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Evolution from traditional dairy-based fermented beverages to emerging plant-based alternatives

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Fermented beverages have received significant research and industry attention due to recent findings showing the association between consumption of these beverages and nutritional, functional, and medicinal benefits. Fermented beverages are produced using various substrates including dairy, cereals, fruits, vegetables, legumes, nuts, and seeds through microbial fermentation resulting in beverages with probiotic and other functional ingredients, such as bioactives, antioxidants, vitamins, and minerals beneficial for human health. Moreover, fermentation brings a lot of value to the product due to extended shelf-life, enhanced sensory characteristics, increased digestibility and availability of nutrients, improved safety from microorganisms and pathogenic strains. There are various kinds of dairy fermented beverages including kefir, yogurt drinks, lassi, buttermilk, kumis, ayran known for their probiotic and nutritional value. However, cereal-based fermented drinks still remain an important part of the daily diets and food supply in many countries. Due to increasing cases of lactose intolerance and veganism, environmental sustainability, and preventive nutrition, there is a growing tendency to shift the demand from milk-based to plant-based fermented beverages. The fermentation method, bacteria utilized, qualities, health consequences, industrial practices, and future prospects of fermented beverages are all thoroughly reviewed in this paper, which covers both conventional and novel fermented beverages.

Keywords: Fermented beverage, Probiotics, Antioxidants, Shelf life, Bioavailability

Introduction

Fermentation has been one of the most extensively studied applications in the processing of foods among all ancient cultures. This technology was applied since ancient times in various parts of the world. While this process used to be an empirical way of preserving food, we now know the underlying biochemical principles behind it. Despite that, the importance of fermented products remains very high today because these foods and beverages are consumed on a global scale and their consumption offers a lot more than just food preservation[1]. The fermentation process itself is based on the metabolism of bacteria and yeasts. These microorganisms undergo anaerobic or facultative fermentation processes that result in the production of various compounds like organic acids, ethanol, CO_2, and others[2]. All these products are responsible for acidification, taste formation, and food preservation. In recent decades, an increased awareness regarding the importance of the human microbiome has resulted in an increased interest in fermented foods. Probiotic content, as well as bioactive metabolites that are produced during fermentation, make fermented beverages capable of having multiple physiological functions. These may include their antioxidant, antimicrobial, anti-inflammatory, and antidiabetic properties along with other activities and

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also modulation of the human microbiota[3,4]. Moreover, fermentation enhances the availability of nutrients and reduces antinutrient substances.

The story of fermented beverages can be seen as the story of local innovations. Indigenous fermented drinks evolved depending on the locally available substrates and microflora, and some are still regularly consumed. Dairy-based fermented beverages include kefir, yoghurt drinks, buttermilk, and lassi. All these beverages contain high amounts of protein, calcium, B-vitamins, and live cultures of lactic acid bacteria[5]. They have been reported to have beneficial effects on digestion and gut flora balance. Just like dairy-based beverages, cereal-based fermented beverages represent one of the main groups of traditional beverages. Beverages made from fermented cereals are commonly found in the Asian, African, and European cuisines and include boza, togwa, kvass, and fermented rice drinks. Fermentation of grains such as wheat, maize, barley, millet, and rice improves their digestibility and bioavailability. Fermentation reduces the amount of antinutrients that inhibit the uptake of minerals and protein, such as phytates and condensed tannins[6]. In most traditional fermented beverages, lactic acid bacteria (LAB) play a key role in their development. LAB belong to the genera *Lactobacillus*, *Leuconostoc*, *Pediococcus,* and *Streptococcus*. They are responsible for lactic acid generation, competition with pathogenic microorganisms, formation of aromas and flavors, and health benefits that are often associated with the consumption of fermented beverages[7]. Yeasts such as *Saccharomyces cerevisiae* are mainly involved in the production of ethanol and aromatic components during mixed fermentation.

One of the changes that has taken place over recent years, both among consumers and researchers, is the increased use of alternative sources of food. The growth in demand for alternative beverages that do not come from milk can be attributed to factors like lactose intolerance, veganism and the environmental footprint associated with the production of milk. There has been growing research into beverages made through fermentation using fruits, vegetables, cereals, legumes and nuts. Such beverages have high levels of vitamins, fibre, phenolic antioxidants and phytochemicals that are active in the body[8]. They should not only be regarded as alternative beverages but also as functional foods. One beverage that has received much attention lately is Beetroot Kanji. Beetroot (Beta vulgaris) is a nutritious substrate with betalains that comprise nitrogen-containing pigments known to have strong antioxidants along with other chemicals like phenolic acids, ascorbic acid, folate, potassium and nitrates[9]. Spontaneous lactic acid fermentation results in the proliferation of the indigenous LAB populations and causes acidification, improving the microbial safety, enhancing sensory features and boosting the accessibility of nutrients[10]. Studies conducted on fermented beetroot have shown that their ability to act as antioxidants increases compared to unfermented substrates due to retention and formation of other bioactive substances in fermentation[11].

Although several review articles have discussed fermented foods, probiotics, dairy-based fermented beverages, or plant-based fermented beverages individually, very few studies have comprehensively compared the evolution from traditional dairy-based fermented beverages to emerging plant-based alternatives. Furthermore, recent advances in fermentation technology, precision fermentation, artificial intelligence, sustainability, and commercialization have not been integrated into a single review. Therefore, an updated and comprehensive review is required to summarize current knowledge and identify future research opportunities. This review provides a comprehensive comparison of traditional dairy-based and emerging plant-based fermented beverages by integrating information on fermentation technology, microbial diversity, nutritional composition, health benefits, sustainability, industrial trends, and future technological advances. Unlike previous reviews that primarily focus on individual beverage categories, this review critically compares dairy and plant-based alternatives, discusses emerging technologies such as precision fermentation and artificial intelligence, and identifies current research gaps for the development of next-generation functional beverages.

