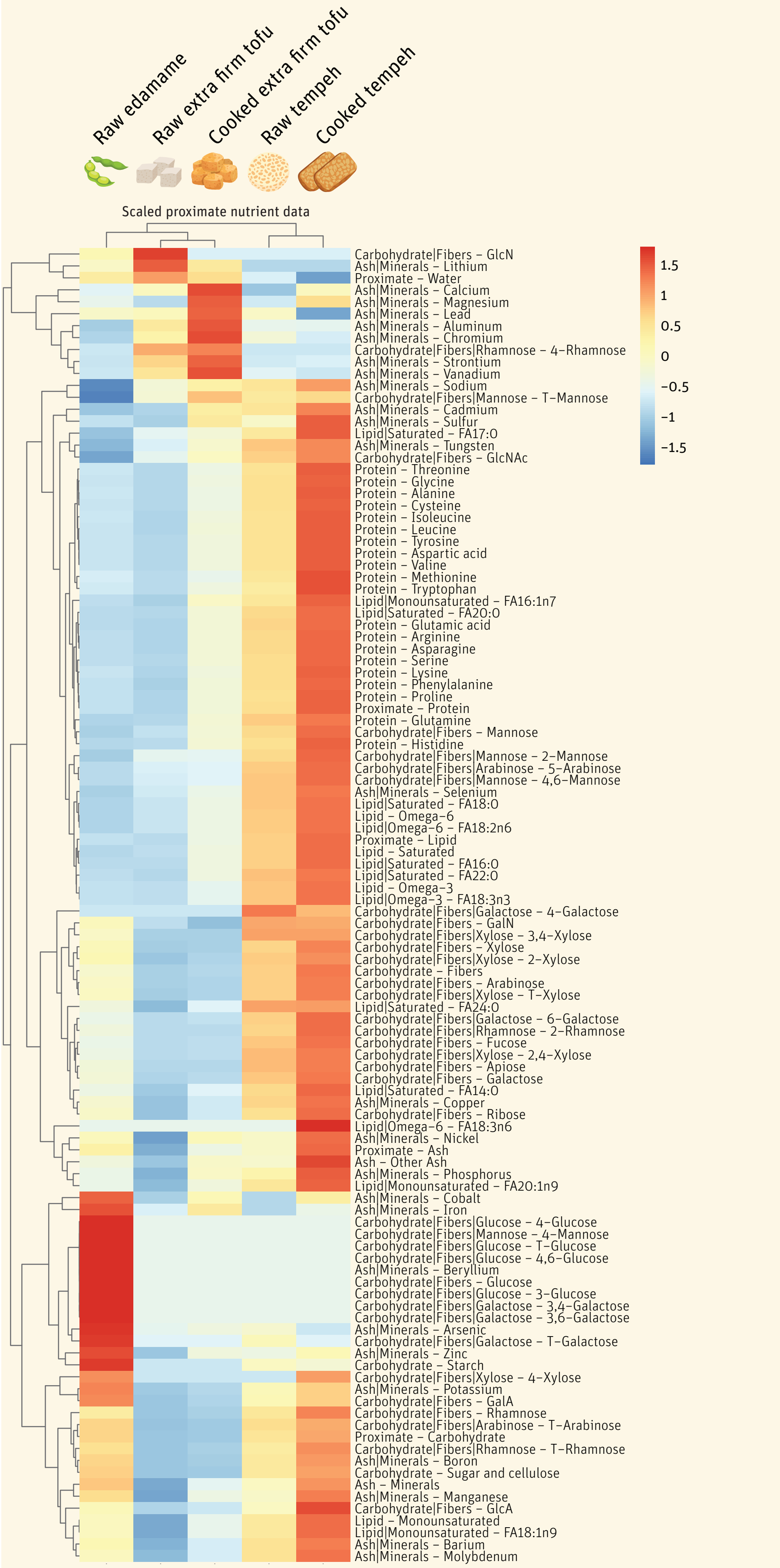
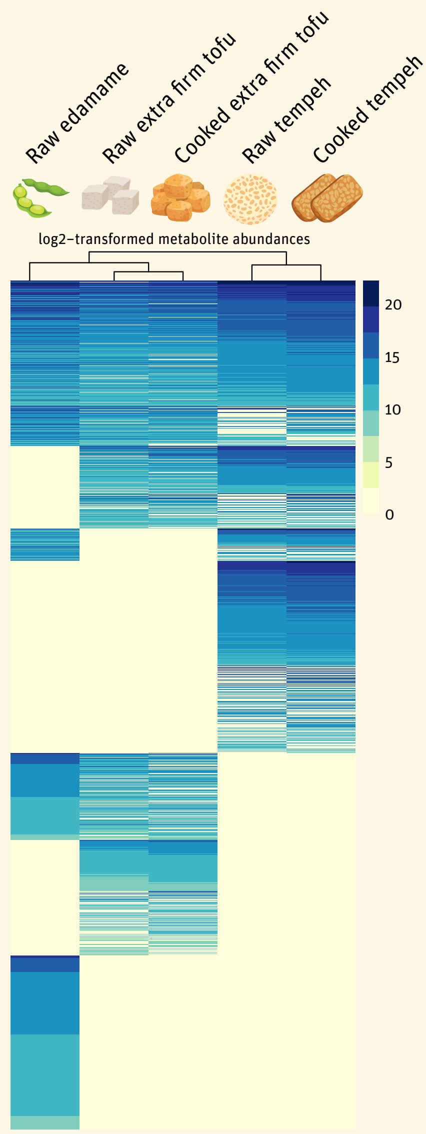


Figure 2: Differences in the metabolites and other small molecules among all soy-based foods



Selling tempeh at a traditional market stall in East Kutai, Indonesia.
Photo credit: Bijinangkaa/Shutterstock.com

This PTFI standardized metabolomics approach captures the relative abundance of thousands of small molecules found in foods, many of which are currently unknown and unnamed. Metabolite abundances have been log2 transformed and sorted by presence/absence and then abundance in the edamame, tofu, and tempeh samples. Pale yellow represents metabolites that have not been detected in those samples, while darker shades of blue represent higher metabolite abundances.

