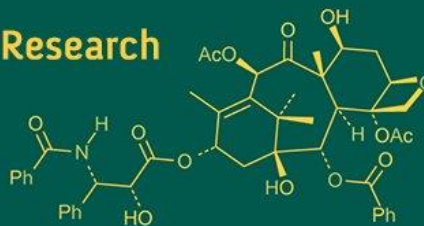


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Millet-based probiotic beverages: Nutritional profile, fermentation strategies, functional properties, and future prospects

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Abstract

Millet is a nutrient-rich, climate-resilient cereal grain widely recognized for its functional, nutritional, and sustainable properties. Due to its high content of dietary fibre, resistant starch, minerals, antioxidants, and bioactive compounds, millet serves as a suitable substrate for the development of probiotic functional beverages. Millet-based probiotic beverages have recently gained significant attention as gluten-free, lactose-free, and plant-based alternatives to conventional dairy products. This review summarizes the nutritional composition, functional properties, and prebiotic potential of millets, as well as the roles of probiotics, prebiotics, and synbiotics in the development of functional beverages. Traditional fermented millet beverages and recent processing technologies, such as ultrasonication, homogenization, and high-pressure microfluidization, are discussed for improving probiotic viability, physicochemical stability, sensory quality, and shelf life. Furthermore, regulatory aspects, current challenges, and future opportunities associated with millet-based probiotic beverages are critically highlighted. Overall, millet-based probiotic beverages have considerable potential as sustainable, health-promoting functional food products.

Keywords: Millets, probiotic beverages, nutritional profile, fermentation strategies, functional properties, prebiotic potential

Introduction

Millets are among the oldest cultivated cereal crops, traditionally consumed in Asia and Africa due to their adaptability to arid climatic conditions and high nutritional value (Harish *et al.*, 2024) [27]. In recent years, increasing awareness of functional foods, sustainable agriculture, and gluten-free diets has renewed global interest in millet-based foods and beverages (K. K. Meena, Meena, *et al.*, 2024) [45]. Rich in dietary fibre, minerals, antioxidants, and bioactive compounds, millets are now recognized for their potential to improve digestive health, glycemic control, cardiovascular health, and overall human well-being (Mohan *et al.*, 2025) [53].

Growing awareness of gut health and functional nutrition has increased global interest in probiotics and prebiotics in recent years (Markowiak & Ślizewska, 2017) [42]. Probiotics are beneficial live microorganisms, while prebiotics are non-digestible compounds that stimulate the growth of beneficial gut microbes (K. K. Meena *et al.*, 2022) [48]. Their regular consumption helps maintain balanced intestinal microbiota, improves digestion and immunity, enhances nutrient absorption, and reduces the risk of gastrointestinal and metabolic disorders, thereby promoting overall health and well-being (Arapović *et al.*, 2024) [7].

In addition, plant-based and dairy-alternative beverages have gained considerable attention in recent years due to the rising demand for functional, lactose-free, vegan, and sustainable food products (McClements & Grossmann, 2021) [44]. Traditionally, beverages prepared from cereals, legumes, and nuts were widely consumed in many cultures for their nutritional and digestive benefits (Perveen & Chishty, 2025) [63]. These beverages are rich in dietary fibre, proteins, vitamins, minerals, antioxidants, and other bioactive compounds that support gut health, immunity, and overall metabolic health. Therefore, the development of innovative plant-based functional beverages has become increasingly important to meet modern

nutritional requirements and the growing preference for healthier and environmentally sustainable diets (Sethi *et al.*, 2016) ^[74].

Moreover, millets are climate-resilient crops that can grow under harsh conditions such as drought, high temperatures, poor soil fertility, and limited water availability with minimal agricultural inputs. Their ability to thrive in rainfed and marginal lands makes them environmentally sustainable, easily accessible, and important for stable food production under changing climatic conditions (Wilson & VanBuren, 2022) ^[88]. Moreover, millet cultivation plays a vital role in improving food security and reducing hunger and malnutrition, particularly in developing countries (Mukherjee *et al.*, 2025) ^[54]. Therefore, increasing millet production and utilization is essential for promoting sustainable agriculture and national nutritional security.

Therefore, this review focuses on millet-based probiotic beverages as emerging functional drinks and highlights millets as sustainable substrates for probiotic fermentation. It discusses their nutritional and health benefits, fermentation and processing techniques, probiotic viability, and applications in dairy and plant-based beverage systems. The review also covers recent developments, regulatory aspects, and future opportunities for their utilization in the functional food industry.

Nutritional content of millets

Millets, often termed “nutri-cereals,” are a diverse group of small-seeded cereals widely cultivated in Asia and Africa for their drought tolerance, low water requirement, and adaptability to poor soils, which make them particularly suitable for semi-arid and rain-fed regions where rice and wheat show limited productivity (K. K. Meena, Taneja, Jain,

et al., 2025; Muskan *et al.*, 2025) ^[47, 49, 55]; together Asia and Africa account for >95% of global millet production, with India leading output and states such as Rajasthan, Karnataka, Maharashtra, Uttar Pradesh and Madhya Pradesh contributing substantially, especially in pearl millet, followed by finger millet and small millets. Nutritionally, millets supply 60-70% carbohydrates, appreciable dietary fibre, resistant starch, B-complex vitamins, and essential minerals including iron, calcium, magnesium, phosphorus, and zinc, along with polyphenols and flavonoids that confer antioxidant capacity and other bioactivities (Anal *et al.*, 2024; Anitha, Kane-Potaka, Botha, *et al.*, 2021) ^[5, 6]. Consequently, compared with polished rice and refined wheat, millets provide higher fibre and complex carbohydrates that support digestion, satiety, and glycaemic control. Their low glycaemic index, resistant starch content, and inherent gluten-free status render them advantageous for managing diabetes, obesity, cardiovascular disease, and gluten intolerance (Saleh *et al.*, 2013; Gatal *et al.*, 2026) ^[70, 23]. Moreover, the fermentability of millet substrates promotes probiotic growth and viability, enhancing the nutritional and functional attributes of fermented beverages, for example, pearl millet improves probiotic survival and nutrient density, foxtail millet affords low glycaemic formulations with good digestibility, and sorghum contributes resistant starch and phenolics that increase antioxidant activity and fermentation stability (Pei *et al.*, 2022; Sharma & Nirajan, 2018; Khalid *et al.*, 2022) ^[62, 77, 34]. The combined agronomic resilience, nutrient profile and functional properties of millets underpin their recognition at the international level and support their development as sustainable ingredients for health-promoting beverages and diets (Yadav *et al.*, 2023) ^[89].