Literature search methodology

The literature included in this review was collected through a comprehensive search of major scientific databases, including Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar. The search was conducted using combinations of keywords such as fermented beverages, dairy fermented beverages, plant-based fermented beverages, functional beverages, probiotics, lactic acid bacteria, precision fermentation, artificial intelligence in food fermentation, metabolomics, Beetroot Kanji, and sustainable fermentation. Peer-reviewed research articles, review papers, and book chapters published primarily between 2005 and 2025 were considered. Greater emphasis was placed on recent publications (2015-2025) to ensure that the review reflects current scientific developments. Articles not published in English, duplicate records, conference abstracts without full texts, and studies unrelated to fermented beverages or functional food applications were excluded. The selected literature was critically evaluated to provide a comprehensive overview of fermentation technology, microbial diversity, nutritional composition, health benefits, industrial applications, sustainability, and emerging trends in dairy- and plant-based fermented beverages

Fermentation technology and microbial dynamics

Fermentation process and key parameters

In fermented beverages, the quality, safety, nutritional composition, and sensory characteristics are largely determined by fermentation conditions. During fermentation, microorganisms convert carbohydrates into organic acids, ethanol, carbon dioxide, and numerous bioactive metabolites through controlled metabolic activities. The efficiency of this process depends on several parameters, including the choice of starter culture, fermentation temperature, pH, fermentation time, oxygen availability, and substrate composition. Careful optimization of these parameters improves microbial growth, enhances probiotic viability, increases bioactive compound production, and ensures product safety and shelf stability.

Effect of temperature

Temperature is one of the most critical factors influencing microbial growth and metabolic activity during fermentation[12]. Most lactic acid bacteria associated with fermented beverages are mesophilic and exhibit optimum growth between 30 and 37°C, although some thermophilic species grow optimally at temperatures approaching 42°C[1]: whereas yeasts such as *Saccharomyces cerevisiae* generally exhibit optimum activity between 25-30°C. Excessively high temperatures may inhibit microbial growth and reduce probiotic survival, whereas lower temperatures slow fermentation and delay acid production[13]. Therefore, maintaining an appropriate fermentation temperature is essential for obtaining desirable flavour, texture, and microbial stability.

Effect of pH

The gradual reduction in pH during fermentation results from the production of organic acids, mainly lactic acid. Acidification inhibits spoilage microorganisms and foodborne pathogens while improving product safety[14]. The decrease in pH also promotes protein coagulation in dairy beverages and influences colour stability, texture, and flavour development in plant-based beverages.

Fermentation time

Fermentation time directly influences microbial population, acidity, flavour development, and bioactive compound formation. Short fermentation periods may result in insufficient acid production and poor probiotic growth, whereas prolonged fermentation can produce excessive acidity and undesirable sensory characteristics[15]. Therefore, optimization of fermentation duration is essential to achieve balanced flavour and maximum functional properties.

Starter cultures

Starter cultures consist mainly of selected strains of lactic acid bacteria and yeasts that initiate controlled fermentation. Common bacterial cultures include *Lactiplantibacillus plantarum*, *Lacticaseibacillus casei*, *Lactococcus lactis*, *Streptococcus thermophilus*, and *Leuconostoc* spp., while yeasts such as *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* contribute to flavour development and metabolite production. The selection of starter cultures significantly influences probiotic viability, nutritional quality, sensory properties, and shelf life of fermented beverages[16].

A summary of these key fermentation parameters and their effects on beverage quality is presented in Table 1.

Microbial dynamics and functional properties

Fermentation is a controlled biochemical process in which microorganisms convert carbohydrates present in dairy- and plant-based substrates into organic acids, alcohols, carbon dioxide, and a wide range of bioactive metabolites through enzymatic activity[17]. In fermented beverages, lactic acid bacteria (LAB) are the predominant microorganisms, often acting in association with yeasts and, in certain products, acetic acid bacteria. During fermentation, these microorganisms metabolize sugars via homofermentative or heterofermentative pathways, resulting in the production of lactic acid, ethanol, carbon dioxide, exopolysaccharides, vitamins, bioactive peptides, and other functional metabolites[16]. These biochemical transformations lower the pH, inhibit spoilage and pathogenic microorganisms, improve flavour, texture, digestibility, and nutrient bioavailability, and extend shelf life. The efficiency of fermentation is influenced by several factors, including the selection of starter cultures, fermentation temperature, pH, fermentation time, substrate composition, and oxygen availability, all of which determine the quality, safety, probiotic viability, and functional properties of the final beverage[18].

Nutritionally abundant, fermented beverages from milk

Table 1. Key factors influencing the fermentation process and their effects on the quality of fermented beverages

Parameter	Influence on fermentation	Effect on beverage quality
Temperature	Controls microbial growth	Flavour, probiotic viability
pH	Acidification	Safety, texture, preservation
Fermentation time	Metabolite production	Acidity, flavour, bioactive compounds
Starter culture	Determines microbial activity	Functional properties, shelf life
Oxygen availability	Influences yeast metabolism	Aroma, carbonation

have plenty of quality proteins, amino acids, vitamins, minerals, beneficial microorganisms, and bioactive compounds. Due to the process of fermentation, the enzymes released by microbes facilitate partial hydrolysis of milk proteins into amino acids and peptides[19]. The latter, in turn, can possess biological functions, including antioxidant, anti-hypertensive, antimicrobial, and immunological properties[20]. Moreover, through fermentation, the amount of lactose is significantly decreased, which makes fermented beverages easier to digest for lactose intolerant persons[21]. The beneficial effects of probiotic beverages from milk are due to their probiotic microflora, namely beneficial bacteria like *Lactobacillus, Lactococcus, Leuconostoc, Streptococcus,* and *Bifidobacterium*[22]. In addition to the maintenance of proper microbiota in the gut, probiotic bacteria stimulate digestion, increase the ability to absorb nutrients, and help the body resist various diseases. As for yeasts, *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* contribute to the characteristic flavour and natural carbonation of kefir and kumis through the production of ethanol, carbon dioxide, and volatile aroma compounds[23]. The regular intake of probiotic beverages from milk leads to better gut health and reduces the likelihood of developing GI disorders[24].

