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Fermented Millet Products: Exploring Nutritional and Health Potentials in African and Asian Cuisine-A Review

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ABSTRACT

This review delves into the expansive realm of fermented millet cuisines prevalent across African and Asian regions, elucidating their cultural significance, nutritional attributes, and prospective health advantages. Within African culinary traditions, staples such as Tô, Ogi, and Fura play pivotal roles, offering indispensable nutrients including protein, iron, and zinc, alongside fostering digestive health and bolstering immune function. Similarly, across Asian nations, an intricate tapestry of fermented millet delicacies emerges, ranging from Koozh in South India to Niandoubao in Northeast China, each with distinct flavors and potential health-enhancing properties. Moreover, beverages like Makgeolli from Korea and Amazake from Japan stand out, providing essential vitamins, minerals, and probiotics, thereby contributing to overall vitality and wellness. However, challenges such as the lack of standardized processing techniques, limited awareness of their benefits, and declining traditional knowledge pose significant barriers to maximizing their potential. Addressing these obstacles is essential to fully harness the nutritional and cultural value of fermented millet foods. Contributions made through this study include the synthesis of existing knowledge on the nutritional and health benefits of fermented millet cuisines, the documentation of their cultural significance, and the identification of pathways for enhancing their utilization in addressing global nutritional challenges. This review accentuates the profound significance of fermented millet dishes as indispensable components of cultural heritage, culinary diversity, and holistic well-being within both African and Asian societies.

Keywords: *Fermented millet products, Grains, African, Asian, Dietary, Food, Malnutrition, Anti-oxidant and Anti-inflammatory properties, Probiotics, Gut Health, Nutrition, Food Security*

1.0 Introduction

Millets, including sorghum, pearl millet, finger millets, and various small millet varieties, are highly adaptable to semi-arid climates and are predominantly cultivated in Asia and Africa. These grains are crucial for dryland farmers due to their resilience and high nutritional value. In Africa, which accounts for 59% of the global millet-growing area and 55% of its production, and Asia, contributing 38% of the area and 42% of production [1], sorghum and pearl millet dominate, with a combined 90% of the market share [2]. India leads in millet cultivation and production in Asia, while African countries like Sudan, Nigeria, Niger, Ethiopia, Mali, Burkina Faso, and Chad are significant producers, with sorghum and pearl millet making up 54% of global production. The importance of millets in maintaining food security in semi-arid regions is underscored by their adaptability and role in local diets. Exploring their nutritional benefits through technologies such as fermentation and malting is vital for improving food security and health outcomes.

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Fermentation, a traditional and cost-effective technology, enhances millet-based foods by improving their storage life, organoleptic properties, digestibility, and nutrient bioavailability [3]. It is also known for increasing the nutritional value by reducing antinutritional factors and enriching the products with probiotics, which support gut health and potentially reduce diarrhea and malnutrition in children [4]. Fermented millet products are associated with a lower risk of chronic diseases like cardiovascular diseases, type 2 diabetes, and certain cancers [5]. The process involves fostering beneficial microorganisms to metabolize sugars, producing lactate, ethanol, and acetate, which enhance food characteristics [6]. Both natural and controlled fermentation methods are used, with natural fermentation often practiced in households, while controlled methods are preferred in commercial settings for their consistency and safety [7, 8, 9]. Overall, fermentation significantly improves protein digestibility and nutritional quality while mitigating antinutritional factors, emphasizing the health benefits of fermented millet products [5]. The objective of this paper is to assess a variety of fermented millet products originating from various nations, analyzing their nutritional and nutraceutical advantages. Through an exploration of the wide range of culinary practices and scientific progressions related to millets, this review aims to enhance comprehension of their capacity to foster human health and overall well-being.

2.0 Introduction to Millets and their fermentation

2.1 Millets as Essential Grains in African and Asian Dietary Practices

Millets, a group of small-seeded grains including sorghum, pearl millet, and finger millets, hold a paramount position in the dietary practices of Africa and Asia [10]. These humble yet versatile grains have been sustaining populations across these regions for centuries, offering a plethora of nutritional benefits and playing a vital role in cultural and culinary traditions [11]. In both Africa and Asia, millets are cherished for their adaptability to harsh climatic conditions, particularly in semi-arid regions where other crops struggle to thrive [12]. Their ability to withstand drought and poor soil conditions makes them indispensable for ensuring food security in these areas. Moreover, millets require minimal water and inputs, making them a sustainable choice for resource-limited farmers. Beyond their resilience, millets boast impressive nutritional profiles, rich in essential nutrients such as proteins, dietary fibers, vitamins, and minerals [10]. They are particularly valued for their high content of micronutrients like iron and zinc, addressing prevalent deficiencies in these regions. Additionally, millets are gluten-free, making them suitable for individuals with gluten intolerance or celiac disease.

