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Fermented millet products: An overview

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Abstract

Millet plays a significant role in food production and nutrition. Due to its high nutritional content, millet is also becoming more popular in cities as a better substitute for rice and wheat. Though India is the largest producer of millets, it stands behind sub-Saharan Africa in consumption. The first processed foods that people consumed were fermented foods and beverages. The extended shelf life, safety, and organoleptic qualities of fermented millet foods were the primary reasons for their significance. Increasing evidence indicates that fermented millet foods can also have improved functional and nutritional qualities as a result of substrate modification and the synthesis of bioactive end products. Millet fermentation enhances protein and carbohydrate digestibility and mineral availability. In fermented foods microbes sharing genetic similarities with probiotic strains are present. Despite the paucity of clinical research on fermented millet foods, there is evidence that these foods offer health benefits that extend well beyond the nutritional value of their ingredients. These foods have therapeutic properties such as antidiabetic, anti-inflammatory, antimicrobial, antitumerogenic, antioxidant and so on. This review highlights various types of fermented millet foods and their health benefits.

1. Introduction

Millets are annual grasses mainly produced for their grain. For the people living in the semi-arid tropical regions of the world, millets are the most significant food crop and their primary source of energy and protein. Today, millets account for 45% of all land planted to food plants in India and are a significant part of the country's subsistence system (Malathi *et al*., 2016). There are many varieties of millets grown in the world sorghum millet (jowar), proso millet (chena/barri), pearl millet (bajra), foxtail millet (kakum/kangni), finger millet (ragi), browntop millet (korle), barnyard millet (sanwa), little millet (moraiyo), buckwheat millet (kuttu), amaranth millet (rajgira) and kodo millet (Ajagekar *et al*., 2023). Millet-fermented products are foods prepared from millet grains that have undergone bacterial or yeast fermentation (Rao and Nune, 2021). Although, significant dehulling, polishing, and milling limited the amount of dietary fiber and micronutrients in millets, germination and fermentation boosted the overall nutritional qualities of millets maximizing the nutrient value, enhancing nutrient bioavailability and promoting food and nutritional security (Gowda *et al*., 2022).

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2. Millet production scenario

Asia is the second-largest producer of millet, behind Africa. The world's largest millet producer is India. Despite not being a common food crop in developed countries, millet is an essential part of many people's diets (Rao *et al*., 2021). In 2020, the two millet kinds grown in India, Pearl Millet and Sorghum, accounted for approximately 19% of global millet production (Khunt *et al*., 2022). In India, almost 11 million hectares of land are used for cultivating millet. 33.77 million tonnes of millet were produced in India in 2020-21. India's major millet-producing states are Uttar Pradesh, Rajasthan, Maharashtra, and Karnataka. The most commonly grown millet in India is pearl millet (bajra), which is followed by finger millet (ragi), foxtail millet and little millet (Wimalasiri *et al*., 2023).

3. Nutritional properties of millets

Sorghum is rich in bioactive phenolic compounds, including luteolin, apigenin, gallic acid, vanillic acid, ferulic acid and 3-deoxyantho-cyanidins (3-DXA) (Xu *et al*., 2021). The bioactivity of sorghum was influenced by phenolic substances such as phenolic acid, flavonoids, tannins and stilbenes; vitamins such as B-complex, A, D, E, and K; and minerals such as zinc, magnesium, phos-phorus and potassium (Khalid *et al*., 2022). Finger millet is high in minerals (2.5-3.5%), phenolics (0.3%-3%), calcium (0.34%), dietary fiber (18%), phytates (0.48%), and protein (6%-13%) (Chandra *et al*., 2016). Carbohydrates have a low glycemic index since they are mainly made up of resistant starch, dietary fiber, and slowly digesting starch. About 7% of finger millet is protein (Gull *et al*., 2014). The protein from pearl millet has a greater prolamin proportion and is gluten-free. Omega-3 fatty acids and other essential nutritional fatty acids including decosahexaenoic acid, eicosapentaenoic acid, and alpha-linolenic acid are abundant in pearl millet (Nambiar *et al*., 2011). A good supply of iron, calcium, potassium, phosphorus, zinc, magnesium, vitamin B-complex, niacin, and folic acid is proso millet. With the exception of lysine, proso millet has substantially greater concentrations of the essential amino acids (Kalinova and Moudry, 2006). High concentrations of vitamins and minerals, including the B-complex vitamins, pyridoxine, folic acid and niacin, iron, calcium, magnesium, potassium, and zinc are found in kodo millet (Karak and Thapa, 2023). Since kodo millet is so easily digested, it can be advantageous when formulating products for both infants and the elderly (Khare *et al*., 2020). Foxtail millet has the highest protein content. Additionally, foxtail millet has a high concentration of linoleic and stearic acids, which support the maintenance of a healthy lipid profile. With the exception of lysine and methionine, it is rich in vitamins, minerals, resistant starch, and other essential amino acids (Sharma and Niranjan, 2017). Little millet is high in sulfur-containing amino acids (cysteine and methionine) and lysine, which is absent in most cereals. It also has a protein content of about 8.7% and balanced amino acid profiles (Neeharika *et al*., 2020). Additionally, it is a good source of micronutrients like niacin, iron, and phosphorus (Patil *et al*., 2014). Barnyard millet has antioxidant property with carotenoids and tocopherols. Bioactive compounds such as phenolic acid, phytic acid, tannin, flavonoids, saponins, alkaloids, catechins and phytosterols are also present (Ramadoss and Shanmugam, 2024). Millets offer a sustainable and affordable way to treat long-term health problems as consumers look for natural substitutes for manufactured medications (Sibi *et al*., 2024).