Taking an integrative approach to link food and health, the PTFI has further standardized multi-omics tools for human serum for application in clinical interventions and for the identification of biomarkers of consumption and disease risk. The PTFI is beginning to collaborate with partners to integrate these tools in nutrition interventions and clinical trials. Ultimately, this knowledge is expected to unlock the biomolecular pathways of food for health. For example, previous research has found that diets rich in fermented foods are associated with increased microbiota diversity and decreased inflammatory markers.[4]

> **"Diets high in fermented foods are associated with increased microbiota diversity and decreased inflammatory markers"**

Conclusion and recommendations

Foodomics can provide valuable knowledge on how fermentation transforms food quality through metabolomic and biochemical processes into new components with their own functional attributes. This knowledge can be translated to inform sustainability solutions, from revitalizing local food systems to more precise formulation for improving the quality of fermented foods.

We recommend the following research and translation efforts for the wide-scale application of foodomics towards more informed sustainability solutions.

1. Map quality of fermented foods: Apply foodomics to characterize the composition of diverse fermented foods, with a focus on foods from LMIC. Synthesize findings to identify biomolecular signatures of fermentation as well as identify key variables that drive shifts in food quality. Complement this knowledge with lifecycle analysis and greenhouse gas emissions to characterize sustainability attributes for identifying climate solutions.

2. Scale evidence on fermented food and health linkages : Apply foodomics in community-engaged nutrition interventions and clinical trials in diverse contexts to characterize the health attributes of fermented foods and associated biomarkers in human blood serum.

3. Translate knowledge for impact: Translate knowledge from point 1 and point 2 through training and other capacity-strengthening efforts including the creation and distribution of decision-making tools for more precise formulation of fermented foods. Use an equity lens to co-create knowledge assets to empower stakeholders for informing conservation and promotion efforts of fermented foods in ways that better support people and the planet.

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Acknowledgement

We are grateful for the support of The Periodic Table of Food Initiative (PTFI) by The Rockefeller Foundation, the Foundation for Food & Agriculture Research, Seerave Foundation, Fourfold Foundation, Atria Health Collaborative, and the Bill & Melinda Gates Foundation. The content presented here is solely the responsibility of the authors and does not necessarily represent the official views of the funders of the PTFI or the institutions with which the authors are affiliated.

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Leveraging Food Technology for Fermentation: A Driving Force in The Future of Food

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Key messages

- The cross-disciplinary integration of food engineering and biotechnology with fermentation bioprocesses has spurred an advanced biomanufacturing revolution.
- Of particular interest among fermentation-enabled edible biomaterials is the emerging field of alternative proteins.
- With the vast biological diversity of microbial species and their nearly infinite capacity for biological synthesis, fermentation-based methods hold the key to realizing and scaling up unique alternative protein solutions.
- The discovery of versatile strains capable of metabolizing sidestreams will be crucial to upcycling, value addition, and building a zero-waste bioeconomy model.
- In LMIC, solutions to protein diversification and food security could be achieved through the establishment of a self-reliant biomanufacturing and food processing industry producing novel proteins from fermentation.

The creation of novel bioproducts

Traditional fermentation practices in food preparation have been utilized for millennia to enhance the taste, flavor, texture and nutritional properties of foods such as milk, vegetables, fruits, cereals, bamboo and even meat.[1,2] Hundreds of species of microorganisms, including bacteria, yeast and algae, are now used in the food processing sector, with finely optimized bioprocesses that can improve nutrient digestibility and bioavailability, and lower antinutritional factors in various traditional protein sources.[2,3] Some examples of this are bread, wine, beer, kombucha, tempeh and fermented sausages. Over the past few decades, the cross-disciplinary integration of food engineering and biotechnology with fermentation bioprocesses has spurred an advanced biomanufacturing revolution, leading to the boom of large-scale food, beverage nutraceuticals, and bio-industrial sectors creating novel bioproducts that cater to the culinary industry. [4,5]

Of particular interest among fermentation-enabled edible biomaterials is the emerging field of alternative proteins (also known as smart proteins or sustainable proteins), which are animal-product alternatives produced from plants or animal cells (cultivated meat), or by way of fermentation.[6] Industrial animal agriculture practices account for up to 20 percent of all global greenhouse gas emissions, and as the demand for animal protein grows, alternative proteins are poised to become the climate-effective solution.[7] The production of alternative proteins requires fewer natural resource inputs, such as land and water, resulting in significantly lower emissions, preventing air pollution and water eutrophication.[7,8] Furthermore, alternative protein manufacturing does not require the use of antibiotics in livestock production, reducing the risk of antibiotic-resistant superbugs, antimicrobial resistance (AMR) and zoonotic disease outbreaks commonly associated with animal agriculture practices.[9] Food production revolutions via alternative proteins therefore promise to have a tremendously positive impact on climate and public health by enabling the shift away from the resource-intensive methods of current agricultural practices.