Though fermented beverages from milk have great nutritional value, some of them may not suit every individual. For instance, lactose sensitivity is common enough to occur even when consuming fermented beverages since fermentation only slightly diminishes the number of sugars. Moreover, milk contains casein and whey proteins, which cause allergic reactions in sensitive people[25]. Also, due to the nature of milk, some dairy-based beverages may contain too much saturated fat and cholesterol harmful to the body when consumed regularly[26]. Another reason not to choose fermented beverages from milk is the problem associated with environmental issues since the process of producing these beverages includes intensive milk production[27]. The overall fermentation process involved in the production of fermented beverages is illustrated in Figure 1.

Traditional dairy-based fermented beverages

Global traditional dairy fermented drinks

Dairy-based fermented beverages belong to the oldest and most commonly enjoyed fermented products across the world. They are made through the fermentation process of milk using microbes such as lactic acid bacteria and yeast, which enhance taste, shelf life, nutrient content, and other attributes. Such beverages can be classified as vital functional food products due to their beneficial probiotic contents and other nutrients like bioactive peptides, vitamins, minerals, and essential amino acids, which aid human wellbeing[22]. The milk is a suitable substrate for the multiplication of microbes due to its nutritional value and is converted to lactic acid during the process[28,29].

Kefir

Kefir is one of the most extensively researched fermented milk products and is said to have been first made in the

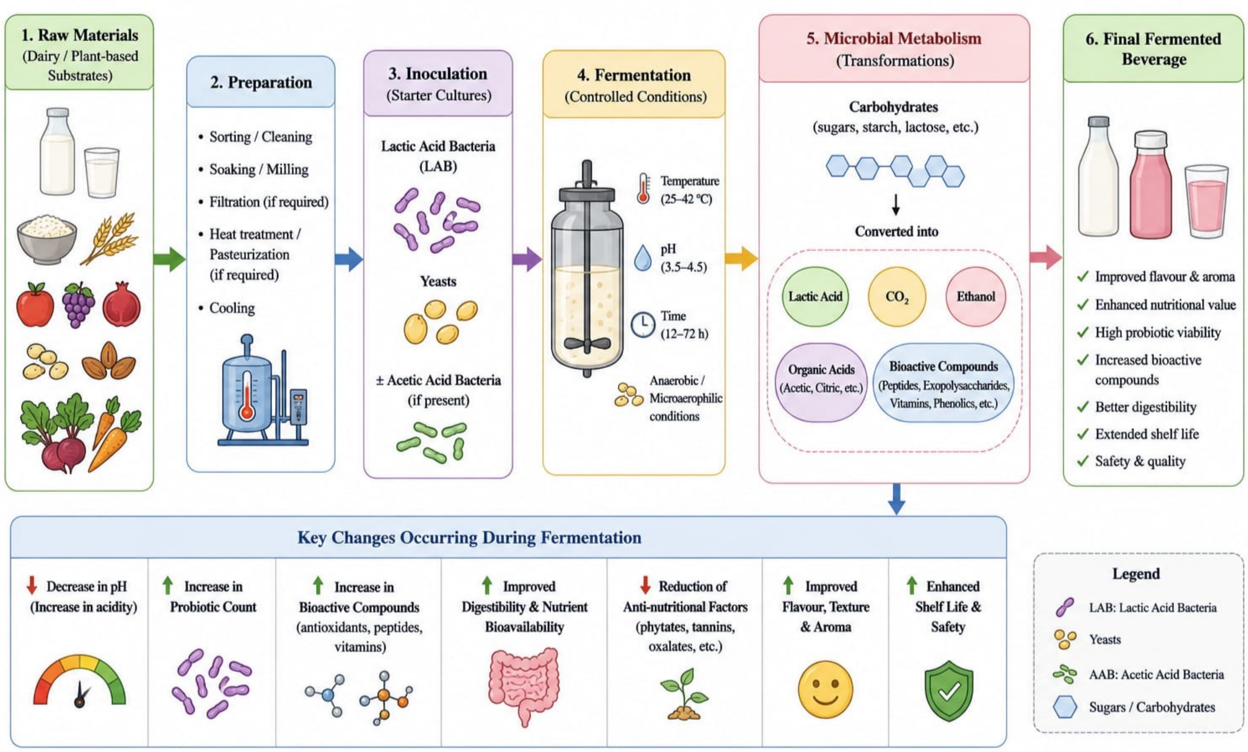

Figure 1. Illustration of fermentation process in fermented beverages

Caucasus Mountain area. Traditional preparation of kefir involves fermenting the milk obtained from cows, goats, or sheeps with the help of kefir grains. Kefir grains contain a blend of natural microorganisms, including lactic acid bacteria, acetic acid bacteria, and yeasts in a polysaccharide matrix termed kefiran. The common microorganisms present in kefir grains include *Lactobacillus kefiri, Lactococcus lactis, Leuconostoc spp., Acetobacter spp.,* and *Saccharomyces cerevisiae, Kluyveromyces marxianus* yeasts. Kefir is a well-known probiotic with several therapeutic applications. Research shows that kefir possesses antimicrobial, antioxidative, anti-inflammatory, antidiabetic, and immunomodulating activities[30].

Yoghurt

Yoghurt is considered to have originated in the Middle East and Central Asia, where milk fermentation took place due to natural causes at warm temperatures. Nowadays, there are a number of yoghurt beverages consumed around the globe, and they are usually made with starters like *Lactobacillus delbrueckii subsp. bulgaricus* and *Streptococcus thermophilus*. In addition to this, probiotic yoghurt beverages can include some other strains *like Lactobacillus acidophilus, Lacticaseibacillus casei,* and *Bifidobacterium* strains to increase their beneficial qualities. Moreover, through fermentation, lactose in the product is reduced, making yogurt beverages easily digested even by people with lactose intolerance[31].

Kumis

Kumis is a traditional fermented mare's milk beverage that originated in the Central Asian steppes, especially among Mongolian and Turkic nomadic communities. This is produced by a mixed fermentation of lactic acid bacteria and yeasts, which makes the beverage slightly alcoholic and gives it a distinctive flavor. Common microorganisms include *Lactobacillus delbrueckii, Lactobacillus plantarum, Lactococcus lactis* and yeasts such as *Saccharomyces cerevisiae* and *Candida spp.* Kumis is valued for its refreshing taste, nutritional value and probiotic potential[1].