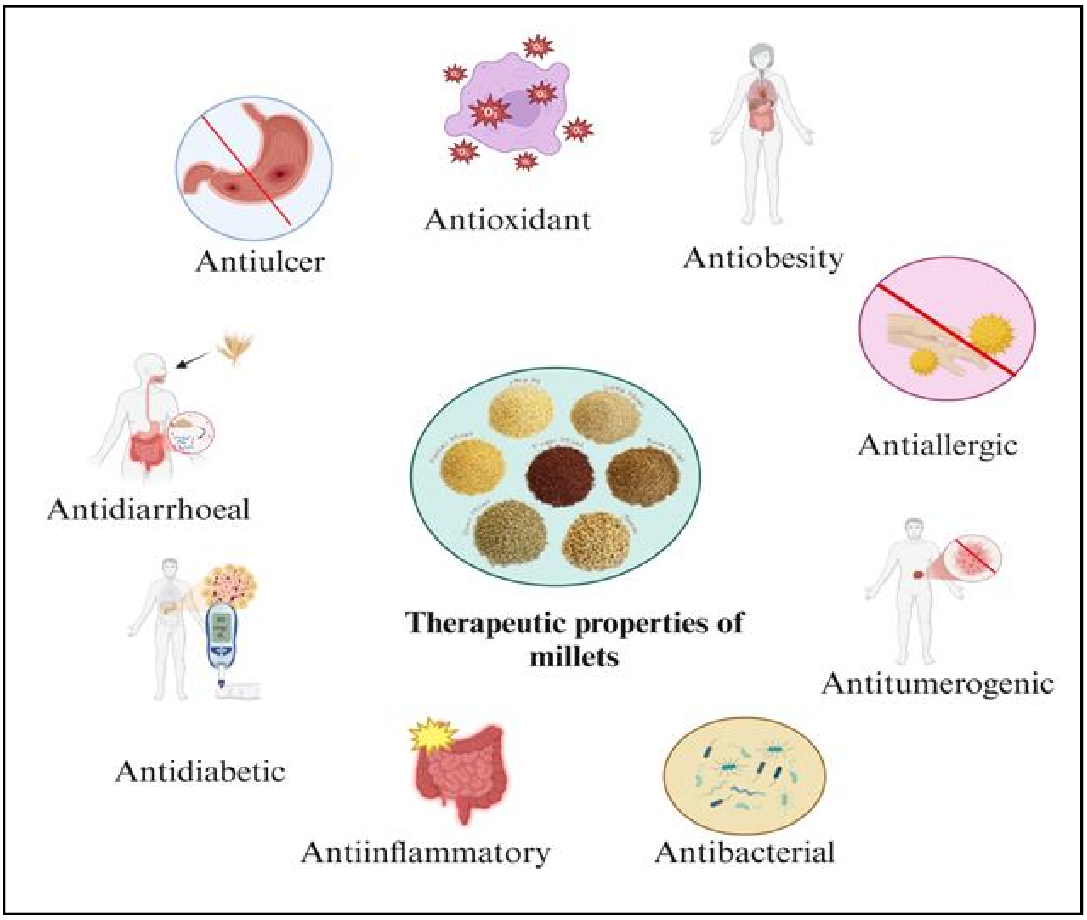

Figure 1: Therapeutic properties of millets

4. Therapeutic properties of millets

According to studies, celiac patients can eat a variety of minor cereals that are "gluten-free," reducing their risk of developing a number of severe long-term problems from the condition (Jhan *et al*., 2020). Better postprandial and fasting glucose management is made possible by millet. Increased leptin levels, decreased insulin resistance, and decreased inflammation may all contribute to glucose-lowering effects. Millet protein prevents obesity, type 2 diabetes, and cardiovascular disorders because it increases adiponectin concentration, which improves insulin sensitivity and cholesterol metabolism (Sabuz *et al*., 2023). Phenolics found in millet have been demonstrated to be effective in halting the initiation and *in vitro* growth of cancer (Bunkar, 2021). Millets' high polysaccharide, phytochemical, and dietary fiber content helps prevent lifestyle diseases like diabetes, gastrointestinal disorders, cardiovascular disease, cancer, and inflammation, as well as aid in weight loss (Math *et al*., 2024). A number of studies have demonstrated the strong antitumor properties of polyphenols obtained from millets. According to Hosoda *et al*. (2012), millets' polyphenol has the ability to reduce inflammation (Xu *et al*., 2021).