> **"Alternative proteins promise to have a tremendously positive impact on climate and public health"**

The technology for creating next-generation alternatives

In the broad spectrum of alternative proteins (from plant-based foods to cell-based meat produced in bioreactors), fermentation acts as the binding technology for creating next-generation alternatives to conventional animal protein.[10] Primary ingredients derived from fermentation, such as single-cell proteins, fats and flavoring agents, have the potential to create robust meat, dairy and egg alternatives with realistic sensory and functional attributes.[10] Additionally, being scalable and process-efficient, fermentation-enabled alternative proteins could be the answer to helping restore food production ecosystems and fulfill global dietary needs in the coming decades. Specifically, in the context of low- and middle-income countries (LMIC), establishing a self-sustaining food biomanufacturing sector would ensure food security, job creation and holistic local economic growth. Drawing parallels with the bioenergy/biofuels sector boom in emerging economies such as India and Brazil,[11,12] we expect to see a similar growth trend in fermentation-related food manufacturing over the coming decade. This article will dive deeper into such upcoming opportunities, with examples from LMIC that position biomanu facturing front and center to ensure food/nutritional security and 'clean-green-circular' economic growth.

Emerging trends in fermentation for sustainable future foods

Microbial fermentation has a long history in industrial and food biotechnology and has evolved far beyond its historical definition as a preservation technique or flavor modulator. With the vast biological diversity of microbial species and their nearly infinite capacity for biological synthesis, fermentation-based methods hold the key to realizing and scaling up unique alternative protein solutions.[4,13] Cutting-edge synthetic biology tools and fine-tuned bioprocesses have been applied to tailor the simple microbiological process of fermentation to manufacture ingredients and food products with better nutritional indices, functional properties and desirability.[14] A great example of this is 'biomass fermentation', whereby microorganisms such as bacteria, micro-/macroalgae, yeast and fungi are employed for the production of nutrient-rich, single-cell proteins and mycoproteins, offering high protein and micronutrient content for use as primary ingredients in plant-based meat substitutes and the nutritional fortification of foods.[15,16] For example, cultivated algal biomass (e.g., *Arthrospira platensis*) or filamentous fungi (e.g., QuornTM, *Fusarium venenatum*) are common biomass-derived ingredients with a rich nutritional profile (ideal PDCAAS, vitamins A, B, C, E and omega-3 fatty acid content, etc.) used in plant-based meat analogues and functional foods.[15,16]

> **"Fermentation-based methods hold the key to realizing and scaling up unique alternative protein solutions"**

Another example of biotechnological advancements applied in food technology is 'precision microbial fermentation', whereby microorganisms and their bioprocesses are precisely engineered and orchestrated to produce targeted functional molecules (specific proteins, enzymes, flavor molecules, pigments and fats).[17,18] Currently, precision fermentation (PF)-derived ingredients such as heme protein, lipids, milk proteins (casein and whey), enzymes, and even non-animal-sourced growth factors, vitamins, amino acids and fatty acids are manufactured for use in plant-based meat/dairy alternatives, and in cultivated meat products.[17,18] However, the production of purified ingredients from precision fermentation requires multiple processing steps (compared to primary protein ingredients derived from whole fermented biomass), consequently increasing manufacturing costs. With promising technical innovations in the sector (e.g., strain improvement for increased titer and downstream product recovery rates), there is progress being made to lower PF-ingredient costs; this could enable their widespread use in the biofortification of foods.[17,18]

Improving processes and adding value

Systems-biology-assimilated insights have helped uncover the immense biological diversity of microbial strains, such as ones with improved growth potential to support long-term continuous culture, enhanced nutritional characteristics and flavor profiles, or novel feedstock preferences.[19] Particularly, the discovery of versatile strains capable of metabolizing sidestreams will be crucial to upcycling, adding value and building a zero-waste bioeconomy model. For instance, commonly used feedstocks for fermentation are refined sugary substrates, which are unsustainable and expensive.[20] To break free from this paradigm, fermentation bioprocesses are innovating to utilize a wider range of inputs including agricultural residues / agro-industrial sidestreams (sugarcane trash / bagasse, brewer's spent grain, fruit and vegetable processing waste, soy meal / soy straw, barley straw/husks, canola meal), and even industrial off-gas feed such as methane, hydrogen and carbon dioxide (**Figure 1**).[20-22]