Culturally, millets hold deep-rooted significance in the daily lives and rituals of communities across Africa and Asia [11]. They are often featured prominently in traditional ceremonies, festivals, and religious rituals, symbolizing prosperity, fertility, and communal harmony. Moreover, millets are integral to the culinary heritage of these regions, serving as staple ingredients in a myriad of dishes ranging from savory porridges and flatbreads to fermented beverages and sweets. In African cuisine, millets are commonly used to prepare dishes such as injera in Ethiopia, couscous in North Africa, and tuwo in West Africa. Similarly, Asian culinary traditions feature millets in diverse recipes like roti in India, bajra khichdi in Rajasthan, and idli in South India. These culinary creations not only showcase the versatility of millets but also reflect the ingenuity and resourcefulness of local cooks in maximizing the nutritional potential of these grains.

Furthermore, millets play a crucial role in preserving biodiversity and traditional agricultural practices in Africa and Asia [12]. Many indigenous varieties of millets have been cultivated for generations, adapted to local climates and environmental conditions. By promoting the cultivation and consumption of these diverse millet varieties, communities can safeguard agricultural biodiversity and maintain ecological resilience in the face of climate change. In conclusion, millets represent more than just a staple food source in African and Asian dietary practices. They embody resilience, nutritional richness, cultural heritage, and ecological sustainability [10]. As global attention increasingly turns towards sustainable and nutritious food systems, millets stand out as a shining example of how traditional grains can offer holistic solutions to complex challenges. Embracing and revitalizing the role of millets in modern diets can not only promote human health and well-being but also foster socio-cultural resilience and environmental sustainability for generations to come.

2.2 The significance of fermented millet products in addressing nutritional needs and food security challenges

Fermented millet products have significant potential to address nutritional needs and food security challenges in Africa and Asia. Derived from millets like sorghum, pearl millet, and finger millet, these products undergo fermentation processes that enhance their nutritional value by improving the bioavailability of essential nutrients such as proteins, vitamins, and minerals, which is crucial in regions plagued by malnutrition and dietary deficiencies. Fermentation also reduces the levels of anti-nutritional factors in millets, making these products more beneficial for overall health [5]. Additionally, the longer shelf life of fermented millet products compared to non-fermented counterparts enhances food security by providing a stable food source throughout the year, particularly in communities with limited access to fresh produce [4]. Moreover, fermentation promotes the utilization of locally available resources and traditional knowledge, fostering self-reliance and sustainability in food production systems [7]. By leveraging natural fermentation processes and local microbial communities, communities can produce nutritious millet products using simple and cost-effective methods. Thus, fermented millet products offer a promising solution for improving health outcomes and food availability in resource-constrained settings.

2.3 Traditional millet Fermentation Techniques employed in African and Asian Societies

Traditional millet fermentation methods in African and Asian societies represent a rich tapestry of techniques passed down through generations, reflecting the cultural diversity and ingenuity of these regions. These methods, which vary according to local customs, available resources, and environmental conditions, all aim to enhance the flavor, texture, and nutritional value of millet-based foods. A prevalent method is spontaneous or natural fermentation, which relies on indigenous microorganisms in the environment to initiate the process. Millet grains are soaked, ground, and left to ferment under ambient conditions, allowing wild yeasts and lactic acid bacteria to proliferate and convert sugars into organic acids and alcohols, producing distinctive flavors and aromas [13]. Another common technique is back-slopping, where a portion of a previous successful fermentation batch is used to inoculate a new batch, ensuring the transfer of beneficial microorganisms and consistency in the fermentation process, particularly in households and small-scale production [13]. In addition to these traditional methods, controlled fermentation is also employed, especially in commercial settings, involving the deliberate inoculation of millet with specific starter cultures containing selected strains of bacteria or yeasts, which allows for greater control over the fermentation process and results in more consistent product quality [8]. Across Africa and Asia, fermented millet products, such as the sour porridge of West Africa, the tangy fermented beverages of East Africa, and the savory flatbreads of South Asia, are integral to culinary traditions and dietary practices. Preserving these traditional fermentation methods enables communities to continue producing nourishing and flavorful millet-based foods for generations to come, celebrating their cultural heritage and nutritional wisdom.

2.4 Factors influencing fermentation processes across various millet products

Various factors influence fermentation processes across different millet products in Africa and Asia, reflecting the intricate interplay of cultural traditions, environmental conditions, and technological practices. Environmental factors such as temperature, humidity, and altitude play a crucial role in shaping fermentation kinetics and microbial activity [14].

Microbial diversity, influenced by the type of millet, fermentation method, and environment, contributes to the development of unique flavors and aromas in fermented millet products [15]. Fermentation time and duration are also significant, impacting factors such as acidity, flavor development, and the breakdown of complex compounds [16]. The choice of fermentation vessels and equipment, ranging from traditional clay pots to modern fermenters, affects fermentation parameters such as temperature control and microbial interactions [14]. Pre-processing techniques like soaking, milling, and cooking alter the physical and chemical properties of millet grains, influencing microbial growth and fermentation outcomes [16]. Moreover, indigenous knowledge and traditional practices passed down through generations play a crucial role in shaping fermentation processes, reflecting cultural preferences and dietary habits [15]. These factors collectively contribute to the diversity and richness of fermented millet products across Africa and Asia, highlighting the complex yet fascinating nature of millet fermentation.