A prevalent endocrine condition that affects millions of people globally is diabetes mellitus (Swetha and Velraj, 2023). The beneficial effect of the finger millet-based diet was demonstrated by two experiments on male Wistar rats that showed a considerable drop (33%-41%) in glycated hemoglobin levels in the diabetic experimental group as compared to the diabetic control group (Choudhury and Bhatia, 2024). Foxtail millet have antioxidants that fight against conditions like diabetes, cancer, heart disease, and other diseases, halting the decline of human health (Karpagapandi *et al*., 2023). Phenolic compounds present in pearl millet have antidiabetic properties (Pei *et al*., 2022). Barnyard millet has a low carbohydrate content and digests slowly. It has a good dietary fibre content which makes them ideal for obesity, CVD and diabetic patients (Kaur *et al*., 2020). Various therapeutic properties of millets are shown in Figure 1.

5. Fermentation process

The process of fermentation depends on enzymes and catalysts produced by microorganisms like bacteria, yeast, and moulds to chemically change the substrate's complex organic molecules into simpler, more bioactive, beneficial, and nutrient-dense substances (Campbell-Platt, 1994). The process of spontaneous fermentation of millets produces a series of fermentation organisms known as "the usual suspects" that are comparable internationally for similar products and processes (Gänzle and Zheng, 2018). The basic operations to produce some fermented beverages are steeping, milling, slurrying, sieving, fermentation, sedimentation, and cooking. But crucial processes in the production of fermented beverages include malting, mashing, and fermentation (Amadou, 2019). The U.S. Food and Drug Administration has categorized LAB and its by-products as generally recognized as safe (GRAS) (Sharma *et al*., 2023). The International Scientific Association for probiotics and prebiotics (ISAPP) reconstructed fermented foods and beverages in 2019 as foods produced by specific microbial growth and enzymatic changes of food components (Qin *et al*., 2022). The gastrointestinal system contains probiotics that aid in controlling dangerous bacteria and fostering good microbiota (Ullagaddi and Murkhandi, 2024). The common bacteria involved in fermentation include *Lactobacillus*, which is used to ferment food based on sorghum and millet, such as ogi, a traditional African porridge (*Lactobacillus fermentum*). A common bacterium called *Lactobacillus plantarum* is employed in the fermentation of millet-based goods including kaffir beer and idli, a popular Indian breakfast meal. The bacterium frequently encountered during the fermentation of finger millet products, including the traditional Indian flatbread called Bhakari, is called *Leuconostoc mesenteroides*. A particular kind of bacteria called *Pediococcus pentosaceus* is often found during the fermentation process of items made from pearl millet, such as Mahewu, a traditional fermented beverage from Zimbabwe (Rao and Nune, 2021).

5.1 Types of fermentation

Lactic acid fermentation is mostly carried out by lactic acid bacteria (LAB) and various organic acid types, the primary metabolite of which is lactic acid (Sionek *et al*., 2023). Alkali fermentation frequently takes place during seed fermentation and is carried out by various *Bacillus* and fungal species (Owusu-Kwarteng *et al*., 2022). In acetic fermentation, the primary agents responsible are acetic acid bacteria (AAB). Acetic acid is the principal result of the conversion of alcohol to acetic acid by AAB (mostly Acetobacter) in the presence of excess oxygen (Ruan *et al*., 2023). Yeasts are the predominant organisms used in alcohol fermentation process, which yields CO_2 and ethanol as its main products (Loying *et al*., 2024). The schematic representation of the types of fermentation in millets are shown in Figure 2.

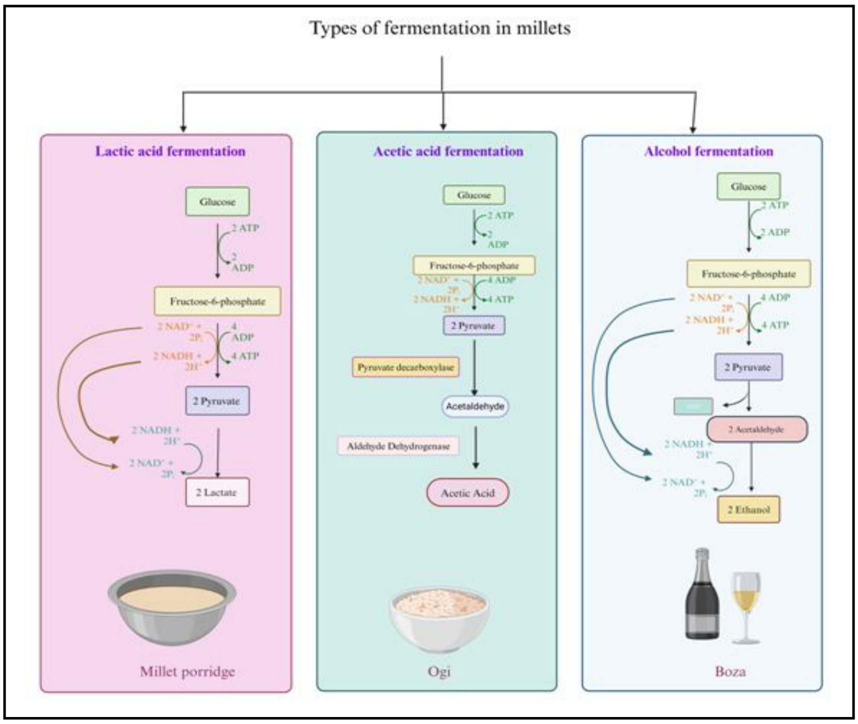

Figure 2: Types of fermentation in millets

5.2 Traditional Foods

Traditional millet-based products are common globally, with fermentation being a usual process. Millet products have been a traditional staple in the Indian subcontinent, Africa, and Central America (Saeed *et al*., 2022).