FIGURE 1: Cultivating alternative proteins from commodity crop sidestreams

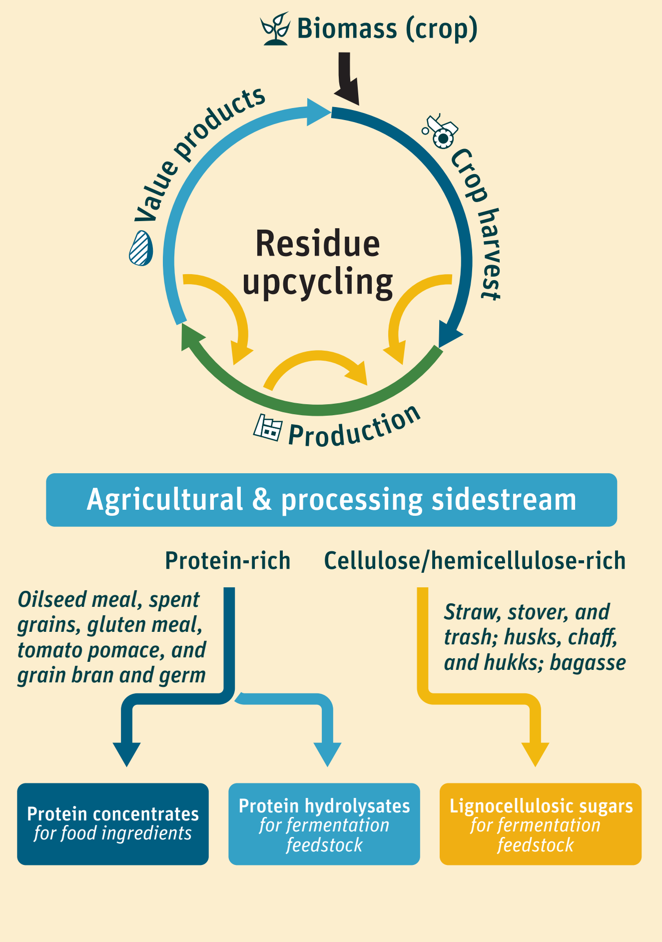

Figure adapted from 'Cultivating alternative proteins from commodity crop sidestreams' GFI report (October 2023)

Successful demonstration of waste valorization for value addition has been seen in the biorefinery industry, where second- and third-generation feedstocks are widely used to achieve zero-waste and a diversified product portfolio.[22] Similarly, microbial SCP production from biowaste and industrial sidestreams in the 'fermentation-for-food' scenario would increase the overall sustainability and economic feasibility of the process.[22] Solar Foods is one company that is demonstrating the power of waste valorization via gas fermentation by using a proprietary hydrogen-oxidizing bacterial strain to metabolize carbon dioxide and hydrogen from air to produce edible SCP (branded Solein®), containing 65– 75% protein, carbohydrates, lipids and micronutrients.[23] Therefore, tapping into AI and systems biology tools for strain discovery and custom design of microbial hosts with unique metabolic pathways that consume a wide range of feedstocks would unlock unlimited opportunities for cost-effective food production. Overall, such emerging techniques would widen the fermentation toolkit and its applications in the food and nutrition sector by helping formulate nutrient-dense and tastefully curated foods that resemble, or are better than, conventional animal protein.

> **"It is vital to harness local agricultural bioresources to the highest degree, reducing dependency on food imports and creating a self-sufficient value chain"**

Opportunities in biomanufacturing for LMIC

LMIC face several challenges in food and nutritional security. According to the World Health Organization (WHO), protein and micronutrient deficiency affects over 150 million children worldwide, primarily in LMIC. [24] Such a high prevalence of nutrition deficiency leads to severe malnourishment, with long-term health complications in children.[24] To combat such extreme cases of deficiency and fulfil local dietary needs, it is vital to harness local agricultural bioresources to the highest degree, thereby reducing dependency on food imports and creating a self-sufficient value chain.[25] Furthermore, long-term and larger-scale solutions to protein diversification and food security could be achieved through the establishment of a self-reliant biomanufacturing and food processing industry producing novel proteins (and other nutrients) from fermentation, with improved bioavailability and digestibility.[25] LMIC could also explore appropriate waste valorization of locally available agricultural and industrial sidestreams for fermentation feed to increase value addition and provide additional revenue generation for farmers.[20] As a result, a thriving biomanufacturing industry would lead to a self-sustaining growth ecosystem, with job creation across the value chain (from farming to direct employment opportunities in processing/production), fostering skilled talent generation to boost the region's capacity-building and overall economic development. Down the line, with sector maturity, public- and private-sector investments would further propel infrastructure, innovation and technology transfer, resulting in the establishment of a self-reliant model of economic growth.

Such revolutionary industrial manufacturing initiatives can only be driven by national-level policy frameworks. A demonstrable model of this is currently underway in India where the Ministry of Science & Technology, Government of India announced a national initiative on 'Fostering High-Performance Biomanufacturing: An Integrated Approach Towards Promoting Circular Economy for Green, Clean and Prosperous India' in July 2023.[26] As the Indian bioeconomy is expected to grow to $300 billion by 2030, the new policy highlights the critical role of biotechnology and fermentation-derived food solutions in driving economic growth sustainably.[27] Such national-level initiatives led by growing economic powers like India have the potential to become a successful case study for fermentation-derived protein solutions to alleviate malnutrition concerns and draw up a replicable model for stable bioeconomy growth that can holistically benefit LMIC and the Global South.

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Fermentation as a Climate Adaptation Strategy for Food Security in East Africa

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Key messages

- Biomass fermentation is uniquely powerful because it can generate large yields of protein 365 days per year, 24 hours per day and is a 'climate-proof' process.
- Sub-Saharan Africa and LMIC need a diversified portfolio of climate resilient protein-production solutions.
- At Essential, we have developed a novel scientific strategy to produce, a protein that is cost-competitive with soy through the conversion of agricultural byproducts.
- There is an opportunity to use fermentation to transform how we tackle malnutrition and food insecurity around the world.