Table 1: Nutritional composition of different types of millets

Millet Type	Energy (kcal)	Carbohydrates (g)	Protein (g)	Fat (g)	Dietary/Crude Fiber (g)	Calcium (mg)	Iron (mg)
Finger Millet	328-336	72.0-72.6	7.3-7.7	1.3-1.5	3.6-15.0	300-350	3.9-4.6
Pearl Millet	348-361	61.8-67.5	10.9-11.6	5.0-5.4	1.2-8.0	42-50	2.8-8.0
Foxtail Millet	331-351	60.9-63.2	11.2-12.3	4.3-4.5	8.0-11.1	31-35	1.1-2.8
Proso Millet	341-356	63.8-70.4	12.0-12.5	1.1-3.5	2.2-3.0	14-18	0.8-3.8
Barnyard Millet	300-307	55.0-65.5	6.2-11.2	2.0-3.9	6.0-10.1	11-20	5.0-15.0
Kodo Millet	309-345	65.9-78.2	6.8-8.3	0.5-1.4	9.0-13.1	27-35	0.5-1.7
Little Millet	329-341	67.0-68.8	7.1-7.7	4.2-4.7	7.0-8.6	12-17	7.0-9.3
Sorghum (Jowar)	329-349	72.0-72.6	10.4-10.6	1.9-3.1	1.6-8.4	13-25	3.9-5.4

Functional properties of millets

Millets are rich sources of dietary fibre, proteins, essential minerals, and bioactive compounds, which contribute significantly to their functional and health-promoting properties (K. K. Meena, Taneja, *et al.*, 2024) ^[46]. Their high fibre and resistant starch content support glycaemic regulation, digestive health, and enhanced satiety, while phenolic compounds, flavonoids, and carotenoids provide notable antioxidant activity (Sunil *et al.*, 2024) ^[83]. Millets also contain important minerals, including iron, calcium, magnesium, phosphorus, and zinc; however, antinutritional factors, such as phytates and tannins, may reduce their

bioavailability. Processing methods such as soaking, germination, and fermentation improve nutrient accessibility, digestibility, and overall functional quality (Dey *et al.*, 2022) ^[18]. Owing to their favorable techno-functional characteristics and naturally gluten-free nature, millets are widely incorporated into functional foods, including fermented beverages, probiotic products, bakery items, snacks, and ready-to-eat formulations. Furthermore, regular millet consumption has been associated with improved metabolic health and a reduced risk of lifestyle-related disorders (Rajalakshmi *et al.*, 2026; Siroha & Bangar, 2024) ^[65, 78].

Table 2: Functional properties of millet

S. No.	Functional Property	Reported Value/Range	Millet Type	Reference
1	Water Absorption Capacity (g/g)	1.60-1.71	Pearl, Finger and Fonio millet	(Eke-Ejiofor <i>et al.</i> , 2019) ^[21]
2	Oil Absorption Capacity (g/g)	1.55-1.64	Pearl, Finger, and Fonio millet	(Eke-Ejiofor <i>et al.</i> , 2019) ^[21]
3	Bulk Density (g/ml)	0.49-0.59	Millet flour varieties	(Eke-Ejiofor <i>et al.</i> , 2019) ^[21]
4	Swelling Power (g/g)	0.53-0.71	Millet flour varieties	(Eke-Ejiofor <i>et al.</i> , 2019) ^[21]
5	Solubility (%)	18.17-36.08	Millet flour varieties	(Eke-Ejiofor <i>et al.</i> , 2019) ^[21]
6	Water Absorption Index (g/100 g)	8.00±0.00	Kodo millet flour	(Srilekha <i>et al.</i> , 2019) ^[81]
7	Water Solubility Index (g/100 g)	8.06±0.02	Kodo millet flour	(Srilekha <i>et al.</i> , 2019) ^[81]
8	Water Holding Capacity	119-166 g/100 g	Foxtail and Proso millet	(Srilekha <i>et al.</i> , 2019) ^[81]
9	Oil Absorption Capacity	74-124 g/100 g	Different millet grains	(Abulude <i>et al.</i> , 2005) ^[1]
10	Foaming and Emulsifying Properties	Variable depending on processing	Finger millet	(Abulude <i>et al.</i> , 2005) ^[1]

*Adopted from (Jacob *et al.*, 2024; Borah *et al.*, 2026; Bibas *et al.*, 2026) ^[30, 12, 11].

Traditionally fermented millet-based beverages

Traditionally fermented millet-based beverages have constituted an important component of the dietary systems of several Asian and African populations owing to their nutritional, functional, and therapeutic attributes. These beverages originated from indigenous fermentation practices developed to enhance the shelf life, sensory acceptability, and nutritional quality of millet grains under traditional household conditions (Kumawat *et al.*, 2026) ^[38]. Conventionally, millet grains are subjected to cleaning, soaking, malting or milling, followed by grinding into a slurry and spontaneous fermentation mediated by naturally occurring lactic acid bacteria and yeasts. The fermentation process induces significant biochemical modifications that improve nutrient digestibility, enhance mineral bioavailability, and reduce antinutritional compounds such as phytates and tannins. Furthermore, fermentation promotes

the synthesis of bioactive metabolites, organic acids, and B-group vitamins, thereby enhancing the functional and probiotic potential of the beverages (Chamarthy & Tonapi, 2021) ^[14]. Similarly, Adesulu-Dahunsi *et al.*, (2025) ^[3] reported that traditionally fermented cereal-based beverages exhibit considerable probiotic and health-promoting properties by modulating beneficial gut microbiota, improving gastrointestinal health, enhancing immune response, and providing nutritional security. In addition, Shankar & Usha *et al.*, (2014) ^[75] evaluated the microbiological quality of the traditional fermented millet beverage “Koozh” consumed in Tamil Nadu, India, and observed a predominance of beneficial lactic acid bacteria; however, the detection of certain pathogenic microorganisms highlighted the necessity for improved hygienic practices during traditional processing and post-fermentation handling.

Table 3: Traditional fermented millet-based beverages and their health benefits

S. No.	Beverage	Millet Used	Traditional Processing	Major Benefits	Reference
1	Koozh	Finger millet/Pearl millet	Millet flour and rice slurry undergo spontaneous fermentation by LAB and yeasts	Improves digestibility and probiotic potential	(Shankar & Usha, 2014) ^[75]
2	Togwa	Finger millet	Malted millet flour is mixed with water and naturally fermented	Enhances gut health and nutrient bioavailability	(Ratau <i>et al.</i> , 2026) ^[68]
3	Mahewu	Finger millet	Cooked millet porridge subjected to lactic acid fermentation	Provides probiotics and antioxidant activity	(Pswarayi & Gänzle, 2019) ^[64]
4	Boza	Proso millet	Boiled millet mash fermented using LAB and yeasts	Supports gastrointestinal health and immunity	(Hancioğlu & Karapinar, 1997) ^[26]
5	Ogi	Millet/Sorghum	Soaking, wet milling, sieving, and spontaneous fermentation	Improves mineral absorption and gut microbiota	(Amadou, 2019) ^[4]
6	Oshikundu	Pearl millet	Fermented millet beverage prepared using malted millet flour	Provides energy and probiotic benefits	(Amadou, 2019) ^[4]
7	Burukutu	Pearl millet	Malting and alcoholic fermentation of millet grains	Rich source of energy and bioactive metabolites	(Amadou, 2019) ^[4]
8	Bushera	Millet/Sorghum	Fermented millet flour beverage prepared traditionally by spontaneous fermentation.	Enhances immunity and digestive health	(Amadou, 2019) ^[4]
9	Kunun-zaki	Pearl millet	Millet slurry fermented naturally with indigenous microorganisms	Improves sensory quality and probiotic activity	(Efuvwewere & Akona, 1995) ^[20]
10	Jandh	Finger millet	Fermentation of cooked millet grains using traditional starter culture	Provides probiotic and nutritional benefits	(Amadou, 2019) ^[4]