5.2.1 Koozh

A ready to eat (RTE) beverage called koozh is produced using broken rice flour, pearl millet, or finger millet. It is a traditionally prepared millet porridge- food in rural Tamil Nadu, South India (Kumar *et al*., 2010). Koozh is unique because it undergoes fermentation twice-once prior to cooking and again subsequent to cooking (Ilango and Antony, 2014). Fermented koozh has greater levels of free amino acids, phytochemicals, micronutrients including selenium, and radical scavenging action. There was an increase in the protein content (Subastri *et al*., 2015). The predominant microorganism present in Koozh is lactic acid bacteria (LAB). Bioactive ingredients found in koozh, such as ascorbic acid and p-coumaric acid, provide nutraceutical advantages, including antiinflammatory, antiallergenic, antimicrobial, antioxidant, and antidiabetic properties. Additionally, koozh is used to treat several conditions including cardiovascular illnesses and hypercholesterolemia (Saeed *et al*., 2022).

5.2.2 Millet dosa

A typical South Indian food is dosa. Dosas prepared with fermented millet batter are becoming increasingly popular among those seeking out a healthier diet (Devi *et al*., 2011). The natural bacteria in the millet and lentil break down the proteins and carbohydrates in the batter, increasing its nutritional content and facilitating digestion (Behera *et al*., 2020). At room temperature (around 25 to 30°C), fermentation typically takes 8 to 12 h. The protein content was high with 15.1% and increased level of fibre content with 3.8% (Cicilia *et al*., 2024). It has nutraceutical property and antioxidant property with the presence of p-coumaric acid, syringic acid, protocatechuic acid, gallic acid, quercetin and caffeic acid. Essential amino acids such as tryptophan, methionine, cysteine, histidine, isoleucine, valine, and leucine are also increased with a notable decrease in phytate content due to fermentation (Devi and Rajendran, 2021).

5.2.3 Fura

A popular snack in the northern region of Nigeria, fura is a regionally fermented cereal-based dish made primarily from millet or sorghum and spiced with ginger, pepper, black pepper, and gloves to give it the right flavor. This semisolid dish, which is derived from sorghum or millet, serves as a staple diet. It contains up to 11% of protein, minerals like potassium, zinc, magnesium, calcium and iron are present and B vitamins like niacin, pyridoxine, and folic acid are also improved. Phytic acid which lowers cholesterol and lowers the risk of cancer is rich in this fermented food (Gunya *et al*., 2022). During fermentation, folate content is increased to 16.2-31.3 µg/100 g (Bationo *et al*., 2022).

5.2.4 Hussuwa

Hussuwa is a Sudanese product with a sweet-sour taste similar to solid foods that contain malt. The Hussuwa fermentation appears to be dominated by *L. fermentum* strains and *P. acidilactici* strains. *Acetobacter xylinum, Gluconobacter oxydans, Lactobacillus saccharolyticum*, and *Saccharomyces cerevisiae* were identified as possible probiotic bacteria (Yousif *et al*., 2010). The values of pH declined as fermentation proceeded, and titratable acidity and volatile fatty acids increased (Nour *et al*., 1999).

5.2.5 Ting

Ting is a fermented food made from sorghum that is used in Botswana, South Africa, and other states to make porridge or gruel (Adebo *et al*., 2018). The fermentation process can alternatively be back-slopped and finished in 6-24 h. It was best to ferment ting using *Lactobacillus fermentum* FUA 3321 (Adebo *et al*., 2019). The pH was between 3.5 and 4.0. Lactate, acetate, and ethanol were the main metabolites found (Sekwati-Monang and Gänzle, 2011). The reduced pH at this optimal condition, would extend shelf life and preserve the ting better (Adebo *et al*., 2017). Ting possesses elevated levels of total flavonoid content (40.9 mg CE/g), tannin content (14.1 mg CE/g), total phenolic content (46.1 mg GAE/g), and antioxidant activity (3.7 µM TE/g). There are also additional bioactive substances such quercetin, gallic acid, and catechin (Adebo *et al*., 2018).

5.2.6 Togwa

Sorghum, millet, maize or only maize are used to make togwa; they can be ground together or pounded separately. The product undergoes a substantial pH drop from 5 to 3 during the 9-24 h fermentation process. The product can be used as a refreshing beverage or as weaning gruel. *Weissella confusa, P. pentosaseus, L. plantarum, L. fermentum, L. brevis*, and *L. cellobiosus* were the microbes that dominated the fermentation. Antinutritional factors such as phytates, tannins, and trypsin inhibitors which interfere with nutrient absorption were reduced (Mugula *et al*., 2003). The folate content increased to 6.91 µg/100 g in the product (Hjortmo *et al*., 2008).