Essential's low-cost, high-quality, fermentation-derived protein, dried and grinded into a flexible powder that can be integrated into a variety of products. *Photo credit: Essential*

Introduction

Essential is a new bioscience organization creating breakthrough solutions to tackle malnutrition and transform food systems in sub-Saharan Africa. We are leveraging advances in fermentation to create low-cost, high-quality, climate-resilient proteins that can be integrated into products to prevent and treat malnutrition. Fermentation is uniquely powerful because it can generate large yields of protein 365 days per year, 24 hours per day, irrespective of climatic shocks that often destroy agricultural yields and kill livestock.

The problem

Transformative action is needed to address the interrelated problems of malnutrition, food systems, and climate change. In 2022, 828 million people went hungry and roughly 200 million children suffered from stunting and wasting.[1] The lack of affordable, high-quality protein is a major contributing factor to malnutrition. Roughly one billion people lack access to high-quality proteins in their diets.[2] Recent global research demonstrates that approximately 30–40% of stunting is explained by a lack of high-quality protein.[3] Generating affordable, high-quality and resilient protein is a challenge for malnutrition amplified by climate change and extreme weather events.[4-6] Sub-Saharan Africa is particularly vulnerable to these forces given its lack of irrigation, which introduces broad and systemic exposure to climate.[7] Even if we had the solutions to the problems climate change poses, fragmented agricultural systems in sub-Saharan Africa make it challenging and cost-intensive to scale innovations.[8]

> **"Fermentation is a 'climate-proof' process"**


Left: Essential's biosciences facility is located in Mlolongo, just outside Nairobi County, with a team comprised of 13 members. Right: Essential's biomanufacturing process includes transfering the seed produced in this 20 L bioreactor into our 700 L bioreactor. *Photo credits: Essential*

The promise of fermentation

While investing in innovation in traditional agriculture is necessary, sub-Saharan Africa and low-and middle-income countries (LMIC) need a diversified portfolio of solutions to reduce risk and create protein production processes that are resilient to climate change. Fermentation is a 'climate-proof' process that allows microorganisms to convert agricultural byproduct into low-cost, high-quality proteins in an indoor manufacturing-like setup. Fermentation can be used to make high-quality protein even when climate shocks wipe out crop-growing areas and agricultural systems, therefore reducing the vulnerability to climate shocks and mitigating the dire health impacts these cause.

Fermentation is also promising because it makes use of agricultural byproduct that would otherwise be discarded, generating significant environmental benefits. Indeed, food waste and loss costs the global economy roughly US$1 trillion annually in GDP, is responsible for 8–10% of global greenhouse emissions, and accounts for 30% of all land use and its associated losses.[9] Lastly, fermentation can produce high-quality proteins – e.g., digestible proteins that have all the essential amino acids and have a protein digestibility corrected amino acid score (PDCAAS) of .85–95, outperforming many plant and animal proteins.[10]

> **"We are working to integrate our proteins into both humanitarian and commercial markets"**

Essential's strategy

While there has been significant scientific momentum in the alternative protein space in high-income countries, the underlying science in fermentation and biomanufacturing, coupled with additional R&D that we are conducting, provides unique leverage in tackling malnutrition. At Essential, we have developed a novel scientific strategy to bend the cost curve on fermentation and produce a protein that is cost-competitive with soy.

We have designed a biomass fermentation strategy that converts agricultural byproduct into a low-cost, high-quality protein. Whereas precision fermentation uses genetic engineering to modify microorganisms and traditional fermentation focuses on changing the flavor of functionality of ingredients, biomass fermentation leverages naturally occurring microorganisms to create protein-rich ingredients and foods.[11] After our fermentation process is complete, we harvest the protein, dry it, and grind it to have a shelf-stable powder that we can add into products as a fortificant.

We are working to integrate our proteins into both humanitarian and commercial markets. Given that proteins are the largest cost driver across all humanitarian food assistance, generating a low-cost replacement that maintains impact provides a path to reducing the costs of these products and expanding the budget to save more lives. Because 75% of undernourished women and children are not found in the lowest income quintile in sub-Saharan Africa, we are also integrating our proteins into commercial products.[12]

> **"Our north star is delivering cost-effective impact at scale and dramatically reducing malnutrition"**

Catalyzing a biomanufacturing revolution

Since launching in 2022, we have created the first biomanufactured protein in sub-Saharan Africa and designed new low-cost bioreactors and manufacturing processes to scale our approach cost-effectively. We have generated interest from institutional buyers and food companies. We have built a high-performing team, advisory network and board, as well as an operational footprint in East Africa. We are currently building a pilot plant in Kenya, where we will scale our benchtop science and deliver impact. Over the next five years, we will establish commercial-scale biomanufacturing in Kenya and will make enough protein to feed 3.4 million children under the age of five their daily protein requirement for US$2.46 per child per year. Our north star is delivering cost-effective impact at scale and dramatically reducing malnutrition. Our ambitions extend beyond our direct operations. We will create impact at scale by conducting groundbreaking research and catalyzing policy change in malnutrition and climate.

There is an opportunity to use fermentation to transform how we tackle malnutrition and food insecurity around the world. A 2019 report from RethinkX, an independent think tank, framed the precipice we are on: Around 10,000 years ago, humans figured out how to domesticate plants and animals to humanity's great success, and we are now on the forefront of figuring out how to domesticate microbes, hopefully to civilization's great success. It is crucial that we push forward this scientific frontier and use these new technologies to tackle the burning problems of malnutrition and food insecurity.