Role of probiotics and prebiotics in functional beverages
Probiotics

Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer beneficial physiological effects on the host, primarily through modulation of the gut microbiota, enhancement of digestive function, immune regulation, lactose metabolism, and improvement of overall metabolic health (Chowdhury *et al.*, 2024; Dobriyal *et al.*, 2024) ^[20, 15]. The scientific foundation of probiotics emerged in the early twentieth century through

the pioneering work of Élie Metchnikoff, who associated the consumption of fermented milk products with improved longevity and health, followed by Henri Tissier, who identified beneficial intestinal bacteria in breastfed infants. The term "probiotic" was formally introduced in 1965 and later standardized by the World Health Organization and Food and Agriculture Organization in 2001. Commonly used probiotic microorganisms include *Lactobacillus*, *Bifidobacterium*, *Saccharomyces*, *Streptococcus*, and *Enterococcus*, with lactic acid bacteria being the most

widely used group in functional foods and fermented dairy products (K. K. Meena *et al.*, 2024) ^[46]. These microorganisms exert health-promoting effects through multiple mechanisms, including inhibition of pathogenic microorganisms, production of antimicrobial metabolites, enhancement of nutrient absorption, reinforcement of intestinal barrier integrity, and modulation of host immune responses (Mazziotta *et al.*, 2023) ^[43]. Probiotics are widely incorporated into fermented food products such as yogurt, kefir, cheese, kimchi, sauerkraut, and miso, as well as dietary supplements and fortified functional foods, underscoring their growing significance in nutritional therapeutics and health-promoting dietary interventions (Li *et al.*, 2025; Ding *et al.*, 2024) ^[40, 18].

Prebiotics

Prebiotics are defined as selectively utilized, non-digestible substrates that confer health benefits to the host by promoting the growth and metabolic activity of beneficial intestinal microorganisms, particularly *Lactobacillus* and *Bifidobacterium* species (Hutkins *et al.*, 2025) ^[29]. Unlike digestible carbohydrates, prebiotics resist hydrolysis by digestive enzymes in the stomach and small intestine and therefore reach the intact, where they are fermented by beneficial gut microbiota. This selective microbial fermentation enhances gut microbial balance. It leads to the production of short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate, which contribute to improved intestinal health, enhanced mineral absorption, strengthened immune responses, maintenance of intestinal barrier integrity, and inhibition of pathogenic microorganisms (Yoo *et al.*, 2024) ^[90]. The concept of prebiotics emerged in the late twentieth century, with increasing recognition of the relationship between diet and gut microbiota, and the term "prebiotic" was first introduced in 1995 by Marcel Roberfroid and Glen R. Gibson to describe dietary ingredients that selectively stimulate beneficial intestinal bacteria. Since then, extensive research in food science, microbiology, and nutrition has highlighted the significance of prebiotics in functional foods and human health. Commonly studied prebiotics include inulin, fructooligosaccharide (FOS), galactooligosaccharides (GOS), resistant starch, Xylo oligosaccharides (XOS), and isomalt oligosaccharides (IMO), all of which serve as fermentable substrates for beneficial gut microorganisms and contribute to improved gastrointestinal function, metabolic regulation, and overall physiological well-being (Gibson *et al.*, 2017) ^[24].

Synbiotic concept

Synbiotic beverages are functional drinks that combine probiotics and prebiotics in a single formulation to deliver synergistic health benefits. In these beverages, prebiotics serve as fermentable substrates that selectively stimulate the growth and activity of beneficial probiotic microorganisms such as *Lactobacillus* and *Bifidobacterium*, thereby improving their survival, stability, and functionality during processing and storage (Nazhand *et al.*, 2020) ^[57]. The

concept of synbiotics emerged from the growing scientific understanding of the human gut microbiome and the need to enhance the effectiveness of probiotic products through supportive nutritional components, such as inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), and resistant starch. Incorporation of synbiotics improves the nutritional and sensory quality of beverages by enhancing probiotic viability, antioxidant activity, nutrient bioavailability, flavor, texture, and shelf stability (Wang *et al.*, 2024) ^[89]. Regular consumption of synbiotic beverages supports gut microbial balance, digestion, immunity, nutrient absorption, and metabolic health while helping to reduce gastrointestinal disorders. Increasing consumer awareness regarding preventive healthcare, plant-based nutrition, and functional foods has further accelerated the global demand for synbiotic beverages as innovative and health-promoting dietary products. (Sommermeyer & Piątek, 2024) ^[81].

Importance of probiotics and prebiotics in beverages

Probiotic, prebiotic, and synbiotic beverages have gained significant importance in functional food development owing to their ability to enhance gut health, immunity, digestion, and overall metabolic well-being. The incorporation of beneficial microorganisms into beverages originated in traditional fermented foods and has advanced significantly as consumer demand for health-promoting, plant-based products has grown. *Beverages* serve as efficient carriers for probiotics because of their ease of consumption and ability to deliver viable beneficial microorganisms such as *Lactobacillus*, *Bifidobacterium*, *Saccharomyces*, and *Streptococcus* species (Ranadheera *et al.*, 2017) ^[67]. Prebiotics, including inulin, fructooligosaccharide (FOS), galactooligosaccharides (GOS), and resistant starch, further enhance probiotic survival, stability, and activity by providing fermentable substrates for microbial growth. Moreover, synbiotic beverages, which combine probiotics and prebiotics, improve microbial viability, gastrointestinal function, immune modulation, and sensory acceptability throughout storage (Sommermeyer & Piątek, 2024) ^[81]. These beverages are rich in dietary fibre, antioxidants, vitamins, bioactive compounds, and short-chain fatty acid precursors, which support intestinal microbial balance, nutrient absorption, and gastrointestinal integrity. Consequently, regular consumption of such functional beverages is associated with improved digestion, enhanced lactose metabolism, reduced gastrointestinal disorders, strengthened immune responses, and better overall health outcomes. Similarly, Nazhand *et al.*, (2020) ^[57] reported that both dairy and non-dairy functional beverages enriched with probiotics, prebiotics, and synbiotics enhance gut health, immunity, and digestive function. In contrast, Ramiseti & Muchahary, (2025) ^[68] highlighted xanthan gum as an effective stabilizer that improves probiotic viability, gastrointestinal stability, sensory quality, and shelf life of functional beverages.