5.2.7 Ogi

A staple food as well as essential weaning food, ogi is made from fermented maize gruel. It is a semisolid product (fermented maize, millet, or sorghum) that is eaten for breakfast and is a fine paste with a sour gruel flavor. Lactic, butyric, acetic, and formic acids were the most commonly identified acids, whereas *S. cerevisiae* and *Bacillus* sp. were the dominated the flora (Teniola *et al*., 2005). The finger and pearl millet ogi had protein contents ranged from 6.16 to 9.71 and 6.29 to 12.39%, respectively. It has an increased vitamin content such as 0.4 mg of riboflavin and 10.98-52.40 µg/g of folate (Walther and Schmid, 2017; Okoroafor *et al*., 2019).

5.2.8 Bensaalga

This thin, non-alcoholic beverage, termed as gruel, is made by boiling fermented sediments from pearl millet in water. In Africa, people often eat it for breakfast, especially children and people with medical conditions. There were observations of decreased carbohydrate content and increased protein and acidity during fermentation. Phytate is reduced by 50% after leaching and the removal of coarse particles, despite significant nutrient loss. During the 72 h fermentation period, a microbiological analysis of the products revealed a drop in coliforms and a rise in LAB, yeasts, and molds (Ilango and Antony, 2021). There was an increase in folate content of 7.1-7.3 µg/100 g (Bationo *et al*., 2020).

5.2.9 Bushera

Bushera is prepared by combining 240 g of sorghum and germinated millet flour with 1 liter of hot water, then letting it cool for one to six days at room temperature. As a result, the product has a pH between 3.7 and 4.5. The five genera that these LAB belonged to were *Weisella*, *Enterococcus*, *Leuconostoc*, *Lactobacillus*, and *Lactococcus*. Coliforms and yeast were also discovered (Muyanja *et al*., 2003). In comparison to other species, *Lactobacillus brevis* was frequently isolated (Arora *et al*., 2023).

5.2.10 Busaa

Busaa is made from finger millet malt, water, and roasted maize through a spontaneous lactic acid and alcoholic fermentation process. Finger millet malt is allowed to ferment for two to three days at 25°C. After filtering and bottling, it is again allowed to ferment for three to six hours at 25°C. The beverage is pasteurized for 30 minutes at 93°C. When busaa is ready to be consumed, it contains 0.5-1% lactic acid and 2-3% alcohol (Mugula *et al*., 2003). It is rich in thiamin- 0.05 mg; riboflavin- 0.03 mg; niacin- 0.46 mg; vitamin B12- 0.09 µg/ 100 g; pantothenic acid- 0.44 mg/100 mg (Selhub *et al*., 2014).

5.2.11 Mahewu

In South Africa, mahewu is a fermented, non-alcoholic beverage made from maize that is used as a weaning food as well as a staple. Mahewu is made from maize flour or unmalted sorghum meal. A sour porridge is produced by adding maize meal flour, adding water, and letting it ferment for two to four days at room temperature. Heterofermentative *Lactobacilli* sp. and yeast are the major organisms of natural fermentation (Chelule *et al*., 2010). Consumers consider Mahewu is more nutritious than unfermented porridge, which is in accordance with studies showing that fermented cereals have higher levels of free amino acids, lower levels of phytic acid, and higher bioaccessibility to iron, zinc, and calcium than unfermented ones (Kudita *et al*., 2023).

5.3 Baked Foods

5.3.1 Injera

Injera is a flatbread made from finger millet which was a staple in many regions of Ethiopia. Injera goes through two phases of spontaneous fermentation from 24 to 72 h (Baumgarthuber, 2021). The mineral content of injera prepared from finger millet and maize composite flour increased with fermentation time, leading to a significant increase in bioaccessible iron, zinc, and calcium, ranging from 15.4-40.0%, 26.8-50.8% and 60.9-88.5%, respectively. A strong decline in phytate and condensed tannin content was observed in injera (Endalew *et al*., 2024). It has increased folate content of 131 µg/100 g (Tamene *et al*., 2022).

5.3.2 Kisra

Traditional Sudanese kisra is a thin, pancake-like flatbread fermented by yeast and lactic acid bacteria (Zaroug *et al*., 2014). At 18 h, the bacterial population in the batter is maximum. The pH ranged from 3.95 to 5.95 after one complete day. *Pedicoccus pentosaceus* in particular was the predominant bacterium in the microbial population. *L. confusus, L. brevis*, Acetobacter sp., yeasts *Candida intermedia, Debaryomces hansenii*, and molds *Aspergillus* sp., *Pencillium* sp., *Fusarium* sp., *Rhizopus* sp. were among the other bacteria discovered (Ali and Mustafa, 2009). B-vitamins such as thiamine 0.42-0.55 mg/ 100 g; riboflavin 0.12-0.33 mg/100 g and niacin 3.15-3.22 mg/100 g are increased significantly (Hamad *et al*., 1992). Fermentation improves the antioxidant property of kisra with an increase in phenolic compounds (Zaroug *et al*., 2014).