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Fermentation: The Importance of Maintaining Cultural Practices and Knowledge

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Over the last decade or so, fermentation has received a great deal of attention. Trend watchers in the media have repeatedly declared fermentation as one of the biggest new food trends. Chefs at many of the world's premier fine-dining restaurants have embraced the creative possibilities of fermentation; interest in probiotics and potential health benefits of fermented foods has rapidly grown; and consumers in many places have more fermented products to choose from than ever before. All this is true, yet in this framing of fermentation as a fad primarily accessible to the affluent, the most important facts about fermentation are lost.

The inevitability of microbial transformation

There is nothing new about fermentation. It is a force of nature that vastly preceded and enabled our evolution. People everywhere on Earth use fermentation, and have done so since prehistoric times, as one of the ways we make effective use of available food resources, whatever those may be. Fermentation is so widespread because there is a certain inevitability of microbial transformation of our food. Microbiology has illuminated the reality that all the plants and animal products that make up our food are inhabited by elaborate communities of microorganisms. Without specifically knowing this, people everywhere learned lessons, through observation and trial and error, about what conditions cause food to decompose or rot, versus the conditions that improve the food. All known fermentation processes were conceived and developed by generalists, long before our current biological understanding of the process, while producing and learning to preserve and use food.

Gimjang, the traditional practise of preparing Chonggak Kimchi (young radish kimchi) in South Korea.
Photo credit: Stock for you/Shutterstock.com

> **"There is nothing new about fermentation. It is a force of nature that vastly preceded and enabled our evolution"**

The benefits of fermentation

In every case, there are practical benefits of fermentation: it can create alcohol, by far the most widespread application of fermentation; it can preserve food and keep it safe, through the production of by-products such lactic acid, acetic acid, and alcohol; it can predigest food, unleashing the food's full nutritional potential by making nutrients more easily bioavailable, as well as producing a wide variety of metabolites, some beneficial, and huge biodiverse populations of potentially probiotic bacteria; it can make food more flavorful by breaking down macronutrients into amino acids, fatty acids, esters and other by-products with distinctive flavors; it can break down certain toxic or antinutrient compounds found in plants; it can reduce the need for cooking and fuel, as well as produce fuel; it can produce fibers and dyes; it can break down organic waste; and so much more.

The universality of fermentation

Fermented foods and beverages are prominent in the traditions of people in every part of the world. From tropical ferments of palm sap, cassava and cacao to Arctic ferments of fish, marine mammals and birds, fermentation is an important part of the picture everywhere. Every kind of food can be fermented in any number of ways. Generally, what people ferment is what is abundant, such as grains and beans; cabbages and radishes; seasonal fruit; and milk, meat and fish. The process of fermentation helps turn raw products of nature and agriculture into stable, nutritious and flavorful delicacies such as beer and wine; bread and cheese; kraut, olives, and pickles; soy sauce and fish sauce; salami and other cured meats; coffee, chocolate and vanilla; and far beyond. Fermentation figures in cultural traditions everywhere and is important in multiple ways:

> **"Fermented foods and beverages are prominent in the traditions of people in every part of the world"**

nutritionally, economically, and often symbolically as well. Fermentation is an essential part of how people everywhere live.

Personal experience with fermentation

I grew up in New York City eating fermented cucumbers, or 'sour pickles', as we knew them, which migrated to New York with my grandparents and waves of others from Eastern Europe. My gateway to practicing fermentation in the kitchen was sauerkraut, dry-salted shredded cabbage, which I have continued to make since, using not only cabbage. Every year, I harvest hundreds of pounds of daikon radishes from a friend's farm. We chop and shred the daikons, along with other radishes, cabbages and sometimes other vegetables, lightly salt them, and pack them tightly into vessels, pressing to keep the vegetables submerged under their juice as they ferment. This day of work yields many gallons of kraut, more than enough to eat and share all year.

I enjoy learning about and experimenting with different traditions of fermenting vegetables, a practice that is extremely widespread and varied. I have tried a diverse range of seasonings and supplemental ingredients: salt proportions and different kinds of salts or no salt, whole vegetables versus chopped versus stuffed, sun-drying as part of the process, various pickling mediums, and fermentation periods ranging from hours to years. There is no limit to the ways to ferment vegetables or anything else. The process offers many divergent possibilities; ultimately the only limitations are climate and environment, available ingredients, vessels, and most of all, our imaginations. Beyond vegetables, everything we eat can be fermented. Think of all the different ways people ferment milk or wheat!

Traditional practices under threat

Yet many traditional practices of fermentation have already disappeared from usage and memory, and they are at risk almost everywhere. Many people now accept that ancestral food traditions are irrelevant, as modern life constrains access to food sourcing from land and sea while cheap mass-produced food is widely available. These traditional food practices, including fermentation, are extraordinarily varied, and sometimes extremely localized. They have traditionally been carried out by women, as part of their families' subsistence livelihoods or small cottage production.

Safeguarding and promoting fermentation

Sadly, fermentation and related subsistence food practices are endangered due to the dwindling number of people carrying them on. When we consume supermarket food, some of it may be fermented, but one of the things that makes it distinct from earlier food is that its existence is a commodified mystery, no longer the result of visible community activity guided by inherited knowledge. This cultural knowledge is crucial not only for nutrition but also for economic production, food security, and food sovereignty. The cultures and people of any place are disempowered by the loss of fermentation wisdom and all the related cultural information concerning the production, preservation and use of food. Conversely, these practices' continued use and transmission empower all people, especially women – the traditional guardians of most fermentation knowledge. We must find ways to better value, safeguard, and promote this knowledge and these subsistence practices.