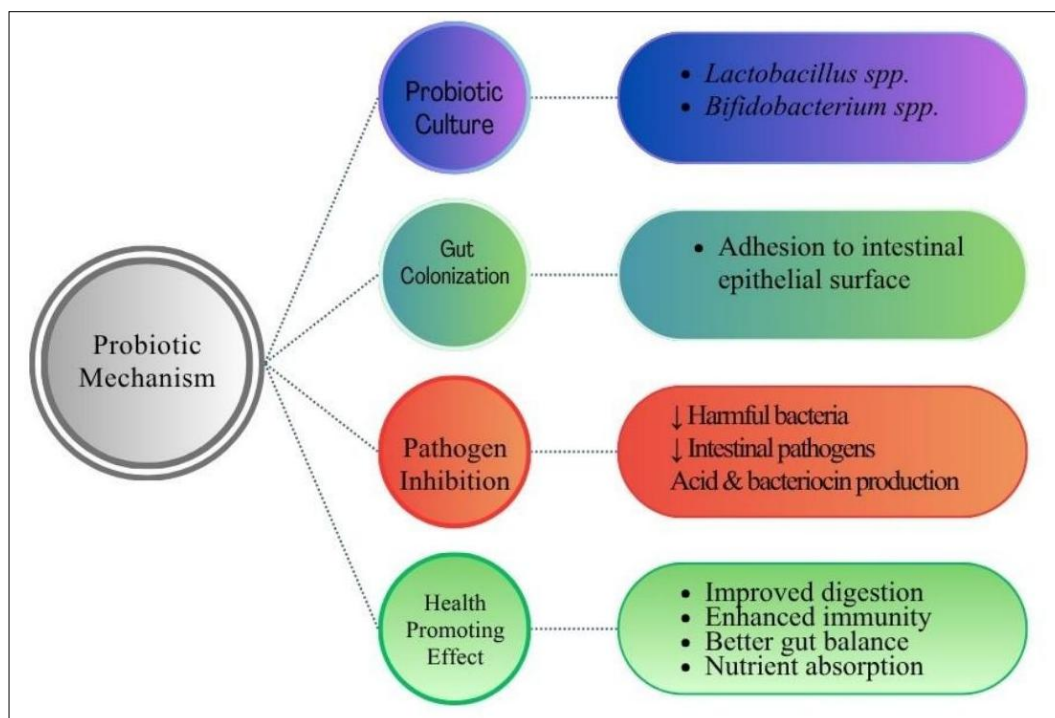


Fig 1: Role of probiotics in millet-based beverages

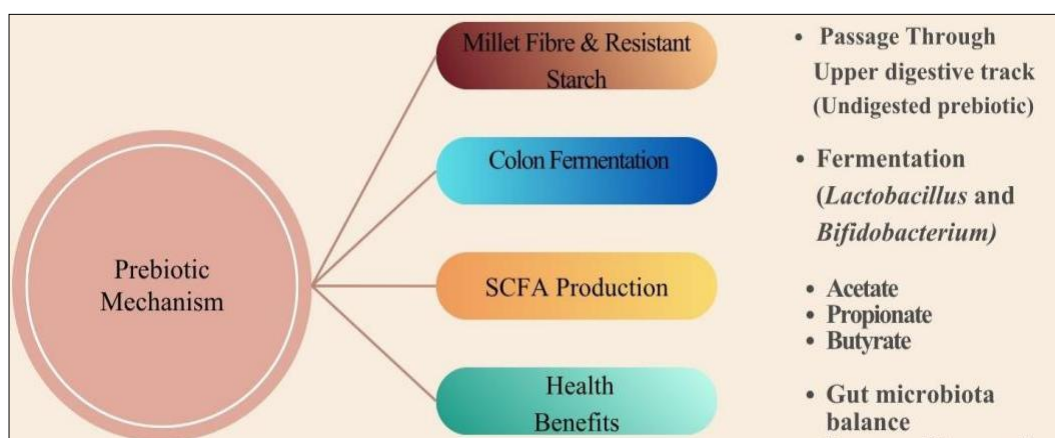


Fig 2: Role of prebiotics in millet-based beverage

Millet-based beverages

Millet-based beverages originated from traditional cereal-based drinks widely consumed in Asian and African communities due to their affordability, high satiety value, and nutritional richness (Adebisi *et al.*, 2018) ^[2]. Traditionally, millets were processed into porridges, fermented drinks, and malted beverages to enhance digestibility, preservation, and sensory acceptability (Soni *et al.*, 2023) ^[80]. In recent years, increased awareness of gluten-free diets, sustainable food systems, and functional nutrition has driven interest in millet-based beverages as healthier alternatives to conventional drinks (Kumawat *et al.*, 2025) ^[39]. Millets are rich in dietary fibre, proteins, essential minerals, vitamins, antioxidants, and bioactive compounds that support improved digestion, glycemic regulation, cardiovascular health, and immune function (Kumar *et al.*, 2018) ^[37]. Beverage preparation generally involves soaking to hydrate grains and reduce antinutritional factors, followed by germination or malting to enhance enzymatic activity, nutrient bioavailability, and functional properties (Mahendran and U, 2025) ^[41]. Subsequently,

roasting is performed to enhance the flavor, aroma, and storage stability of the grains, while grinding converts the roasted grains into fine flour suitable for beverage formulation (Sruthi & Rao, 2021) ^[82]. Thereafter, filtration is performed to obtain a smooth, homogeneous, and sensory acceptable beverage with improved stability and texture (Bembem & Agrahar-Murugkar, 2020) ^[9]. Furthermore, Krishnamoorthy *et al.*, (2025) ^[36] developed a fermented beverage from foxtail millet, pearl millet, and oyster mushroom extract. They reported enhanced nutritional quality, improved sensory characteristics, and extended shelf life in the fermented sample compared to the non-fermented beverage. Similarly, Baranidharan *et al.*, (2026) ^[8] investigated the stabilization of pearl millet beverages using high-pressure microfluidization and soy protein fortification, concluding that the combined treatment effectively reduced sedimentation and improved beverage stability and quality, thereby supporting the development of shelf-stable millet-based functional beverages (K. K. Meena, Taneja, Ojha, *et al.*, 2025) ^[47, 49].