3.0 Nutritional Composition of Millets

3.1 Macronutrient and micronutrient compositions millets

Sorghum, pearl millet, finger millets, and other small millet types offer a diverse array of macronutrients and micronutrients essential for human health. Sorghum, primarily composed of carbohydrates, also contains moderate levels of protein and dietary fiber, along with micronutrients such as iron, magnesium, phosphorus, and B vitamins, making it a nutritious staple [17]. Similarly, pearl millet shares a similar macronutrient profile with sorghum but is particularly rich in iron, zinc, magnesium, and calcium, as well as B vitamins like niacin and riboflavin [5]. Finger millets stand out for their higher protein and dietary fiber content, making them valuable sources of plant-based protein and essential amino acids. They are also rich in minerals like calcium and iron, along with B vitamins such as thiamine and riboflavin [5]. Other small millet types including foxtail millet, proso millet, barnyard millet, and kodo millet, share similar nutritional profiles with sorghum and pearl millet, providing carbohydrates, protein, dietary fiber, and essential micronutrients necessary for a balanced diet Overall, these millet varieties play a crucial role in addressing nutritional needs and contributing to food security in Africa and Asia.

3.2 Comparison of the nutritional contents between fermented and unfermented millet products

The comparison of nutritional contents between fermented and unfermented millet products reveals significant differences in composition and nutrient bioavailability, with fermentation generally enhancing certain vitamins, minerals, and bioactive compounds. Fermentation increases the bioavailability of minerals like iron and zinc by reducing antinutritional factors such as phytates, which is particularly beneficial for populations at risk of micronutrient deficiencies [18]. It also boosts the content of B vitamins (e.g., thiamine, riboflavin, niacin) and vitamin K through the activity of fermentative microorganisms, which are essential for energy metabolism, nerve function, and blood clotting [19]. Additionally, fermentation synthesizes bioactive compounds like antioxidants, phytochemicals, and probiotics, which contribute to reducing inflammation, improving gut health, and enhancing immune function [20]. However, some nutrient losses can occur during fermentation, particularly with water-soluble vitamins like vitamin C, which may degrade due to acidic conditions or enzymatic activity [21]. The specific nutritional impact of fermentation varies based on factors like fermentation duration, microbial activity, and processing techniques, making it important to optimize these variables to maximize the nutritional quality and health benefits of fermented millet products.

3.3 The impact of millet fermentation on nutrient availability and digestibility

Fermented millet products exert a considerable impact on nutrient availability and digestibility owing to the transformative effects of the fermentation process. Primarily, fermentation mitigates antinutritional factors such as phytates, enhancing the bioavailability of essential minerals like iron, zinc, and calcium, which are crucial for overall health [22]. Furthermore, fermentation enhances the digestibility of proteins by breaking down complex protein structures into smaller peptides and amino acids, thereby improving protein utilization by the body [23]. Additionally, the fermentation process stimulates the synthesis of B vitamins such as thiamine, riboflavin, and niacin by fermentative microorganisms, contributing to improved nutritional value [21]. Moreover, fermentation fosters the formation of bioactive compounds, including antioxidants and probiotics, which offer potential health benefits such as reducing inflammation, enhancing gut health, and bolstering immune function [24]. Overall, fermented millet products play a pivotal role in enhancing nutrient availability and digestibility, thereby promoting overall health and well-being.

3.4 Potential of fermented millet products in combating malnutrition and addressing micronutrient deficiencies

In Africa and Asia, where malnutrition and micronutrient deficiencies are prevalent, fermented millet products offer a promising solution to these public health challenges by improving nutritional status and addressing hidden hunger. Millet, a staple crop in these regions, is nutritionally resilient and adaptable to diverse agroecological conditions. Fermentation of millet reduces antinutritional factors like phytates and tannins, thereby enhancing the bioavailability of essential minerals such as iron and zinc, which are crucial for combating iron deficiency anemia and other micronutrient deficiencies [22]. Additionally, fermented millet products are rich in protein, B vitamins, and bioactive compounds essential for optimal health, particularly in areas where diets lack sufficient protein and B vitamins. Fermentation improves protein digestibility and utilization by breaking down proteins into smaller peptides and amino acids [23], while also enhancing the synthesis of B vitamins like thiamine, riboflavin, and niacin, which are vital for energy metabolism and nerve function [21]. Furthermore, fermentation generates bioactive compounds, including antioxidants and probiotics, which support overall well-being by protecting against oxidative stress, and inflammation, and promoting gut health and immune function [24]. Thus, incorporating fermented millet products into diets in these regions offers a sustainable and culturally appropriate means of improving nutritional status and health outcomes.

4.0 Probiotic Content and Gut Health

Probiotics are live microorganisms that confer health benefits when consumed in adequate amounts [25]. These beneficial bacteria, often found in fermented foods and dietary supplements, play a crucial role in maintaining gut health and overall well-being.

By colonizing the gastrointestinal tract, probiotics help balance the gut microbiota, promoting a diverse and harmonious microbial community [26]. This balance is essential for proper digestion, nutrient absorption, and immune function. Probiotics also contribute to gut health by producing short-chain fatty acids, vitamins, and other bioactive compounds that nourish intestinal cells and inhibit the growth of harmful bacteria. [26]. Additionally, probiotics have been associated with various health benefits, including improved digestion, reduced inflammation, enhanced immune response, and even mental well-being. Incorporating probiotic-rich foods such as yogurt, kefir, kimchi, and sauerkraut into your diet can support gut health and contribute to overall vitality.