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Fermentation and Stewardship: Relationships of Tending

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Climate change is a global problem with collective and individual solutions. Building a connection to place is one way to promote stewardship on an individual level. Fermentation offers us a unique way to connect to place, not only by working with ingredients grown and gathered from the land but also through the lessons fermentation teaches us about stewardship itself.

Fermentation and ecological stewardship are both relationships of tending, or of ongoing, consistent care: Neither is a 'one and done' proposition; rather, they are acts of ongoing care. With both, you watch a place unfold and transform over time, whether that place is inside a jar or inside the fence of your backyard. Long, slow tending is foreign to many of our modern lives and offers benefits for mindfulness, reminding us that the pace of life is one we get to set. It's a reminder that when we engage in tending, we are tending to ourselves, too.

And while tending is often an act that reaps the rewards you hope for, whether a jar of sauerkraut or a native plant garden, sometimes it also yields surprises. As any fermenter knows, you can create the perfect environment for a ferment, but occasionally, the microbes simply do not want to play along with your plans!

> **"You watch a place unfold and transform over time, whether that place is inside a jar or inside the fence of your backyard"**

An act of continuing education

Fermentation is a reminder that real stewardship is a willingness to witness and support living beings in their own rich lives in a paradigm of reciprocity and care rather than control. It helps us view the surprises in the land we tend (think a surprise patch of invasive chaff flower) with curiosity rather than fear, which helps us then continue to tend more effectively and intentionally. When we are curious, we are willing to research more fully, listen more openly, and choose a path to address a problem from a more grounded, calm and intentional place. This kind of tending reminds us that, whether we are fermenting or gardening (or both), the act of tending is an act of continuing education, one where we are asked to learn and become better stewards as our knowledge continues to grow.

Finally, fermentation offers us lessons in resilience as stewards and as people. Beneficial microbes are everywhere and can be used to transform whatever food we have to help us make it more delicious, nutritious, and longer-lasting. Fermentation reminds us that even the smallest things can make a big change in their environments, but also that those small things can adapt to what is around them and have a hand in shaping them. For example, lactobacilli can take whatever vegetable you throw at them and transform it through their collective efforts.

We face challenges from a few sides in our efforts to engage in change. Challenges from climate change itself, and from the destructive actions of people, individually or collectively, whether it is your neighbor destroying a grove of trees or a city destroying a forest. How can we tap into the spirit of stewardship to meet these moments?

Some may require adaptability of the landscape itself, like choosing resilient, erosion-preventing plants that can thrive in the USDA's new planting zones and that support drainage during increased rainfall. Some may require collective action (like trying to get a ballot referendum against the city, as seen with Atlanta's Stop Cop City movement[1]), and some may require working with and meeting the communities we have rather than waiting until we are in a community that feels easy and like-minded. This can happen on a neighborhood scale (like planting fruit trees as part of an Edible Neighborhood[2] initiative), or larger (like funding climate-resilient jobs, as the US National Oceanic and Atmospheric Administration (NOAA) does with its Climate-Ready Workforce Initiative[3]).

Whether it's in a jar, our yard or beyond, by intentionally engaging in tending, we have a hand in the transformations taking place and can perhaps move them in the direction we would like to see: one that combines daily acts of tending and care on a small scale, with larger, collective efforts to support climate resilience.

> **"We face challenges from a few sides in our efforts to engage in change. Challenges from climate change itself, and from the destructive actions of people"**

Kraut-chi

Fermentation has long been an important craft for stretching food stores and sustaining our bodies in winter months. I love the modern incarnation of an ancient practice that Sandor Katz calls kraut-chi: basically, a sauerkraut made from whatever grated and shredded vegetables you have on hand. It is a magical way to transform stems and ends, that otherwise might be discarded, into something delicious and healthy.

Photo credit: Jacqueline Schlossman/READYLUCK

- To make kraut-chi, grate tougher fruits and veggies like beet, apple or carrot, as well as aromatics like ginger and onion. More delicate veggies, like green onion, can be sliced or chopped. Add to a bowl with 2-3% salt by weight, or 10-15g salt to 0.45 kg.
- Massage the salt into the veggies until they form a brine. When squeezed, they should release a stream of liquid. Check your brine's salt ratios by tasting. The brine should taste salty like the sea. If it isn't salty enough, massage in a bit more salt.
- Pack your kraut-chi into jars, pour over the remaining brine (if needed) to cover, and close the lid.
- Tend your kraut-chi each day by ensuring the ingredients stay under the brine, 'burping' your jars to release built-up pressure, and topping off with more brine if needed. Once your kraut-chi is as sour as you'd like, store it in the fridge.
- Kraut-chi is one small way to engage in acts of tending and using up food waste: a small act that's part of a larger effort towards climate resilience.

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Call to Action: Scaling Fermentation for Food Security and Climate Resilience

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The most innovative solutions are often not the most complicated ones. Many are hidden in plain sight, rooted in ancient traditions that intersect with modern science. Consider fermentation. This centuries-old practice has long provided humans with nutritious foods and beverages while preserving cultural heritage. Fermentation strengthens local food systems, contributes to climate resilience, and confers numerous health benefits, including improved gut health, metabolic regulation, and immune function.