Lassi

Lassi is a popular fermented milk beverage that originated in the Indian subcontinent and is primarily made with yogurt. Its cooling impact, probiotic advantages, and pleasant flavor have made it popular[32]. Lassi contains beneficial microorganisms such as *Lactobacillus bulgaricus*, *Streptococcus thermophilus*, *Lactobacillus acidophilus*, and other lactic acid bacteria that support digestion and help maintain a healthy gut microbiota. Both sweet and salted forms of lassi are commonly consumed across India.

Ayran

Ayran is a traditional yogurt drink that originated in Turkey, and is popular in the Middle East and surrounding regions. It is a light and refreshing fermented drink made by mixing yogurt with water and salt. Starter cultures such as *Streptococcus thermophilus* and *Lactobacillus delbrueckii subsp. bulgaricus* are mainly responsible for the fermentation process. Ayran is appreciated for its nutritional value, hydration properties and easy digestibility[33].

Buttermilk

Buttermilk is a traditional fermented milk drink. It originated in Europe and South Asia as a by-product of making butter from cultured cream. Modern cultured buttermilk is generally produced by selected lactic acid bacterial starter cultures such as *Lactococcus lactis, Leuconostoc mesenteroides* and *Lactobacillus species*. It is widely eaten because it is light, tastes nice and has probiotic qualities. Buttermilk is rich in beneficial microorganisms and bioactive compounds that support digestive health, hydration and nutrient absorption[34]. The characteristics of the major traditional dairy-based fermented beverages, including their origin, microorganisms involved, and health benefits, are summarized in Table 2.

Limitations of dairy-based fermented beverages

Fermented dairy products are nutrient-dense and offer probiotics, vitamins, minerals, vital amino acids, high-quality proteins, and bioactive peptides that promote general health. Microbial enzymes improve digestibility and nutrient absorption by breaking down milk proteins into simpler peptides and amino acids during fermentation[19]. According to Peres Fabbri *et al*.[20] several of these bioactive peptides include immunomodulatory, antihypertensive, antioxidant, and antibacterial qualities. While yeasts like *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* contribute to the flavor and carbonation of drinks like kefir and kumis, probiotic microorganisms like Lactobacillus, Lactococcus, Leuconostoc, Streptococcus, and Bifidobacterium help maintain gut microbial balance, improve digestion, and strengthen immune function[22]. Additionally, fermentation lowers the amount of lactose in these drinks, which helps many lactose-sensitive people digest them more easily[21].

Dairy-based fermented drinks do have several drawbacks, nevertheless, despite these advantages. Misselwitz *et al*.,[25] state that certain individuals may still have symptoms of lactose intolerance or allergic reactions to casein and whey, two milk proteins. Further, some products may include relatively high levels of added sugars, cholesterol, salt, and saturated fats, all of which can cause metabolic and cardiovascular health problems when consumed in excess[26]. Additionally, during storage, probiotic viability may decline, ultimately reducing functional efficiency. Short shelf life, refrigeration needs, and susceptibility to microbial deterioration may further limit product stability and distribution. Likewise environmental issues related to

Table 2. Comparison of major traditional dairy-based fermented beverages

Beverage	Origin	Main substrate	Predominant microorganisms	Major bioactive compounds	Major health benefits
Kefir	Caucasus Mountains	Cow, goat or sheep milk	*Lactobacillus kefiri*, *Lactococcus lactis*, *Saccharomyces cerevisiae*	Kefiran, bioactive peptides, vitamins	Gut health, antioxidant, antimicrobial
Yogurt	Middle East/ Central Asia	Milk	*Streptococcus thermophilus*, *Lactobacillus delbrueckii* subsp. *bulgaricus*	Bioactive peptides, vitamins	Improved digestion, lactose tolerance
Kumis	Central Asia	Mare's milk	LAB + yeasts	Organic acids, ethanol	Digestive health, probiotic activity
Lassi	India	Yogurt	LAB	Probiotics, peptides	Gut microbiota, hydration
Ayran	Turkey	Yogurt	*Streptococcus thermophilus*, *L. delbrueckii*	Organic acids	Digestive health
Buttermilk	Europe & South Asia	Cultured milk	*Lactococcus lactis*, *Leuconostoc mesenteroides*	Bioactive peptides	Hydration, digestion

dairy farming, such as greenhouse gas emissions, excessive water use, and extensive land use, have increased consumer interest in plant-based fermented substitutes[27].

Overall, dairy-based fermented beverages remain the gold standard for probiotic delivery because of their high nutritional value, superior protein quality, and favourable environment for probiotic survival. However, increasing consumer awareness of lactose intolerance, milk protein allergies, environmental sustainability, and ethical concerns associated with dairy production has accelerated interest in plant-based fermented beverages. Although dairy beverages generally exhibit better probiotic stability and nutritional bioavailability, plant-based alternatives offer advantages such as higher antioxidant content, lower environmental impact, and suitability for vegan consumers. Future research should focus on improving the sensory quality, probiotic viability, and nutritional composition of plant-based fermented beverages to achieve functionality comparable to traditional dairy products.

Emergence of plant-based fermented beverages

Drivers for plant-based alternatives

In recent years, plant-based fermented beverages have grown in popularity and are currently regarded as one of the functional drink market's fastest-growing segments. Growing customer demand for lactose-free, vegan, and health-conscious products is the primary driver of this expansion. These drinks contain beneficial microorganisms like lactic acid bacteria and yeast and are prepared from a range of plant components, including fruits, vegetables, grains, legumes, nuts, and seeds. They are a great substitute for conventional dairy-based probiotic drinks since they are naturally rich in vitamins, minerals, dietary fiber, antioxidants, and phytochemicals[8]. Plant-based fermented beverages have seen a resurgence of interest due to the growing popularity of vegan and flexitarian lifestyles. Due to lactose intolerance, dietary preferences, environmental consciousness, and growing health concerns, many consumers are moving to non-dairy products[35]. These drinks offer substantial nutritional and probiotic advantages, making them a suitable option for people who avoid eating foods derived from animals.