4.1 Probiotic content in fermented millet products and their influence on gut flora

Fermented millet products can serve as excellent sources of probiotics, contributing to the maintenance of a healthy gut flora. During the fermentation process, millet grains undergo microbial transformation by beneficial bacteria and yeasts, leading to the production of probiotics. These probiotics, such as *Lactobacillus* and *Bifidobacterium* species, are known for their ability to colonize the gut and confer health benefits.

Several studies have demonstrated the presence of probiotic bacteria in fermented millet products. For example, research has identified various *Lactobacillus* strains, including Lactobacillus plantarum, *Lactobacillus fermentum*, and *Lactobacillus brevis*, in fermented millet-based foods [27]. These probiotic bacteria play essential roles in promoting gut health by modulating the composition of the gut microbiota, enhancing immune function, and improving digestive processes.

Consuming fermented millet products rich in probiotics can positively influence gut flora composition and diversity. Probiotics help restore microbial balance in the gut by inhibiting the growth of pathogenic bacteria and promoting the proliferation of beneficial bacteria. This balance is crucial for maintaining gut health and preventing gastrointestinal disorders such as diarrhea, constipation, and irritable bowel syndrome. Furthermore, probiotics present in fermented millet products produce metabolites such as short-chain fatty acids, vitamins, and antimicrobial compounds, which contribute to gut health and overall well-being [28]. Short-chain fatty acids, for instance, serve as an energy source for intestinal cells and help regulate immune responses in the gut. By incorporating these probiotic-rich foods into the diet, individuals can support digestive health, enhance immune function, and promote overall well-being.

4.2 The relationship between fermented millet consumption and gastrointestinal health

The consumption of fermented millet products positively impacts gastrointestinal health through several mechanisms, including enhanced digestion, regulation of bowel movements, and modulation of gut microbiota composition. These products contain probiotics like *Lactobacillus* and *Bifidobacterium*, which promote the growth of beneficial gut bacteria while inhibiting harmful pathogens, thereby supporting optimal gastrointestinal function and improved nutrient absorption [28]. Rich in dietary fiber, fermented millet also acts as a prebiotic, stimulating beneficial bacteria and aiding in regular bowel movements, which prevents constipation and promotes digestive health [29].

The fermentation process further enhances millet's digestibility and nutrient bioavailability, reducing gastrointestinal discomfort and improving nutrient absorption [23]. Additionally, fermented millet products contain bioactive compounds, including short-chain fatty acids, vitamins, and antioxidants, which support gut health by maintaining intestinal barrier integrity, reducing inflammation, and mitigating oxidative stress in the gut [28]. Incorporating these products into a balanced diet can significantly contribute to optimal gastrointestinal function and long-term health.

5.0 Antioxidant and Anti-inflammatory Properties

Fermented millet products offer antioxidant and anti-inflammatory properties that contribute to their potential health benefits. By incorporating these products into the diet, individuals can support their overall well-being and reduce the risk of chronic diseases associated with oxidative stress and inflammation.

5.1 The antioxidant compounds and anti-inflammatory characteristics found in fermented millet products

Fermented millet products are rich in antioxidant compounds and exhibit anti-inflammatory characteristics, enhancing their potential health benefits. The fermentation process boosts the bioavailability and activity of these bioactive compounds, which play crucial roles in combating oxidative stress and inflammation. Fermented millet products contain phenolic compounds, such as phenolic acids and flavonoids, which scavenge free radicals and reduce oxidative damage, with fermentation increasing their concentration and antioxidant capacity [30]. Additionally, fermentation can elevate levels of antioxidant vitamins, including vitamin C and vitamin E, which protect cells from oxidative damage and support overall health [31]. Furthermore, fermented millet products produce bioactive peptides—short chains of amino acids with antioxidant and anti-inflammatory properties—that inhibit pro-inflammatory molecules and reduce inflammation [32]. The fermentation process also generates short-chain fatty acids (SCFAs), such as butyrate, propionate, and acetate, which have anti-inflammatory effects and promote gut health [33]. By incorporating fermented millet products into the diet, individuals can benefit from their rich antioxidant content, vitamins, bioactive peptides, and SCFAs, supporting overall well-being and reducing the risk of chronic diseases related to oxidative stress and inflammation.

5.2 The potential role of fermented millet products in reducing the risk of chronic diseases

Fermented millet products have the potential to reduce the risk of chronic diseases due to their antioxidant activity, anti-inflammatory properties, promotion of gut health, and nutrient density. These products contain antioxidant compounds like phenolics, flavonoids, and vitamins, which help neutralize free radicals and reduce oxidative stress, a contributor to chronic diseases such as cardiovascular disease, cancer, and neurodegenerative disorders [30]. Additionally, the presence of bioactive compounds like peptides and short-chain fatty acids provides anti-inflammatory benefits by modulating inflammatory pathways, thus helping to lower the risk of conditions like arthritis, diabetes, and inflammatory bowel diseases [32, 33]. Fermented millet products also support gut health by promoting beneficial gut bacteria and maintaining a diverse microbial ecosystem, with probiotics like Lactobacillus and Bifidobacterium enhancing immune function, nutrient absorption, and reducing gastrointestinal inflammation, thereby lowering the risk of obesity, diabetes, and cardiovascular disease [28]. Furthermore, these products are rich in essential nutrients, including vitamins, minerals, and dietary fiber, which are crucial for overall health and disease prevention, supporting functions like immune health, bone health, and metabolism, and helping to prevent nutrient deficiencies and related chronic diseases [23].