Table 4: Global millet-based beverages and their traditional significance

S. No	Beverage	Country/Region	Type	Brief Description	Reference Link
1	Uji	Kenya, Uganda, Tanzania	Fermented porridge beverage	Nutritious breakfast and weaning drink	(Amadou, 2019) ^[4]
2	Ben-saalga	Burkina Faso	Fermented beverage	Sweet-sour cereal drink is widely consumed locally	(Amadou, 2019) ^[4]
3	Zoom-koom	Burkina Faso	Non-alcoholic beverage	Sweet traditional millet-based refreshment	(Amadou, 2019) ^[4]
4	Chyang (Chee)	Nepal, Sikkim, Bhutan	Mild alcoholic beverage	Fermented probiotic millet drink of the Himalayan communities	(Ray <i>et al.</i> , 2016) ^[69]
5	Kodo ko Jaanr	Nepal, India, Bhutan	Fermented alcoholic drink	Traditional cereal beer is made using a starter culture	(Amadou, 2019) ^[4]
6	Madua Apong	India (Northeast)	Alcoholic beverage	Tribal fermented millet beer	(Amadou, 2019) ^[4]
7	Ambali	South India	Non-alcoholic fermented drink	Thin fermented ragi beverage consumed in summer	(Sarkar <i>et al.</i> , 2015) ^[72]
8	Xiao mi jiao	Taiwan/China	Alcoholic beverage	Traditional millet wine is prepared by fermentation	(D. Sharma <i>et al.</i> , 2026) ^[76]
9	Tchapalo	Ivory Coast, West Africa	Alcoholic millet beer	Traditional fermented Sahel millet beer	(Coulibaly <i>et al.</i> , 2020) ^[16]
10	Pito	Ghana, Nigeria	Alcoholic fermented beverage	Pito is a traditional West African fermented alcoholic beverage prepared mainly from millet or sorghum through natural fermentation.	(Sefa-Dedeh <i>et al.</i> , 1999) ^[73]

Millet-based probiotic beverages

Millet-based probiotic beverages originated from traditional fermented cereal drinks widely consumed in Asian and African communities for their nutritional, digestive, and preservative benefits. In recent years, increasing awareness regarding gut health, lactose intolerance, glutenfree diets, and functional nutrition has accelerated consumer interest in probiotic millet beverages as sustainable and health-promoting alternatives to dairy-based products (Ziaro & Cichońska, 2021) ^[91]. These beverages are commonly formulated using probiotic strains such as *Lactobacillus* and *Bifidobacterium*, which efficiently ferment millet substrates due to their high carbohydrate and fibre content. During fermentation, microbial growth and acid production improve fermentation kinetics, product stability, flavor, and texture, while ultaneously enhancing protein digestibility, mineral bioavailability, antioxidant activity, and bioactive compound concentration and reducing antinutritional factors (Kaila *et al.*, 2025; K. K. Meena, Taneja, Jain, *et al.*, 2025)

[33, 47, 49]. Furthermore, regular consumption of millet-based probiotic beverages supports gut microbial balance, improves digestion and immunity, and provides antioxidant and metabolic health benefits, thereby increasing their significance in the functional beverage industry (Janani & Adeyeye, 2025) ^[31]. In addition, (L. Meena *et al.*, 2024) ^[46] demonstrated that ultrasound-assisted fermentation of finger millet beverages significantly accelerated fermentation kinetics, increased lactic acid production, and improved viscosity and water-holding capacity through structural modification of millet proteins (Joshi *et al.*, 2025) ^[32]. Similarly, (Navyashree *et al.*, 2023) ^[57] developed and optimized a vegan probiotic beverage from white finger millet and reported high probiotic viability, desirable physicochemical properties, good sensory acceptability, and improved nutritional composition, concluding that finger millet serves as an effective carrier for probiotic delivery in beverages suitable for vegan and lactoseintolerant consumers.

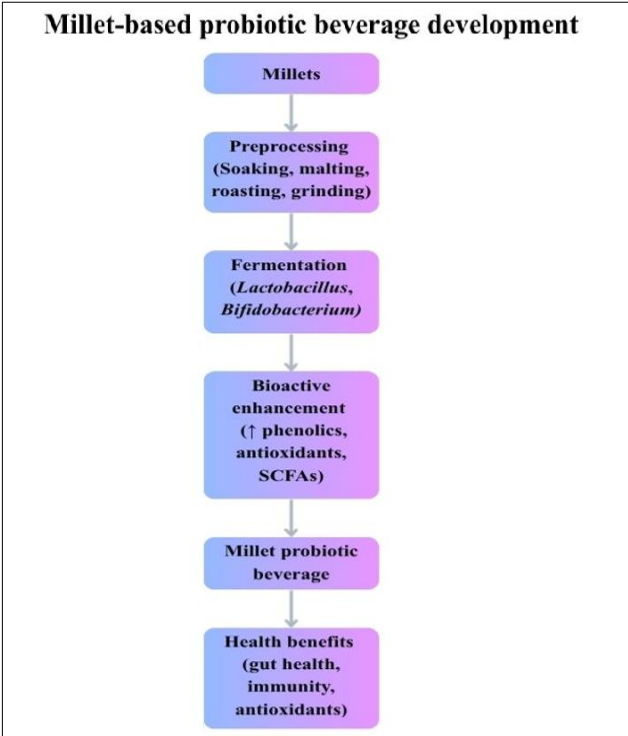


Fig 3: Processing steps of millet-based probiotic beverages

Consequently, millet-based probiotic beverages are functional drinks produced by fermenting millet extracts with beneficial microorganisms such as *Lactobacillus* and *Bifidobacterium*. These beverages are receiving growing attention due to their potential to improve gut health, digestion, immunity, and intestinal microbial balance (Samtiya *et al.*, 2024) [71]. The presence of dietary fibre, resistant starch, minerals, and bioactive compounds in millets supports probiotic growth and enhances the functional properties of the beverage. Consequently, their regular consumption is considered beneficial for overall health, particularly among lactose-intolerant and health-conscious consumers (Gouthami *et al.*, 2024).

Regulatory standards for millet-based probiotic beverages/drinks

The global regulatory landscape for millet-based probiotic beverages is advancing rapidly in response to growing consumer demand for plant-derived functional foods and nutraceutical products. *International* agencies, including the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), together with regulatory authorities such as the European Food Safety Authority (EFSA), the United States Food and Drug Administration (USFDA), and the Food Safety and Standards Authority of

India (FSSAI), have established comprehensive guidelines to ensure product safety, quality, and functional reliability. These regulations emphasize the incorporation of scientifically characterized probiotic strains with proven health-promoting properties, genetic stability, and non-pathogenic status. Millet-based probiotic beverages must comply with stringent microbiological specifications, contaminant thresholds, hygienic processing standards, and standardized manufacturing procedures to ensure consumer safety and product consistency. Furthermore, probiotic microorganisms must maintain adequate viability and metabolic activity throughout storage to deliver the intended physiological benefits. Regulatory frameworks also mandate accurate nutritional labeling and scientifically substantiated health claims supported by experimental or clinical evidence prior to commercialization. Depending on regional policies and product composition, these beverages are categorized as functional foods, novel foods, or fermented cereal-based products. Adherence to Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Point (HACCP) principles, and internationally accepted food safety standards remains essential for ensuring product integrity, regulatory compliance, and global market acceptance.