Another significant factor leading to the rising demand for plant-based beverages is environmental sustainability. According to Poore and Nemecek[27]: the production of plant-based beverages often uses less land and water and produces less greenhouse gas emissions than dairy production. Customers are becoming more interested in ecologically friendly food options as awareness of climate change and sustainable farming systems rises. Additionally, fermentation is crucial for enhancing the functional and nutritional value of plant-based drinks. In order to enhance digestibility, nutrient availability, flavor, and shelf stability, microorganisms create organic acids, vitamins, enzymes, and other bioactive compounds during fermentation[36]. Fermented plant drinks may have antioxidant, antibacterial, anti-inflammatory, detoxifying, and gut-health-promoting qualities, according to research, which boosts their significance in the functional food market[4]. Additionally, many consumers are making the transition to plant-based substitutes due to ethical concerns about large-scale dairy farming and animal welfare. Compared to conventional dairy products, plant-based beverages are frequently thought to be more ethical, sustainable, and environmentally friendly[37].

Types of plant-based substrates

Cereals, legumes, fruits, vegetables, nuts, and seeds are just a few of the substrates that can be used to make plant-based fermented drinks. The raw ingredients employed for fermentation have a significant impact on the nutritional makeup and functional characteristics of these beverages[38]. The characteristics of the major traditional plant-based fermented beverages, including their substrate, microorganisms involved, and health benefits, are summarized in Table 3. Because of their high protein content and nutritional value, soy-based beverages are among the most popular plant-based substitutes. According to Rekha and Vijayalakshmi[39]: fermentation reduces unwanted tastes and antinutritional chemicals while improving the digestibility and sensory qualities of soy drinks. Oat-based drinks are becoming more and more popular due to their high dietary fiber content, especially β-glucans, which are linked to decreasing cholesterol and improving gastrointestinal health. According to Abdelshafy *et al.*[40]: fermentation improves the probiotic potential and nutritional value of oat beverages. Drinks made from almonds and other nuts are prized for their tasty flavor, antioxidants, vitamins, and good fats. According to Jeske, Zannini, and Arendt[8]: fermentation enhances the beverages' microbiological stability, flavor complexity, and nutritional bioavailability. Fermented beverages made from coconuts are highly valued for their rich nutrient profile and refreshing flavor. Because of its high lipid and carbohydrate content, coconut milk supports probiotic fermentation and taste development, making it an ideal substrate for microbial growth[41]. Fermented beverages made from rice are popular in many Asian nations because of their light texture and ease of digestion. According to Tamang[42]: fermentation improves rice-based drinks' flavor, nutrient availability, and probiotic qualities.

Blends created from cereals and legumes are gaining popularity due to their well-balanced nutritional profile, which includes proteins, carbs, dietary fiber, vitamins and minerals. Fermentation enhances the digestibility of these mixes, reduces antinutritional chemicals, and increases their total functional value. Fermented fruit beverages produced from apples, pomegranates, grapes, pineapples, mangoes, and berries have recently gained popularity due to their refreshing flavor and high antioxidant content. Fermentation improves the stability and bioavailability of phenolic chemicals and antioxidants, increasing their potential health effects[43].

Similarly, fermented vegetable beverages made from carrot, tomato, cabbage, and beetroot are recognized for their rich antioxidant, mineral, and bioactive compound content. Their nutritional value, flavor, sensory qualities, and microbiological stability are all enhanced by the fermentation process[44]. Because of its special nutritional and functional qualities, Beetroot Kanji, a traditional fermented beverage from India, has drawn a lot of scientific attention. High concentrations of betalains, phenolic compounds, nitrates, vitamins, and minerals are found naturally in beetroot, which enhances its antioxidant and medicinal properties. Native lactic acid bacteria transform carbohydrates into organic acids and other advantageous metabolites during natural fermentation, enhancing the beverage's flavor, safety, and probiotic value. Fermented beetroot beverages are potential functional beverages for health-conscious consumers because of their antibacterial, anti-inflammatory, antihypertensive, antioxidant, and gut-health-promoting qualities, according to studies[45].

Plant-based fermented beverages have emerged as promising alternatives to conventional dairy products because of their sustainability, rich phytochemical content, and suitability for lactose-intolerant and vegan consumers. However, compared with dairy-based beverages, many plant-based substrates exhibit lower protein quality, reduced

Table 3. Comparison of major plant-based fermented beverages

Beverage	Substrate	Predominant microorganisms	Major bioactive compounds	Health benefits	Limitations
Soy beverage	Soybean	*Lactiplantibacillus plantarum*, *Lacticaseibacillus casei*	Isoflavones, peptides	High protein, cardiovascular health	Beany flavour
Oat beverage	Oats	LAB	β-glucan	Gut health, cholesterol reduction	Lower protein
Almond beverage	Almond	LAB	Polyphenols, vitamin E	Antioxidant activity	Low protein
Coconut beverage	Coconut	LAB, yeasts	Medium-chain fatty acids	Antioxidant, probiotic potential	High fat
Beetroot Kanji	Beetroot	Indigenous LAB	Betalains, phenolics, nitrates	Antioxidant,anti-inflammatory	Limited commercial production
Fruit-based beverages	Fruits	LAB, yeasts	Polyphenols, vitamin C	Antioxidant, immune support	Lower probiotic stability

probiotic stability, and greater challenges related to flavour, texture, and consumer acceptance. Although fermentation improves the nutritional and functional properties of plant substrates, further optimization of starter cultures, fermentation conditions, and formulation strategies is required to enhance product quality and commercial viability. Future research integrating novel processing technologies, precision fermentation, and encapsulation approaches may further improve the functionality and market acceptance of these beverages.