6.0 Functional Properties of Fermented Millets

Fermented millets exhibit a range of functional properties that make them valuable ingredients in the food industry and beneficial additions to the diet. From enhanced nutrient bioavailability to improved digestibility and probiotic effects, fermented millets offer numerous advantages for consumers seeking nutritious, flavorful, and health-promoting foods.

6.1 Functional attributes observed in fermented millet products

Fermentation significantly alters the texture, flavor, and aroma of millet products, enhancing their overall sensory appeal and consumer satisfaction. The process can make millet grains softer and easier to chew, while improving the elasticity and crumb structure of doughs used in bread and pastries, resulting in more tender and aerated products [23]. Fermentation also imparts unique flavors to millet products, characterized by tanginess and depth, due to the production of organic acids like lactic and acetic acid, as well as other flavor compounds generated through microbial metabolism [34]. These compounds contribute to rich, savory, or umami flavors, while the fermentation process also produces distinctive aromas with fruity, floral, earthy, or nutty notes depending on the microbial strains involved [28]. Beyond these sensory enhancements, fermentation helps preserve traditional flavors and culinary heritage associated with millet-based foods, maintaining cultural authenticity and offering consumers a connection to age-old culinary traditions [34].

6.2 Utilization of fermented millet ingredients in the development of food products

Fermented millet products offer numerous opportunities to enhance nutritional value, sensory properties, and health benefits across a wide range of food formulations. These ingredients can be used in baking to improve the nutritional profile and sensory attributes of baked goods such as bread, cakes, and pastries, especially when blended with other flours. Fermentation enhances digestibility and nutrient bioavailability, making millet particularly valuable in gluten-free baking [23]. Additionally, fermented millet is key in traditional beverages like millet beer and non-alcoholic drinks, contributing to their tangy flavor and probiotic content, which supports gut health and immune function [34]. Fermented millet is also used in snack foods, adding nutritional content and flavor, and in traditional fermented foods like idli, dosa, and injera, where it improves texture and digestibility. Furthermore, it can be utilized in dairy-free alternatives like yogurt and cheese, offering lactose-intolerant consumers nutritious and tasty options [23, 34]. Overall, fermented millet ingredients are versatile, contributing to the development of innovative and culturally relevant food products.

7.0 Cultural Significance and Culinary Traditions

7.1 Cultural importance of fermented millet products in African and Asian culinary traditions

African and Asian culinary traditions have a rich cultural significance deeply intertwined with the consumption of millets [23, 35]. Millets, serving as staple crops for millennia, have been integral to the dietary habits and cultural practices of diverse communities across both regions. Dating back to ancient civilizations, such as those in Mesopotamia, the Nile Valley, and the Indus Valley, millets have played a crucial role in shaping culinary heritage and dietary diversity [23]. Cultivated in varied agro-ecological zones, millets offer resilience and nutritional value, making them essential components of traditional diets in Africa and Asia [23, 35]. Utilized in a myriad of culinary preparations, including porridges, flatbreads, fermented foods, beverages, snacks, and desserts, millets reflect local tastes, customs, and food preferences [23, 35]. Moreover, millets hold significance in cultural rituals, ceremonies, and celebrations, symbolizing fertility, prosperity, and abundance; [23, 35]. They are often used in religious offerings, wedding feasts, and harvest festivals, fostering a sense of unity and shared heritage. Additionally, millets contribute to sustainable agriculture, supporting smallholder farmers, promoting resilience to climate change, and enhancing soil health [23]. Overall, millets play a multifaceted role in African and Asian societies, serving as symbols of heritage, identity, and resilience while contributing to dietary diversity, culinary creativity, and sustainable livelihoods.

8.0 Traditional fermented millet dishes from diverse regions

Traditional fermentation practices and recipes involving millet are deeply rooted in the culinary traditions of various regions in Africa and Asia. These practices not only enhance the flavor and texture of millet-based foods but also contribute to their cultural significance nutritional value and health benefits.

These three tables offer insights into the diversity, nutritional properties, and health benefits of fermented millet dishes across African and Asian countries. Table 1 outlines a variety of fermented millet dishes found in African countries, showcasing their cultural significance and culinary diversity. From porridges like Tô and Ogi to beverages like Mahewu and Chicha, these dishes play vital roles in African cuisine, offering both sustenance and tradition. Table 2 delves into the nutritional properties and health benefits of select African fermented millet dishes. These dishes, such as Ogi and Ben Saalga, are rich sources of essential nutrients like protein, iron, and zinc, contributing to overall health and well-being. Additionally, they may aid in digestion, support immune function, and prevent conditions like anemia. Table 3 explores fermented millet dishes from various Asian countries, highlighting their unique flavors and potential health benefits. From Koozh in South India to Niandoubao in Northeast China, these dishes offer a range of nutritional advantages, including probiotic potential, immune system support, and improved gut health. Additionally, beverages like Makgeolli from Korea and Amazake from Japan provide essential vitamins, minerals, and enzymes, promoting overall vitality and wellness.