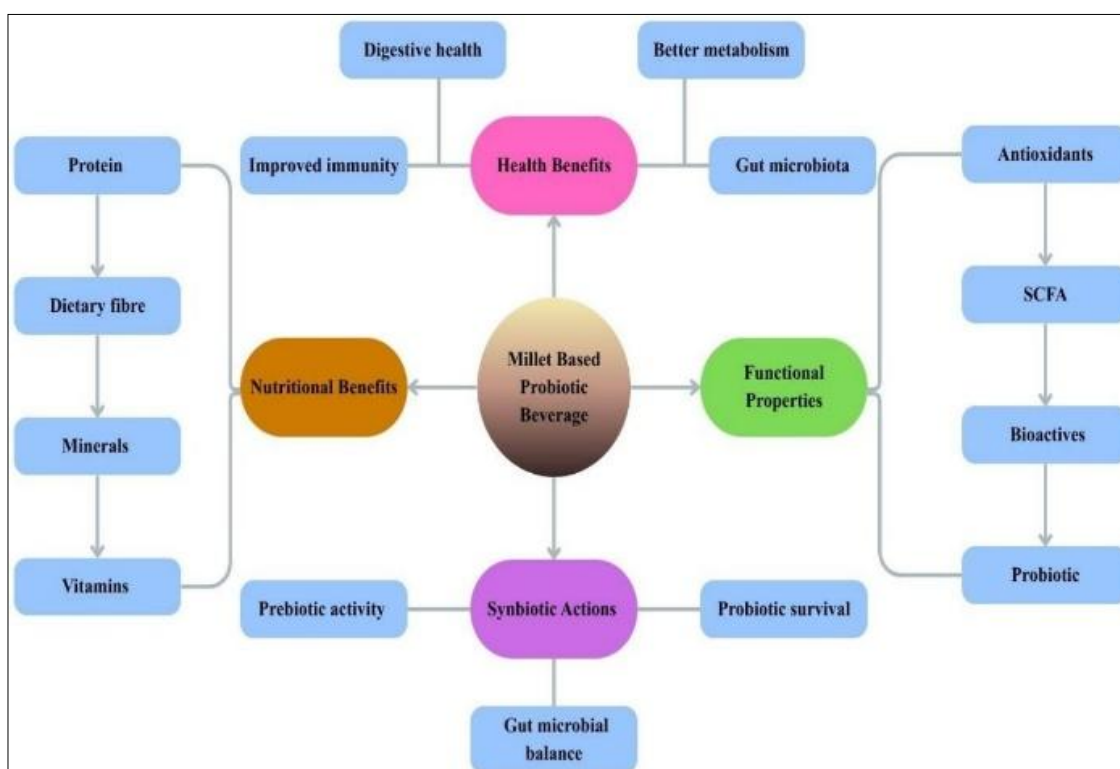


Fig 4: Functional benefits of millet-based probiotic beverages

Prebiotic activity

Prebiotic activity refers to the ability of certain non-digestible food components, known as prebiotics, to selectively stimulate the growth and metabolic activity of beneficial microorganisms in the gastrointestinal tract. These compounds, such as inulin, fructooligosaccharides (FOS), and galacto-oligosaccharides (GOS), are not digested in the upper digestive system and therefore reach the intact. In the large intestine, they are utilized by beneficial bacteria such as *Lactobacillus* and *Bifidobacterium*, which ferment these substrates and produce short-chain fatty acids like

acetate, propionate, and butyrate. This fermentation process improves the balance of gut microbiota, enhances intestinal health, and inhibits the growth of harmful microorganisms. As a result, prebiotic activity contributes to improved digestion, better nutrient absorption, strengthened immune response, and overall gastrointestinal well-being. Therefore, the main outcome of prebiotic activity is the promotion of a healthy gut microbial environment, which supports various physiological functions and contributes to overall human health (Huebner *et al.*, 2008) [28].

Prebiotic activity of millet components

Millet components possess substantial prebiotic potential owing to their high concentrations of dietary fibre, resistant starch, non-digestible oligosaccharides, and phenolic bioactive compounds, which collectively support gastrointestinal health and microbial homeostasis. Millet fibre and resistant starch escape enzymatic digestion in the upper gastrointestinal tract and are subsequently fermented in the, thereby selectively promoting the growth and metabolic activity of beneficial gut microbiota, particularly *Lactobacillus* and *Bifidobacterium*. In addition, millet-derived oligosaccharides and phenolic compounds act as fermentable substrates and bioactive modulators that enhance probiotic proliferation, enzymatic activity, and overall microbial metabolism, while their fermentation leads to the generation of short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate, which play a crucial role in maintaining intestinal epithelial integrity, regulating immune responses, exerting anti-inflammatory effects, and supporting metabolic homeostasis (Tomar *et al.*, 2025) [85]. Furthermore, millet-associated prebiotic constituents modulate gut microbiota composition by inhibiting pathogenic microorganisms and improving microbial diversity, stability, and ecological balance within the intestinal environment; consequently, millet-based beverages demonstrate strong synbiotic potential when combined with probiotic cultures, as they enhance probiotic viability, fermentation efficiency, functional performance, and overall health-promoting properties in advanced functional beverage systems (Ziarno & Cichońska, 2021) [91]. Moreover, Peekhan *et al.*, (2024) [61] optimized a functional millet-based formulation using foxtail, barnyard, and kodo millets and reported high dietary fibre content, enhanced antioxidant and prebiotic activity, and a low glycemic index, thereby confirming its suitability as a health-promoting functional food, while Farzana *et al.*, (2024) [22] demonstrated that fermentation of pearl millet significantly improves mineral bioavailability, increases resistant starch content, enhances phenolic concentration, and stimulates beneficial gut bacteria such as *Bifidobacterium breve*, thereby strengthening the overall nutritional and functional quality of millet-based probiotic formulations.

Fermentation

Fermentation is one of the oldest food preservation techniques, with origins traced back to 6000-7000 BCE in ancient civilizations such as Mesopotamia, Egypt, China, and India, where naturally occurring microorganisms converted sugars into acids, alcohol, and gases, thereby enhancing preservation, flavour, and shelf life of foods like bread, beer, wine, yoghurt, and fermented vegetables; its scientific basis was later established by Louis Pasteur in the nineteenth century, who confirmed microbial involvement and laid the foundation of modern fermentation science, which is now widely applied in food, pharmaceutical, and biotechnology industries for producing functional foods, beverages, enzymes, antibiotics, and bioactive compounds. *Fermentation* is a biochemical process mediated by yeasts,

bacteria, or moulds under anaerobic or low-oxygen conditions that improves sensory, nutritional, and functional properties of foods (Kitessa, 2024) [35], while in the human, fermentation of prebiotics produces short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate that enhance gut health by lowering intestinal pH, inhibiting pathogens, strengthening the gut barrier, and regulating immunity and metabolism.

Prebiotics are naturally present in fruits, vegetables, legumes, cereals, and millets, with millet-based substrates showing strong functional potential due to their high dietary fibre and bioactive compounds. At the same time, fermentation efficiency is influenced by temperature, pH, oxygen availability, substrate composition, and time (Tamang *et al.*, 2020) [84], which together determine microbial growth and product quality. Moreover, fermentation is extensively utilized across food, beverage, and pharmaceutical industries for the production of dairy and cereal foods, alcoholic drinks, antibiotics, enzymes, and vitamins, thereby contributing to improved preservation, enhanced nutritional value, and development of probiotic-rich functional foods with significant health-promoting effects.