5.3.3 Millet sourdough bread

The quality of breads, biscuits, and cakes can be enhanced by using sourdough, an acidic paste often prepared through spontaneous or control fermentation of moistened cereal flours (Akinola *et al*., 2017). The starter consisted of previously typed cultures of yeast (*Saccharomyces cerevisiae and Candida milleri*) and lactic acid bacteria (*Lactobacillus plantarum, Pediococcus pentosaceus, and Lactobacillus pentosus*) from spontaneously produced pearl millet sourdough. There was a range of 13.07% to 14.32% protein, 1.77% to 1.99% ash, 8.01% to 9.32% fat, 0.77% to 1.25% crude fiber, 21.08% to 22.65% moisture, and 51.28% to 54.23% carbohydrates. The greater the number of starters used in pearl millet sourdough breads, the higher the crude protein content (Akinola *et al*., 2020). The consumption of bread products which contain lactic acid, whether it is produced during fermentation or added, had been shown by Ostman *et al*. (2002) to lower postprandial glucose and insulin responses in people without a history of illness. Therefore, a better option for diabetic individuals and others with comparatively reduced insulin capability was promised by the bread's comparatively lower carbohydrate content (Adepehin *et al*., 2022).

5.3.4 Millet biscuits

Biscuits are a perfect flour-based snack that both young and old can eat and enjoy (Crofton and Scannell, 2020). The macro and micro-mineral contents of biscuits prepared from 72 h fermented flours were noticeably greater than those of biscuits manufactured from native flours. The spontaneous fermentation is associated with higher improvements in minerals like copper, iron, manganese, and zinc. The minerals in native flour formed insoluble complexes with anti-nutritional elements like tannins and phytates. These complexes are broken down during fermentation, increasing the mineral bioavailability (Mudau *et al*., 2022).

5.4 Dairy based products

5.4.1 Fermented milk

Fermented milk had been produced from millets like barnyard, kodo, foxtail, proso, and little millet. The maximum extraction yield was found in proso and foxtail millets (Sheela *et al*., 2018). The fermentation process increases the bioavailability of minerals in fermented milk, particularly calcium, potassium, zinc, magnesium, potassium iodide, and phosphorus, which are generated by lactic acid (García-Burgos *et al*., 2020).

5.4.2 Millet yogurt

Millet milk (15%) and dairy milk with a 6 h fermentation time have been combined to produce a millet yogurt with acceptable organoleptic properties (Semwal *et al*., 2021). The antibiotic activity of the developing bacteria, such as *Lactobacilli* in yogurt and other substances that produce antibacterial qualities including hydrogen peroxide, lactic acid, bacteriocins, and antibiotics, determines the bactericidal action of fermented milk (Vieco-Saiz *et al*., 2019)

5.4.3 Millet curd

Curd is obtained by fermenting the milk that is extracted from the millets after they were first germinated. According to Sheela *et al.*

(2018), the millet milk yield and, in turn, the curd yield are directly impacted by the germination process. The millet milk yield is influenced by the water absorption capacity and germination percentage, which were higher after 24 h of soaking and germination. Proso millet, little millet, and foxtail millet produced the highest percentage of milk. The resulting millet milk was pasteurized and fermented for six hours using commercial curd culture NCDC 260. The millet milk curd had a pH between 3.5 and 4.16.

5.4.4 Fermented millet sprout beverage

Pearl millet (23.9%), finger millet (30%), and sorghum (21.1%) were combined with 25% skim milk to create a fermented millet sprout beverage that required 12 h of soaking and 48 h for germination. The optimized fermented millet sprout milk beverage had 0.23% iron, 7.1% TS, 1.3% fat, and 0.5% protein. The beverage had a lactic acid content of 0.587% (Sudha *et al*., 2016). A beneficial milk beverage based on kodo millet was standardized. The protein digestibility of the beverage made from malted millet was more significant (Geetha and Preethi, 2020).

5.4.5 Rabadi

A popular beverage in North-Western parts of India, rabadi is made by fermenting pearl millet flour, wheat and sorghum with butter milk (Modha and Pal, 2010). During fermentation, thiamin, riboflavin, and nicotinic acid contents increased. As a result, it is determined that this kind of cultured product is beneficial for populations with poor intakes of B vitamins (Dhankher and Chauhan, 1989). According to Kaur *et al*. (2009), employing *Morchella* sp. for fermentation increased the protein content of wheat from 11.2 to 21.3%, that of pearl millet from 12.2 to 20.3%, and that of sorghum from 9.2 to 14.7%. The notable increase in flavonoids such as quercitin and pelargonidin was also observed. They are beneficial for diabetes, edema, blood abnormalities, gout, piles, varicose veins, degradation of the muscles, cardiovascular illnesses, and cancer (Miller, 1996).

5.5 Alcoholic beverages

5.5.1 Jiu

The general Chinese term for “distilled liquor” is jiu. There are several varieties of Jiu, each with a unique flavor and name. Jiu has 40% to 45% alcohol content. Jiu is a staple of Chinese (Wagner, 2005). The energy-dense liquor facilitates meal digestion. The microbes that are involved are yeasts (*Saccharomyces* sp., *Candida* sp., *Hansenula* sp.), bacteria (acetic acid bacteria, LAB) and filamentous fungi (*Rhizopus* sp., *Mucor* sp., *Aspergillus* sp.) (Chen and Xu, 2013).