Table 1 Different fermented millet dishes in African countries

Dish Name	Country/Region	Description
Tô	West Africa	Fermented millet or sorghum porridge, a staple in West African cuisine [36,37].
Ogriɔ	Ghana	Common Ghanaian breakfast: fermented millet porridge often served sweetened [36].
Mawe	Kenya	Luo community's fermented millet porridge, popular for breakfast or snack [38].
Ogi	Nigeria	Nigerian breakfast dish: fermented maize, sorghum, or millet pudding
Mahewu	Southern Africa	Fermented maize or millet drink, popular in Southern Africa [39].
Uji	East Africa	Porridge made from fermented grains like millet, sorghum, or maize [39].
Bouille	Senegal	Senegalese breakfast porridge: fermented millet or sorghum, often sweetened [39].
Couscous	North Africa	North African staple dish, sometimes made from millet among certain communities [36].
Masa	Nigeria/Niger	Popular Northern Nigerian and Nigerien snack: fermented rice or millet pancake [37].
Oshikundu	Namibia	Ovambo people's fermented millet porridge, a Namibian staple [36].
Thobwa	Malawi	Malawian beverage: fermented millet or sorghum, often sweetened [39].
Kenkey	Ghana	Ghanaian fermented maize dish, sometimes prepared with millet [36].
Garri	Nigeria/West Africa	West African food made from fermented cassava, sometimes including millet [36].
Gowe	Ethiopia	Ethiopian fermented drink made from millet or other grains [39].
Kishk	Egypt	Egyptian fermented dish made from bulgur or wheat, sometimes substituted with millet [36].
Koko	Ghana	Ghanaian fermented millet porridge, often served for breakfast [36].
Tchap	Cameroon	Cameroonian fermented sorghum or millet dish [36].
Chicha	Ethiopia	Ethiopian fermented beverage made from millet or barley [36].
Muratina	Kenya	Kenyan fermented beverage made from millet, honey, and yeast, consumed during celebrations [36].
Kamutefu	Democratic Republic of Congo	Congolese fermented millet bread served with soups or stews [36].
Ben Saalga	Burkina Faso	Traditional Burkinabé fermented millet drink, often enjoyed during social gatherings and ceremonies.
Fura	Nigeria/West Africa	Nigerian/West African millet balls often consumed as a snack or street food.
Ting	Burkina Faso	Traditional fermented millet drink consumed in Burkina Faso, particularly during celebrations and social gatherings.
Dengue	Burkina Faso	Another name for Ting, a traditional fermented millet drink popular in Burkina Faso.

Table 2 Nutritional and health benefits of some African dishes made from fermented millets

Dish Name	Nutritional Properties	Health Benefits	References
Ogi	Moisture: 5.50-9.00 g/100g, Crude protein: 4.12-12.6 g/100g, Crude fat: 0.65-2.49 g/100g, Crude fiber: 0.25-3.34 g/100g, Ash: 0.44-2.97 g/100g, Carbohydrates: 21.63-81 g/100g, Ca: 7.96-1414.09 mg/100g, Mg: 11.71-325.7 mg/100g, P: 48.10-915.30 mg/100g, Na: 2.54-2.98 mg/100g, K: 2.32-290.02 mg/100g, Fe: 5.58-97.91 mg/100g, Cu: 0.40-21.6 mg/100g, Zn: 1.91-28.39 mg/100g, Mn: 0.55-0.65 mg/100g, Phytates: 0.18, Tannin: 0.13.	Meets nutritional requirements, aids in digestion, and provides essential minerals and vitamins.	[40, 41]
Ben Saalga	Crude protein: 8.22 g/100g, Crude fat: 0.69 g/100g, Crude fiber: 2.14 g/100g, Ash: 1.41 g/100g, Fe: 8.33 mg/100g, Zn: 2.05 mg/100g.	Provides protein, iron, and zinc, aids in growth and development, may help prevent anemia.	[42]
Koko	Crude protein: 2.44 g/100g, Crude fat: 2.06 g/100g, Crude fiber: 0.27 g/100g, Ash: 0.44 g/100g, Moisture: 57.71 g/100g, Carbohydrates: 36.78 g/100g, Phosphorus: 1.20 mg/100g, Calcium: 4.80 mg/100g, Magnesium: 52.13 mg/100g, Potassium: 84.61 mg/100g, Sodium: 3.20 mg/100g, Iron: 5.27 mg/100g, Zinc: 0.36 mg/100g, Niacin: 2.27 mg/100g, Riboflavin: 0.15 mg/100g, Thiamin: 0.10 mg/100g, Tocopherol: 5.63 mg/100g, Ascorbic acid: 7.23 mg/100g.	Provides energy, supports bone health, and boosts immune system.	[43,24]
Fura	Crude protein: 9.18 g/100g, Crude fat: 3.45 g/100g, Moisture: 7.3 g/100g, Ash: 1.87 g/100g, Crude fiber: 2.35 g/100g, Carbohydrates: 75.67 g/100g, Calcium: 1.61 mg/100g, Iron: 3.45 mg/100g, Phosphorus: 7.30 mg/100g.	Rich in protein, carbohydrates, and essential minerals, supports energy production and muscle function.	[44, 45]
Ting	Not evaluated.	Provides energy, aids in hydration.	[46]
Dengue	Moisture: 46.34%, Protein: 6.12%, Crude fat: 3.00%, Ash: 1.06%, Carbohydrates: 43.48%.	Hydrating, provides protein and energy, may support immune function.	[47]
Gowe	Crude protein: 11.1%, Crude fat: 1.1%, Crude fibers: 1.3%, Ash: 2.0%, Tannins: 0.05%, Phytate: 0.2%, Total cyanide: 12.5%.	Rich in protein and fiber, supports digestive health.	[48]