Fermentation of plant-based beverages

Microbial cultures used

The most significant microorganisms in the fermentation of plant-based drinks are lactic acid bacteria. Fermented fruit, vegetable, cereal, and legume beverages are frequently linked to species such *Lactobacillus plantarum, Lactobacillus fermentum, Leuconostocmesenteroides, and Pediococcus pentosaceus*[7]. These microbes support probiotic activity, taste development, acid generation, and preservation[7]. To increase the functional value and health advantages of plant-based beverages, a number of probiotic strains are added. These probiotic microorganisms improve immunity, aid in digestion, maintain the balance of gut microbes, and promote intestinal health in general. Numerous factors, including as substrate composition, fermentation conditions, and storage stability, affect probiotics' capacity to endure and operate[46]. Furthermore, the fermentation of plant-based beverages depends on yeasts. One of the most frequently reported yeast species involved in flavor creation, sugar metabolism, and the synthesis of volatile chemicals is Saccharomyces cerevisiae[47]. Yeast and lactic acid bacteria coexist in mixed cultures in many traditional fermented drinks, which enhances their functional qualities and sensory appeal[7].

Enhancing the probiotic viability, sensory acceptability, and shelf stability of plant-based beverages has been the focus of recent advancements in fermentation technology[8]. To boost fermented beverages' nutritional value and therapeutic potential, researchers are also investigating the addition of herbs, spices, medicinal plants, and functional components[48]. Plant-based fermented beverages are anticipated to play a significant part in the future functional food sector as consumer demand for sustainable and health-conscious products rises.

Technological challenges

Despite their growing popularity and health benefits, plant-based fermented beverages have several technological challenges related to product quality, sensory acceptability, and storage stability. Both consumer acceptance and the commercial production of functional beverages are impacted by these problems[49]. Numerous problems with texture, flavor, stability, and nutritional value affect consumer adoption of plant-based fermented beverages. Because plant substrates typically include lesser concentrations of proteins and lipids, one of the main challenges is obtaining a smooth and creamy mouthfeel similar to dairy-based beverages[50]. Because of this, some drinks may have phase separation, sedimentation, or a slightly gritty mouthfeel, all of which might lessen their sensory appeal[8]. Another crucial element is flavor, since some plant materials, particularly legumes and cereals, naturally have earthy, bitter, or beany tastes that consumers might not like. Microorganisms produce volatile chemicals and organic acids during fermentation, which can enhance flavor. However, unfavorable tastes can also result from inappropriate fermentation conditions.

To achieve acceptable sensory qualities, starting cultures must be carefully chosen, and fermentation conditions must be optimized[4]. Furthermore, changes in pH, microbial activity, oxidation, and sedimentation during storage might impact both quality and probiotic viability, making it difficult to maintain product stability and shelf life[50]. Phytates, tannins, oxalates, and enzyme inhibitors are examples of antinutritional substances found in plant-based raw materials that may lower nutrient availability and digestion[51]. Complete removal is frequently challenging and depends on the type of substrate, microbial culture, and fermentation conditions used, even though fermentation can greatly reduce these chemicals[43].

Strategies to improve quality

Various technological methods have been invented to improve stability, sensory characteristics, and nutritional qualities of plant-based fermented beverages. Among the most widespread techniques for improving sensory properties, texture, and availability of nutrients is the enzymatic treatment method[35]. Due to their ability to break down complicated carbohydrates, proteins, and constituents of plant cell walls, enzymes, including amylases, cellulases, proteases, and pectinases, make texture and sensory attributes better, improve digestibility, and reduce problems related to viscosity[52]. One more key strategy for improving the nutritional qualities of plant-based beverages is fortification. In order to increase the levels of certain nutrients and improve their functional value, various nutrients, including vitamins, minerals, proteins, dietary fiber, omega-3 fatty acids, and other bioactive substances are added to them[53].

Shelf life, safety and regulatory consideration

The shelf life of fermented beverages depends on the stability of probiotic microorganisms, bioactive compounds, and sensory quality during storage. To provide health benefits, fermented beverages should contain an adequate number of viable probiotic microorganisms at the time of consumption. However, factors such as low pH, oxygen exposure, storage temperature, and prolonged storage can reduce probiotic viability, which is further described in Table 4. Refrigerated storage and suitable packaging materials help maintain microbial stability and extend product shelf life, while techniques such as microencapsulation have been investigated to further improve probiotic survival[54]. Although fermentation naturally inhibits many spoilage and pathogenic microorganisms through acid production, proper hygiene and quality control remain essential. The use of high-quality raw materials, selected starter cultures, and good manufacturing practices (GMP) together with Hazard Analysis and Critical Control Point (HACCP) systems helps ensure microbial safety and product consistency. Regular microbiological testing is also necessary to verify the absence of foodborne pathogens and maintain consumer safety. The commercialization of fermented functional beverages must comply with food safety and labeling regulations established by regulatory authorities such as the Food Safety and Standards Authority of India (FSSAI): the European Food Safety Authority (EFSA): and the United States Food and Drug Administration (FDA). These regulations require accurate labeling of ingredients, probiotic strains, viable cell counts (where applicable): storage conditions, and scientifically supported health claims. Continued research and standardized guidelines will further facilitate the safe development and commercialization of fermented beverages.

Nutritional and functional comparison between dairy and plant-based fermented beverages

Dairy and plant-based fermented beverages are widely recognized as functional foods. However, there is considerable variation in composition, probiotic survival, and other factors that influence the functionality of different beverages. Fermented dairy and plant-based beverages have variable protein content and bioavailability[55]. Dairy-based beverages are generally recognized as high-quality protein sources, as they are complete and contain all essential amino acids in corresponding amounts. Casein and whey are milk proteins that are among the highest in protein quality and are digested easily[56]. During fermentation, the preparations of dairy beverages in the prior step enhances protein digestibility and absorption, as the proteins are hydrolyzed to smaller peptides and amino acids by the microbial enzymes. Based on the substrate, many plant-based beverages are deficient in some amino acids and have low protein content. However, beverages based on soy, legumes, and cereal-legume combinations may offer better protein and dietary diversity. The fermentation of plant-based beverages may enhance the digestibility of proteins by lowering some anti-nutritional factors, such as phytates and enzyme inhibitors[57].