5.5.2 Huangjiu

China’s national alcoholic beverage is huangjiu. The value of millet can be lifted by brewing Huangjiu with it. The microbial community is essential to the fermentation of millet Huangjiu. Huangjiu’s flavor compounds are complex and microbes play a key role in their synthesis (Yan *et al*., 2022). Throughout the millet Huangjiu fermentation process, the levels of citric and malic acid progressively increased, which have beneficial effects on the liver and reduce fatigue (Zhou *et al*., 2023).

5.5.3 Tchoukoutou

Tchoukoutou is a common alcoholic beverage with an acidic taste, good digestion, and an alcohol flavor that is produced by malting red sorghum. Three steps involved in preparing it includes malting, brewing and fermentation. The beer is consumed in two to three days, and if it is left longer, the alcohol content rises significantly. Tchoukoutou supplies fat, protein, iron, and energy. *S. cerevisiae* was the probable probiotic bacterium that was reported (Nout, 2009). It has increased folate content of 3-18 µg/100 g (Walther and Schmid, 2017).

5.5.4 Kodo ko jaanr

The most popular fermented alcoholic beverage, known locally as “kodo” in the Eastern Himalayan areas of India, Nepal, and Bhutan’s Darjeeling highlands and Sikkim, is called “kodo ko jaanr.” It is made from dry finger millet seeds (Amadou, 2019). *Pichia anomala, Candida glabrata*, and *Saccharomycopsis fibuligera* were the flora discovered. Yeast dominates the fermentation process (Thapa and Tamang, 2004).

5.5.5 Jandh

One of the main traditional alcoholic beverages of Nepal is jandh. It is a type of beer. It has a sweet and a bit tart taste (Dahal *et al*., 2005). Finger millet is fermented to produce Jandh. Because of its excellent tonic properties, the beverage is highly valued particularly by new mothers (Amadou, 2019).

6. Advantages

Fermentation increases the bioavailability of essential nutrients like vitamins (especially B vitamins), minerals (iron and zinc), and amino acids, improving the nutritional profile of millet. The bacterial culture that is present in fermented milk determines its vitamin content. By being used by the developing bacteria in milk, the majority of vitamin B groups, particularly riboflavin, thiamin, and nicotinamide were increased double (Yoshii *et al*., 2019). The overall phenolic contents in the millet increased by more than 30% after three days of fermentation utilizing a variety of natural microorganisms, primarily *Lactobacilli* (Balli *et al*., 2020). The fermentation process breaks down complex carbohydrates, making fermented millet products easier to digest, particularly for individuals with digestive issues or gluten sensitivity. Fermentation reduces levels of antinutrients like phytic acid, tannins, and enzyme inhibitors that can interfere with nutrient absorption, increasing the bioavailability of minerals. The bio-conversion of phenolic compounds from their linked or conjugated forms to their free ones is said to be enhanced by fermentation, leading to a higher concentration of phenolic components with stronger antioxidant potential (Acosta-Estrada *et al*., 2013). Fermented millet can be used in a wide range of dishes, from traditional porridge to bread, pancakes, and beverages, making it a versatile ingredient in diverse cuisines. Additionally, millets are used to make distilled drinks that are marketed to people seeking low-calorie and gluten-free beverages (Math *et al*., 2024). Fermentation enhances the flavor of millet by adding a pleasant tanginess, depth, and richness, making the final product more appealing. Fermentation acts as a natural preservative, extending the shelf-life of millet products without the need for artificial additives. It brings changes in the pH of the product aiding in food preservation. Modha and Pal (2010) reported that fermented pearl millet-based milk beverage has sensorily acceptable quality and shelf-life of 7 days without any preservative at refrigerated storage (5-7°C) when packed in glass bottles. Fermentation increases the antioxidant levels in millet, providing greater protection against oxidative stress and contributing to overall health. Sourdough fermentation considerably increased the *ex vivo* antioxidant activity in fermented millet flour compared to the unfermented one, based on the phenolic enrichment verified by chemical analysis (Balli *et al*., 2020). Millet is naturally gluten-free, and fermented millet products can be a safe and nutritious choice for individuals with gluten intolerance or celiac disease. Fermented millet contains beneficial bacteria (probiotics) that support gut health, boost the immune system, and improve digestive function. Numerous epidemiological studies have shown that eating cereal fermented meals on a daily basis in large quantities has been linked to a lower risk of diabetes, cancer, and cardiovascular disease (Oguntoyinbo and Narbad, 2015). In the developing world, particularly Africa, probiotic yogurt-which is made up of a Fiti sachet containing *Lactobacillus rhamnosus* GR 1 and *Streptococcus thermophilus* C106 has been used to treat disease and malnutrition (Di Stefano *et al*., 2017). Fermented millet has a lower glycemic index compared to non-fermented varieties, helping to regulate blood sugar levels and making it a better choice for diabetics. Chronic liver illnesses are associated with inflammation, which leads to increasing hepatic damage and fibrosis. According to Shi *et al*. (2017), D-galactosamine-induced liver damage is prevented by *Lactobacillus rhamnosus, Lactobacillus salivarius* or *Pediococcus pentosaceus*. The gut microbiota, including the probiotics *Bifidobacterium* and *Lactobacillus*, which are known to have antidiabetic properties, and the prebiotics *Faecalibacterium*, *Eubacterium*, and *Roseburia*, used the finger millet's prebiotic content to produce colonic short-chain fatty acids (SCFAs). Notably, by producing propionate and Amuc 1100 protein, the mucus-degrading *Akkermansia muciniphila* that is generated by finger millet can also aid in the relief of diabetes. Numerous millet bioactives successfully reduced gut inflammation and, consequently, the host's chance of developing diabetes by controlling harmful gut bacteria like Shigella and *Clostridium histolyticum* (Singh *et al*., 2022).