Table 3 Nutritional and health benefits of fermented millet dishes from Asia

Dish Name	Description	Nutritional & Health Benefits	References
Koozh	Fermented millet porridge consumed in South India. Can be thick or thin consistency, served with buttermilk. Commonly consumed by weaning babies, the elderly, and the sick.	Crude protein: 17.02 mg/g, Carbohydrates: 61.52 mg/g, Free amino acids: 12.46 mg/g, Calcium: 38.2 mg/g, Potassium: 36.46 mg/g, Phosphorus: 17.4 mg/g, Total phenol: 0.46 mg/g, Total flavonoid: 0.26 mg/g. Immunity boosting, probiotic potential, improves gut health.	[49]
Rababi/Kharode	Traditional fermented millet and buttermilk-based food in Western India. Rich in minerals, low in anti-nutrients.	Moisture: 7.32-7.65%, Protein: 13.25-13.56%, Crude fat: 3.62-3.67%, Ash: 4.03-4.25%, Crude fiber: 1.83-1.98%.	[50]
Ambali	Thick batter prepared by fermenting ragi millet flour in Karnataka, India. Consumed with yoghurt or curd. High in dietary fibre, aids in weight loss, promotes gut health.	Moisture: 91.5%, Crude protein: 1%, Crude fat: 0.32%, Ash: 1.22%, Carbohydrates: 3.42%, Calcium: 58mg, Sodium: 23mg, Potassium: 06mg.	[51, 52]
Bibdya	Staple of Northern Maharashtra, India. Made from fermented sorghum paste with spices. Cooked by roasting method. Rich in energy, protein, vitamins, minerals, and phytochemicals.	Crude fibre: 2.1%, Ash: 1.6%, Carbohydrates: 72.6%, Amylose: 21.2%, Energy: 349 kcal/100 g.	[51]
Kharodya	Made of fermented pearl millet in India. Fermented in buttermilk, cooked in boiling water, seasoned with salt and sesame seeds. Sundried to make snacks.	--	[51]
Niandoubao	Fermented proso millet bread from Northeast China. Hand-shaped and steamed. Rich in starch, with probiotic effects.	Starch: 55.01-71.59 mg/g. Probiotic properties, antagonistic effect against E. coli, starch metabolism enhancement.	[53]
Makgeolli	Korean traditional rice wine, sometimes made with millet. Milky, sweet, and tangy flavor. Contains probiotics, vitamins, and minerals.	--	[54]
Amazake	Traditional Japanese sweet, non-alcoholic beverage made from fermented rice or millet. Rich in vitamins, minerals, and enzymes. Known for its high nutritional value and energizing properties.	--	[55]
Laozao	Traditional Chinese fermented rice or millet wine. Contains probiotics and antioxidants. Consumed for its potential health benefits including improved digestion and immune function.	--	[56]
Jiu Niang	Chinese fermented glutinous rice or millet porridge. Sweet, slightly alcoholic, and aromatic. Contains beneficial bacteria and enzymes. Consumed for its digestive health benefits.	--	[57]
Millet Wine	Traditional alcoholic beverage in Taiwan made from fermented millet. Rich in antioxidants and potentially probiotic. Consumed for its unique flavor and potential health benefits.	--	[58]

9.0 Geographical distribution of fermented millet products across Africa and Asia

Fig. 1 and 2 illustrate the geographical distribution of fermented millet products across Africa and Asia, respectively. Fig. 1, represents the variety and spread of traditional fermented millet products in African countries. Notable examples include Nigeria's Ogi, Ghana's Koko, and Kenya's Uji. These products are integral to the local diets and cultural practices, showcasing the diverse culinary heritage within the continent. Fig. 2 presents a similar overview for Asia, highlighting countries known for their unique fermented millet products. This map emphasizes the importance of millet as a staple grain in China, India, Korea and Japan's culinary traditions. Together, these figures underscore the significance of fermented millet products in continents, reflecting regional dietary preferences, agricultural practices, and cultural traditions. These maps serve as a visual representation of the global culinary diversity rooted in fermented millet.