Recent techniques for optimization of fermented millet-based beverages

Optimization of millet-based fermented beverages involves the systematic regulation of formulation and processing parameters to achieve superior physicochemical, microbiological, nutritional, and sensory quality, including control of millet concentration, fermentation time, temperature, inoculum level, and sugar content to ensure efficient fermentation, balanced acidity, improved viscosity, enhanced probiotic viability, and overall product stability (Weldeabzgi *et al.*, 2025) [87]. In this context, Neeru *et al.*, (2024) [58] optimized a pearl millet-buttermilk-based traditional fermented beverage (rabadi) by evaluating multiple formulations under controlled fermentation conditions. They reported that the optimized sample exhibited improved antioxidant activity, increased phenolic content, and reduced tannin levels, while FTIR analysis confirmed the presence of key bioactive compounds, including carbohydrates, proteins, fatty acids, and phenolics, thereby demonstrating the nutritional enhancement of millet-based fermentation systems. Similarly, Mishra *et al.*, (2025) [51] developed and optimized a ragi-based probiotic camel milk beverage using a Central Composite Rotatable Design by adjusting ragi concentration and fermentation time, which resulted in enhanced antioxidant potential, improved sensory acceptability, increased flavonoid and polyphenol content, and stable probiotic viability during storage for up to 21 days, with metabolomic and FTIR analyses further confirming the enrichment of functional bioactive compounds. Overall, these studies highlight that optimizing millet-based fermented beverages significantly improves fermentation efficiency, probiotic stability, functional properties, and consumer acceptability, thereby supporting their development as nutritious and health-promoting functional foods.

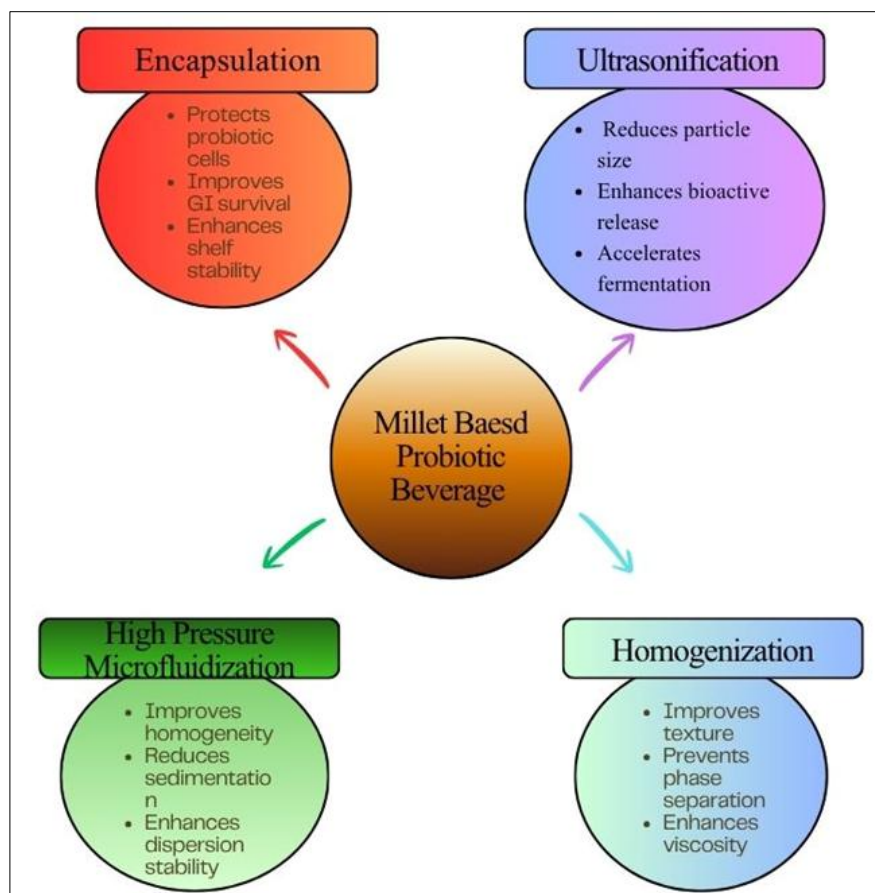


Fig 5 Emerging technologies in millet beverage processing

Ultrasound treatment

Ultrasound treatment is a non-thermal processing technology operating at high frequencies (20-100 kHz) that induces cavitation and microstreaming, thereby enhancing mass transfer, particle disruption, and microbial interactions, and in millet-based beverages it is applied to improve extraction efficiency, fermentation performance, and physicochemical stability through disruption of starch-protein matrices, increased nutrient release, and improved substrate availability for probiotic fermentation, while also accelerating the activity of probiotic strains such as *Lactobacillus* and *Bifidobacterium*, resulting in enhanced acid production, faster fermentation kinetics, and reduced processing time along with improved texture, viscosity, and sensory acceptability due to reduced particle size and sedimentation. In this context, Meena *et al.*, (2024) ^[46] demonstrated that ultrasound-assisted processing of white finger millet-based probiotic beverages optimized via response surface methodology significantly improved phenolic and flavonoid content, antioxidant activity, reducing sugars, and viable probiotic counts while enhancing fermentation kinetics and overall beverage quality, thereby confirming finger millet as a suitable substrate for probiotic beverage development. Similarly, Nesha *et al.*, (2026) ^[59] reported that ultrasonication of a synbiotic millet-based beverage from *Bati mandia* with *Leuconostoc mesenteroides* effectively reduced processing time while improving protein, fibre, microbial load, and bioactive compound content, reducing *anti-nutritional* factors, and enhancing sensory and functional properties, ultimately concluding that ultrasound is a rapid, efficient, and sustainable technique for producing high-quality millet-based functional beverages.

High-pressure microfluidization

High-pressure microfluidization (HPMF) is a non-thermal processing technique operating at very high pressures (50-200 MPa) that forces liquid through microchannels, generating intense shear and cavitation forces, and in millet-based beverages it is employed to reduce particle size, homogenize the system, and enhance physical stability by minimizing sedimentation and phase separation, while ultaneously disrupting starch-protein matrices to improve nutrient release, antioxidant activity, texture, viscosity, sensory quality, and probiotic stability in fermented formulations. In this context, Baranidharan *et al.*, (2026) ^[8] demonstrated that HPMF applied to pearl millet extract in combination with soy protein isolate significantly improved dispersion and structural modification of starch-protein complexes, resulting in reduced sedimentation, enhanced viscosity and homogeneity, and extended shelf life up to 12 days, thereby confirming improved physicochemical stability and beverage quality. Similarly, Bhukya *et al.*, (2025) ^[10] reported that microfluidization effectively reduced particle size and enhanced homogeneity through shear and cavitation effects, leading to improved rheological properties, better dispersion of bioactive compounds, and overall enhancement of stability, nutritional quality, and sensory acceptability, thereby establishing HPMF as a highly effective technique for producing stable and nutritionally enriched millet-based functional beverages.