7. Handling and storage of fermented foods

Once fermented, millet products can spoil quickly if not properly stored, requiring refrigeration to maintain freshness. The tangy and sometimes sour flavor resulting from fermentation may not appeal to everyone, making it less popular for certain consumers. Fermentation is a time-consuming process, often requiring several hours or days to achieve the desired results, which may not be convenient for quick meal preparation. If proper hygiene and handling are not maintained during fermentation, there is a risk of contamination by harmful microorganisms, which can lead to foodborne illness. Fermented millet products may not be suitable for individuals with specific dietary restrictions or allergies, such as those sensitive to fermented foods or with histamine intolerance. Some nutrients, like heat-sensitive vitamins, may degrade during the fermentation process, potentially reducing the overall nutritional value of the millet. In fermented milk, vitamins like thiamine (B1), riboflavin (B2), and ascorbic acid drop by around half after being used by the developing bacteria in milk (Yoshii *et al*., 2019). Fermentation can be inconsistent, leading to variations in taste, texture, and quality, which can make it difficult to achieve a uniform product. The large levels of antioxidants, nutraceuticals, and lactic acid created during spontaneous fermentation may have contributed to the low mean scores for taste of 72 h fermented biscuits, particularly dark brown finger millet biscuits. This may also have contributed to the biscuits' undesirable flavor (Mudau *et al*., 2022).

8. Dosage/ maximum permissible levels

No observed adverse effect level (NOAEL) is the highest dose or exposure level of a substance at which no adverse effects are observed in a study population (usually animals or humans) over a specified period of time. It is determined through experimental studies, such as toxicological or clinical trials. It is used to identify the safe exposure level of a substance and to establish safety guidelines, such as acceptable daily intake or reference dose. NOAEL is derived from dose-response studies where subjects are exposed to varying doses of a substance, and the effects are monitored. It helps in determining safe exposure limits for humans and the environment. NOAEL for certain probiotic strains are listed in Table 1.

Table 1: No observed adverse effect level (NOAEL) for probiotic strains

Probiotic organism	No observed adverse effect level (NOAEL)	Reference
Lactobacillus brevis KB290	10^{10} cfu/kg/day	Yakabe *et al*., 2009
Lactobacillus pentosus strain b240	2000 mg/kg/day	Szabo *et al*., 2010
Limosilactobacillus fermentum PS150	4.3×10^{11} cfu/kg/day	Cheng *et al*., 2025
Streptococcus salivarius DB-B5	10 billion cfu/day	Li *et al*., 2021
Lactobacillus plantarum strain PS128TM	2400 mg/kg/day	Liao *et al*., 2019

9. Future perspectives

Fermented millet foods have a promising future due to their nutritional benefits, sustainability, and growing consumer interest in traditional and functional foods. As plant-based diets gain traction, fermented millet foods can serve as a nutritious and sustainable protein source. Innovations in food technology can lead to new fermented millet-based products, such as snacks, beverages, and ready-to-eat meals. Fermented millet foods can be fortified with additional nutrients or functional ingredients to cater to specific health needs. With increasing global interest in ancient grains and fermented foods, there is potential for fermented millet products to expand into international markets. As global cuisines become more interconnected, fermented millet foods can gain acceptance and popularity outside their traditional regions. Educating consumers about the benefits of fermented millet foods will be crucial for market growth. Developing efficient supply chains for millet production and processing will be essential to meet growing demand. Governments and organizations can promote millet cultivation and fermentation through policies and incentives.

10. Conclusion

Products made from fermented millet are a varied and wholesome range of food choices that have several culinary and health advantages. Fermented millet products support sustainable food systems and cultural heritage preservation in addition to providing improved digestibility and nutrient bioavailability. The remarkable health advantages of consuming fermented millet products are still being discovered by scientific investigation. These foods are a vital source of probiotics, vitamins, and minerals that enhance immune system function, gastrointestinal health, and general wellbeing. Additionally, millet becomes a more bioavailable source of vital micronutrients for people all around the world due to the fermentation process. Fermented millet products are a tempting way to enhance public health outcomes in light of concerns about diseases connected to food and nutritional deficits. Fermented millet products have the potential to take the place of starchy foods globally as customer preferences continue to go toward healthier and more environmentally friendly food options. The full potential of millet fermentation to advance human health, protect cultural heritage, and facilitate cooperation between researchers, food producers, and policymakers.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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