The dataset on the number of publications related to the functional properties of millets and millet products from 2000 to 2024 (Fig. 3) reveals a significant upward trend in research activity. Starting with just 20 publications in 2000, the early 2000s showed modest numbers, gradually increasing to 46 by 2004. A notable rise began around 2011, with publications growing from 109 to 216 by 2015, reflecting increased interest in this area. This upward trajectory continued through 2020, where the number of publications reached 432. The most dramatic increase occurred between 2021 and 2023, with publications jumping from 619 in 2021 to a peak of 927 in 2023, before slightly decreasing to 387 in 2024. This surge in recent years underscores a burgeoning interest in the functional properties of millets, likely driven by their potential health benefits and applications in food science. Overall, the data highlights a growing body of research, with the number of studies rising markedly over the past two decades, suggesting that millets are increasingly recognized for their valuable functional properties.

Fig. 1 Distribution of Fermented Millet Products in Africa

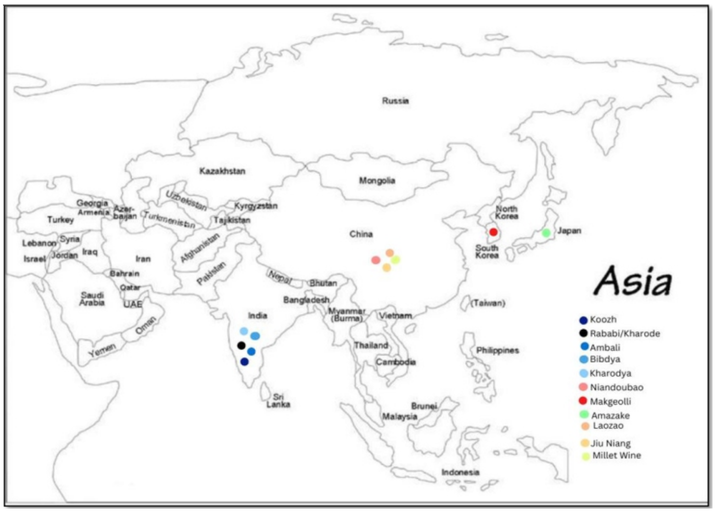

Fig. 2 Distribution of Fermented Millet Products in Asia

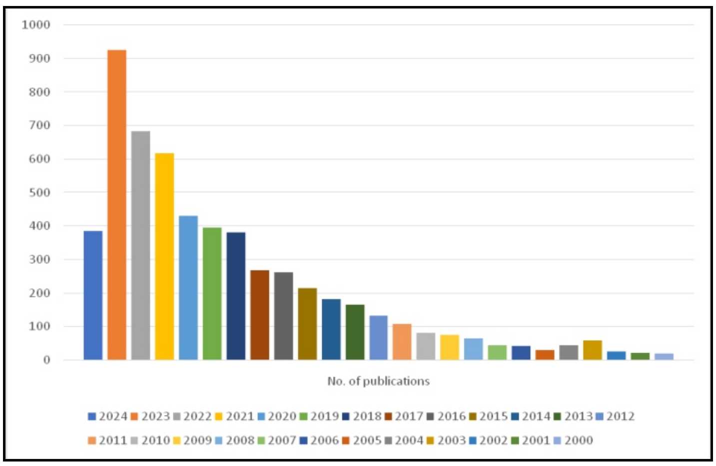

Fig. 3 Number of publications on functional properties of millets and millet products from 2000-2024

10.0 Future directions

Looking ahead, it is crucial to adopt a multifaceted strategy to enhance the prominence of fermented millet foods. Firstly, extensive research efforts are needed to comprehensively understand the nutritional advantages and health impacts of these foods, particularly their role in improving gut health and combating malnutrition in semi-arid regions of Africa and Asia. Simultaneously, endeavors to increase public awareness and educate stakeholders about the importance of fermented millet foods should be intensified. This involves advocating for policies that bolster their production and distribution, as well as fostering culinary innovation to incorporate them into contemporary diets. Additionally, exploring commercial processing methods to expand the production and preserving cultural heritage is vital for the food industry. Collaborative partnerships among researchers, policymakers, industry stakeholders, and local communities will play a crucial role in driving progress towards unlocking the potential of fermented millet foods to address nutritional challenges and alleviate hunger in vulnerable populations.

Conclusion

In nutshell, fermented millet products stand as a pivotal asset in the fight against malnutrition, food insecurity and an overall enhancement of public health across Africa and Asia. Through heightened awareness of their benefits, continued scientific inquiry, and innovative commercial processing techniques, we can actively rejuvenate their consumption and fully harness their capacity to tackle nutritional hurdles within these locales.

Future scope of the study

Future research should prioritize elucidating the nutritional properties and health benefits of fermented millet foods, with particular emphasis on their potential to enhance gut health and address malnutrition in semi-arid regions of Africa and Asia. Concurrently, targeted initiatives should focus on public education, policy advocacy to support sustainable production and distribution, the development of innovative processing technologies, and the integration of fermented millet foods into contemporary diets, ensuring cultural heritage preservation and scalability within the food industry.

Conflict of Interest

There are no conflicts of interest among the authors.

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