Dairy-based fermented drinks also provide a rich source of calcium, phosphorus, vitamin B12 and riboflavin, as well as high-quality proteins. Milk naturally contains these nutrients and they are generally highly bioavailable[58]. Plant-based fermented beverages provide dietary fiber, phenolic compounds, antioxidants, and vitamins, depending on the raw material[59]. Nonetheless, non-dairy drinks may have less calcium, B12 and other vital nutrients, unless they are fortified. Fermentation enhances mineral bioavailability of plant substrates by reducing the concentration of antinutritional factors and improving absorption. The functional value of fermented drinks is determined by probiotic viability. The buffering capacity and other nutritional characteristics of dairy substrates create a favourable environment for the growth and survival of probiotic microorganisms. Consequently, it has been shown that probiotic bacteria have better stability and survival in dairy-based beverages during storage. Plant-based fermented drinks are being studied as potential probiotic carriers due to their composition rich in sugars, prebiotics and other bioactive molecules that create proper conditions for various micro-organisms[41]. Recent advances in fermentation technology and encapsulation techniques have further improved the viability of probiotics in non-dairy beverages.

Plant-based fermented beverages are often considered superior in terms of antioxidant activity because they are naturally rich in phenolic compounds, flavonoids, betalains, carotenoids, and other phytochemicals. Fermentation enhances the release and bioavailability of these antioxidant compounds, thereby increasing their therapeutic potential[10]. Beverages prepared from fruits,

Table 4. Factors affecting probiotic viability and shelf-life of fermented beverages

Factor	Effect on beverage quality	Possible mitigation strategy
Storage temperature	Reduced probiotic survival at higher temperatures	Refrigerated storage (4-8°C)
Oxygen exposure	Oxidative stress and loss of viable cells	Oxygen-barrier packaging
Low pH	Cellular injury and reduced probiotic viability	Selection of acid-tolerant strains; encapsulation
Storage duration	Gradual decline in microbial count	Optimization of formulation and storage conditions
Light exposure	Degradation of vitamins and bioactive compounds	Opaque or UV-protective packaging
Microbial contamination	Spoilage and safety risks	GMP, HACCP, hygienic processing

vegetables, cereals, and herbs have been reported to exhibit significant antioxidant and anti-inflammatory activities. Although dairy-based fermented beverages also possess antioxidant properties due to the production of bioactive peptides and microbial metabolites during fermentation, their antioxidant capacity is generally lower than that of many plant-based beverages[57].

Several health-promoting bioactive chemicals are present in both plant-based and dairy-based fermented beverages, contributing to their functional qualities. Bioactive peptides, organic acids, bacteriocins, vitamins, and exopolysaccharides that may have antihypertensive, antibacterial, immunomodulatory, and cholesterol-lowering properties are produced during fermentation in dairy products[60]. Bioactive substances such polyphenols, flavonoids, betalains, dietary fiber, and natural antioxidants contribute to the antibacterial, anti-inflammatory, antidiabetic, cardioprotective, and gut-health-promoting properties of plant-based beverages[10]. Consequently, despite the fact that their content and modes of action vary depending on the substrate and fermentation method employed, both types of fermented beverages provide important nutritional and functional advantages.

Overall, both dairy- and plant-based fermented beverages possess unique nutritional and functional advantages. Dairy-based beverages remain superior sources of high-quality proteins and exhibit excellent probiotic stability, whereas plant-based beverages offer greater diversity of phytochemicals, antioxidants, dietary fibre, and environmental sustainability. Rather than replacing one another, these beverages should be considered complementary functional foods that can satisfy the nutritional needs and dietary preferences of different consumer groups. Future research should focus on improving the sensory quality, probiotic viability, and nutritional balance of plant-based fermented beverages while maintaining their sustainability advantages. Overall, the comparative characteristics of dairy- and plant-based fermented beverages are summarized in Table 5, providing a concise overview of their similarities and differences.

Health benefits of fermented functional beverages

Fermented functional beverages are becoming increasingly popular due to their potential health benefits and rich nutritional profiles. These beverages contain probiotics, bioactive peptides, vitamins, organic acids, antioxidants, and phytochemicals that may help promote overall health and well-being[54]. Regular consumption of fermented beverages has been associated with improved digestive health, stronger immunity, antioxidant protection, and reduced risk of several lifestyle-related disorders[61]. One of the major health benefits of fermented beverages is their positive effect on gut health and digestion. The probiotic microorganisms in these beverages help maintain a healthy balance of the gut microbiota by supporting beneficial bacteria and inhibiting harmful bacteria[24]. These probiotics improve digestion, nutrient absorption, and intestinal health, while also helping reduce digestive problems such as diarrhea, constipation, and irritable bowel syndrome[62]. In addition, lactic acid bacteria present in fermented beverages produce antimicrobial compounds that help support gut stability and digestive function. Recent studies have also highlighted the connection between fermented beverages and the gut-brain axis. Probiotics present in fermented drinks may influence neurotransmitter production and help reduce stress-related symptoms by modulating gut microbiota composition[4]. Although research in this field remains in its early stages, fermented functional beverages have attracted considerable scientific interest due to their potential role in modulating mood, cognitive function, and psychological well-being through interactions within the gut-brain axis. Fermented beverages have been extensively associated with immunomodulatory effects. Probiotic microorganisms and bioactive metabolites produced during

Table 5. Comparative characteristics of dairy- and plant-based fermented beverages

Parameter	Dairy-based beverages	Plant-based beverages
Primary substrate	Milk	Cereals, legumes, fruits, vegetables, nuts, seeds
Major microorganisms	LAB, yeasts	LAB, yeasts
Protein quality	High, complete proteins	Variable; generally lower except soy
Dietary fibre	Absent	Present
Bioactive compounds	Bioactive peptides, vitamins	Polyphenols, flavonoids, betalains, dietary fibre
Probiotic viability	Generally high	Moderate; depends on substrate
Digestibility	High	Improved after fermentation
Antioxidant activity	Moderate	High
Lactose	Present	Absent
Environmental impact	Higher	Lower
Consumer suitability	General population	Vegans, lactose-intolerant individuals
Major limitations	Allergies, lactose intolerance	Lower protein, flavour challenges

fermentation are reported to influence immune responses and regulate inflammatory pathways[63]. Therefore, regular probiotic beverage consumption may help strengthen host resistance to infections and immunological competence. Because fermented drinks contain probiotics, phenolic compounds, antioxidants, and bioactive peptides, they also show notable anti-inflammatory and antioxidant qualities. Beetroot kanji has garnered significant interest among vegetable-based fermented drinks due to its remarkable anti-inflammatory and antioxidant properties. Fermentation enhances the bioavailability and stability of the phenolic chemicals and betalains found in beetroot. Fermented beetroot drinks may therefore have immune-boosting, antibacterial, anti-inflammatory, and antioxidant properties [64].