Fermentation operates at the intersection of tradition and innovation, addressing today's most urgent challenges in nutrition and health. As this report has highlighted, fermentation holds immense potential for addressing food and nutrition security, particularly in LMIC but many questions remain. Chief among them: How do we capitalize on this knowledge and on what works? What is needed to bring existing solutions to scale, to keep innovating, and to achieve sustainable impact?

> **"How do we capitalize on this knowledge and on what works? What is needed to bring existing solutions to scale, to keep innovating, and to achieve sustainable impact?"**

Leveraging Fermentation for Change

Fermentation extends beyond health to address broader food systems and climate change challenges. By transforming agricultural byproducts into high-quality proteins and nutrient-dense foods, it tackles malnutrition while reducing food waste. (Fermentation as a Climate Adaptation Strategy for Food Security in East Africa). For example, in East Africa, fermented milk products improve dietary diversity and provide essential micronutrients to communities facing chronic undernutrition.

Women, often at the forefront of fermentation practices in LMIC, use these methods to sustain livelihoods and improve household nutrition. Small-scale fermentation enterprises, led by women, amplify their economic agency while delivering transformative impacts on local food security. Scaling these practices not only creates jobs, bolsters rural economies, and strengthens climate-adaptive food systems but also helps address essential dietary deficiencies like vitamins B and C (Fermentation: A Promising Approach for Enriching Food with Natural B Vitamins).

The interconnected challenges of malnutrition, unsustainable food systems, and climate change necessitate bold and transformative solutions. Fermentation offers a climate-resilient pathway forward. Unlike traditional agriculture, which is increasingly vulnerable to extreme weather events, fermentation thrives in controlled indoor environments, allowing for year-round production of high-quality proteins and nutrients. The success of fermented cassava products in West Africa, which extend shelf life and reduce post-harvest losses, demonstrates fermentation's power to turn local crops into sustainable food solutions.

The Path to Scale

To unlock the full potential of fermentation and ensure that food systems effectively adequately integrate indigenous and fermented foods, it is essential to drive change at the national and global levels. The following actions can pave the way for increased access to nutritious, culturally significant fermented foods while promoting sustainability and innovation, as highlighted in this Special Report.

1. Mainstream Indigenous and Fermented Foods into National Food Policies and Practices: Governments should prioritize the inclusion of indigenous diets and fermented foods in food systems policies and practices. This involves acknowledging their cultural significance, nutritional value, and potential for economic growth. Key actions include:

- Conduct a comprehensive national mapping of fermented foods—assessing their cultural importance, nutritional

value, and market potential to inform policy decisions and investment strategies.
- Review and update food safety protocols, labeling requirements, and market structures to support and standardize traditional fermentation industries.
- Strengthen support to small-scale producers to enhance food safety, scalability, and market reach through trainings, resources, and infrastructure improvements.
- Adopt novel fermentation approaches such as biomass fermentation for alternative protein production, precision fermentation, and waste valorization strategies.

2. Drive Consumer Behavior and Social Mobilization: Increasing the adoption of fermented foods requires both supply-side interventions and demand-side efforts to shift consumer preferences. Key actions include:
- Roll-out national and subnational consumer education campaigns that highlight the health benefits and cultural value of indigenous fermented foods through media, school curricula, and community outreach.
- Engage community leaders, influencers, and grassroots organizations to promote fermented foods as affordable, nutritious options that support local food systems.

3. Facilitate Global Coordination and Knowledge Sharing for Fermentation Advancement: On a global scale, the integration of indigenous and fermented foods into international food systems requires a robust, multilateral approach. This can enhance innovation, market access, and sustainability. Key actions include:
- Establish global knowledge-sharing networks that facilitate cross-border collaboration among governments, researchers, and private-sector players to share best practices, fermentation techniques, and emerging research.
- Build a dedicated platform (community of practice) for LMIC to share localized solutions, fermentation innovations, and policy experiences.

4. Invest in Long-Term Research and Evidence Building: Ongoing research is essential to unlock the full potential of fermentation and guide sustainable policy development. Key actions include:
- Expand research on the long-term health impacts of fermented food consumption, including effects on maternal and child health, gut microbiota, and chronic disease prevention.
- Analyze economic and environmental trade-offs including on the financial viability and ecological impact of scaling fermentation production across different contexts to inform sustainable scaling strategies.

All of these actions are necessary but just the tip of the iceberg in terms of what can be done.

A Collective Call

Fermentation is a game-changing solution to the global crises of malnutrition, food insecurity, and climate change. If scaled effectively, it can reduce food waste, lower greenhouse gas emissions, and provide sustainable nutrition for millions, especially in LMIC. However, this potential will only be realized through immediate, coordinated action across sectors.

To make this happen, we must embed fermentation in national food systems policies and practices, build a community of practice for LMIC, invest in infrastructure and training for small-scale producers, leverage global research and data, drive consumer adoption through targeted campaigns.

Now is the time to act. Governments, industry leaders, researchers, and grassroots organizations must unite to drive real change. Fermentation is not just an ancient practice—it is the future of food security, sustainability, and global health.

> **"Let's scale fermentation. Let's transform food systems. Let's build a healthier, more resilient world—starting today"**

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