Homogenization

Homogenization is a mechanical processing technique that reduces particle size and ensures uniform dispersion in liquid systems through the application of high pressure. In millet-based beverages, it is primarily used to enhance

physical stability by disrupting starch-protein aggregates, preventing sedimentation, and improving overall matrix uniformity, while also contributing to improved texture, viscosity, sensory quality, and enhanced availability of nutrients and bioactive compounds. In fermented systems, it further supports better probiotic distribution and viability, thereby improving functional performance and shelf stability. In this context, Mishra *et al.*, (2024) ^[52] demonstrated that optimization of finger millet beverage extraction using a central composite design, combined with xanthan gum incorporation, significantly improved homogeneity, reduced sedimentation, and enhanced rheological behavior, while ultaneously increasing phenolic content, antioxidant activity, and functional properties and reducing antinutritional factors, thereby confirming improved stability and acceptability. Similarly, Pan *et al.*, (2019) ^[60] reported that controlled processing of millet-skim milk beverages, including soaking in NaHCO₃ solution and blanching, improved physicochemical properties such as pH, viscosity, total solids, and stability, resulting in better uniformity and sensory quality. They concluded that optimized processing conditions effectively enhance the overall quality and stability of millet-based dairy beverages.

Challenges and future prospects
Limitations of millet-based functional beverages

Millet-based probiotic beverages face several challenges, including sedimentation due to high starch and fibre content, poor mouthfeel, undesirable flavor, reduced probiotic viability during processing and storage, and a lack of standardized formulations, which together limit shelf stability, sensory acceptability, and large-scale commercialization. In this context, Perveen & Chishty, (2025) ^[63] reviewed cereal-and millet-based probiotic beverages and reported that although fermentation enhances nutritional value and supports probiotic survival, issues such as variability in processing, inconsistent sensory quality, and limited storage stability persist; therefore, optimization and standardization are essential to improve product performance. Similarly, Challa *et al.*, (2025) ^[13] developed a foxtail millet-based

probiotic beverage using *Lactobacillus* spp. and observed that optimized fermentation (8 h) improved physicochemical properties, mineral content, and consumer acceptability, whereas sedimentation and changes in antioxidant profile still affected stability. Overall, these findings suggest that although millet is a promising substrate for the development of probiotic beverages, further refinement of processing conditions is necessary to enhance stability, functionality, and commercial feasibility.

Future prospects of millet-based probiotic beverages
Millet-based probiotic beverages hold strong future potential as sustainable, plant-based functional drinks owing to their high nutritional value, prebiotic properties, and compatibility with probiotic cultures; however, further advancements are required to enhance their overall stability and acceptability. Accordingly, future research will focus on improving probiotic viability, fermentation efficiency, and product stability through emerging technologies such as encapsulation, ultrasonication, and homogenization, while also developing synbiotic formulations along with flavor and texture masking strategies to improve sensory quality and consumer acceptance; furthermore, standardization of processing conditions and shelf-life enhancement techniques will be essential to facilitate large-scale commercialization. In this context, Janani & Adeyeye, (2025) ^[31] reviewed millet-based probiotic beverages and reported that millets effectively support gut health and probiotic delivery due to their inherent prebiotic nature and fermentation potential, while also emphasizing the increasing global demand for plant-based functional beverages and continuous innovation in product development, thereby concluding their strong promise as sustainable alternatives to dairy-based drinks. Similarly, Kaila *et al.*, (2025) ^[33] developed a *Lactobacillus plantarum*-fermented pearl millet beverage that significantly enhanced the nutritional composition, probiotic viability, bioactive compounds, and antioxidant activity. Further, they demonstrated improved healthspan, reduced oxidative stress, and extended lifespan in *Caenorhabditis elegans*, thereby reinforcing its potential as a functional beverage for gut health promotion and healthy aging.

Challenges and Technological Solutions In Millet-Based Probiotic Beverages		
Challenges	Description	Solution
Sedimentation & Phase Separation	• High starch content • Fibre aggregation	Encapsulation • Protective coating matrix • Improved survival during processing & storage
Low Probiotic Viability	• Acidic stress • Storage instability	Flavour Optimization • Natural flavour addition • Sweeteners/fruits • Texture improvement
Poor Flavour and Mouthfeel	• Grainy texture • Undesirable taste	Cold Storage & Stabilization • Controlled storage • Use of stabilizers
Limited Shelf Life	• Microbial instability • Physicochemical changes	Process Optimization • Optimization of pH • Time & temperature control • Standardized formulation

Fig 6: Challenges and technological solutions in millet-based probiotic beverages

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Conclusion

Millet-based probiotic beverages have emerged as promising next-generation functional foods that address the growing demand for plant-based, sustainable, gluten-free, and lactose-free alternatives with potential gut health benefits. Millets provide an excellent fermentation substrate owing to their rich content of dietary fibre, resistant starch, essential minerals, vitamins, and bioactive phytochemicals, and they also exhibit intrinsic prebiotic properties that support beneficial gut microbiota. Controlled probiotic fermentation further enhances nutrient bioavailability, digestibility, antioxidant activity, and sensory quality, thereby improving the overall functional value of these beverages. Recent advances in processing technologies, including ultrasonication, homogenization, and high-pressure microfluidization, have demonstrated considerable potential to improve probiotic viability, physicochemical stability, and consumer acceptability.

Despite these advantages, challenges such as sedimentation, undesirable sensory attributes, variability in processing protocols, and reduced probiotic survival during storage continue to hinder large-scale commercialization. Future research should therefore focus on developing standardized processing and fermentation strategies to ensure consistent product quality and industrial scalability. Advanced probiotic delivery approaches, particularly microencapsulation and nanoencapsulation, offer promising opportunities to enhance microbial stability and functionality throughout storage and gastrointestinal transit. Furthermore, integrating millet-derived prebiotics with selected probiotic strains can facilitate the development of innovative synbiotic beverages with enhanced health benefits.

The application of emerging non-thermal technologies and multi-omics tools may provide deeper insights into fermentation dynamics, bioactive metabolite production, and host-microbe interactions. Additionally, robust clinical studies are required to validate health claims and strengthen consumer confidence. With continued technological innovation, scientific validation, sensory optimization, and regulatory harmonization, millet-based probiotic beverages are well-positioned to evolve from niche functional products into mainstream dietary interventions that support human health, nutritional security, and environmental sustainability.

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Conflicts of interest/Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author contribution

Conceptualization: Sonali Das and Kamallesh Kumar Meena; Writing—original draft preparation: Sonali Das and Lokesh Kumawat; Resources and supervision: Kamallesh Kumar Meena, and Kusum Meghwal; Writing-review and editing: Kamallesh Kumar Meena and Kusum Meghwal. All

the authors have read and agreed to the published version of the manuscript.

Data availability

All datasets generated or analyzed during this study are included in the manuscript.

Declaration on the use of AI tools

The authors declare that artificial intelligence (AI) tools (ChatGPT (OpenAI), Paperpal, and Grammarly) were used solely for language refinement, grammar correction, and clarity improvement in the manuscript. All scientific content, data interpretation, critical analysis, and conclusions presented in this review are the original work of the authors. The authors take full responsibility for the accuracy, integrity, and originality of the manuscript content.

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