Functional beverages that are fermented may contribute to improving heart health. Some strains of probiotics located in fermented beverages may support improved lipid metabolism, blood pressure, and cholesterol levels. Bioactive peptides formed during fermentation may help to decrease blood pressure by inhibiting the action of the angiotensin converting enzyme. Following that, fermented beverages may assist in the control of diabetes and improve metabolic health. Studies have shown that probiotics and other bioactive components of fermented beverages improve insulin sensitivity, energy balance, and glucose metabolism. The regular consumption of fermented dairy and plant-based beverages is reportedly associated with a lower incidence of obesity, hypertension, and type 2 diabetes. Interestingly, metabolic stress and the complications of diabetes may be lessened by the antioxidant and anti-inflammatory properties of fermented beverages. Many fermented products improve the bioavailability and digestibility of the components, which positively impacts metabolic health and the overall function of the body. Fermented functional beverages are valued not only as conventional nutritional products in the modern food industry, but also as promising therapeutic and nutraceutical products.

Industrial trends and market perspectives

In the past few years, there has been significant market growth for health beverages around the world. A growing global market has increased the demand for health beverages[65]. As these beverages contain probiotics, they are nutritious and may have therapeutic benefits; they can be considered functional foods[66]. The market growth for both dairy- and plant-based, fermented beverages has been enhanced by the growing interest in gut health, immunity, and plant-based, natural nutrition[67]. The evolving field of food biotechnology, coupled with the advancement of fermentation technology, has further supported the creation of novel functional beverages that include enhanced nutritional and organoleptic (i.e. taste and quality) features. The significant growth of the global market for fermented beverages has been attributed to the demand for probiotic and functional foods[66]. Yogurt drinks, kefir, and probiotic dairy-based, fermented beverages, as they are nutritionally beneficial and have a long-standing consumer base, continue to dominate the market. At the same time, plant-based fermented beverages are emerging as one of the fastest-growing sectors within the functional food industry due to increasing veganism, lactose intolerance, and environmental awareness among consumers[68]. Fermented beverages offer significant development potential in North America, Europe, and the Asia-Pacific area, according to a number of market reports. The market for functional beverages has grown worldwide due to the rising demand for kombucha, probiotic fruit drinks, oat-based drinks, and traditional fermented drinks like beetroot kanji. Global consumption of fermented drinks is also rising due to urbanization, rising disposable income, and shifting eating habits[69]. Beverages that offer both functional and nutritional benefits are becoming more and more popular among modern consumers. Natural, minimally processed, probiotic-rich, and additive-free goods are preferred by health-conscious consumers[70]. Low-sugar, low-fat, lactose-free, vegan, and clean-label beverage demand has grown dramatically in recent years.

Plant-based fermented beverages have particularly gained popularity among vegan consumers, lactose-intolerant individuals, and people interested in sustainable dietary practices[71]. In addition, consumers are increasingly interested in traditional and ethnic fermented beverages for their perceived authenticity, natural fermentation processes, and potential health benefits. Sensory attributes such as taste, texture, aroma, and appearance also play important roles in influencing consumer acceptance and purchasing decisions[72]. Functional beverages now offer better probiotic viabiliy, shelf stability, and sensory quality thanks to developments in fermentation technology, starter culture creation, encapsulation methods, and packaging technologies[54]. Furthermore, businesses and researchers are focusing on developing tailored functional drinks that are appropriate for specific health needs like immunity, metabolic health, cardiovascular wellness, and digestive health. In order to create innovative functional beverages with increased sustainability and commercial value, there is also growing interest in underused crops, traditional recipes, and indigenous fermenting techniques[73]. The global commercialization of fermented beverages and consumer awareness have been further pushed by digital marketing, e-commerce platforms, and social media promotion.

Fermented functional beverages rely on food labeling and guidelines to establish the quality and safety of the products[74]. Each country has its own set of food safety standards addressing the safety of probiotic beverages, how probiotics are declared and quantified, as well as the microbial safety of the product. The shelf stability of probiotics and health claims goes hand in hand. Assessment of allergen declaration, nutrients, storage conditions, and the probiotic used are some of the ways to ensure safety of functional beverages[75]. Regulatory authorities evaluate health claims and disease risk reduction claims to ensure they are supported by scientific evidence and do not mislead consumers[76].

Sustainability and environmental impact

Sustainability is becoming more important in the development of fermented functional beverages as concerns about climate change, environmental damage, and resource shortages grow[55]. The environmental impact of these drinks depends on factors like where raw materials come from, how much water and land they use, energy needs, and waste produced[27]. Dairy-based fermented drinks usually have a bigger environmental footprint because dairy farming leads to greenhouse gas emissions, high water use, and large land needs for livestock and feed[77,78]. On the other hand, people who care about the environment are choosing more plant-based fermented drinks made from grains, legumes, fruits, vegetables, and nuts, since these often use fewer resources and create less carbon emissions[27]. Using sustainable farming, better irrigation, and careful crop management can make plant-based beverage production even more environmentally friendly[79].

In the industry, new sustainable technologies are being used to make fermented beverage production more efficient and better for the environment. These include energy-saving processing systems, controlled fermentation, improved starter cultures, and eco-friendly packaging to cut waste and keep products stable[1,]. Circular bioeconomy methods, which make better use of biological resources and reuse food processing byproducts, are also becoming more common[80]. For example, fruit peels, cereal bran, and whey can be used as fermentation materials or sources of useful chemicals, helping to create valuable products and reduce pollution[81]. Fermentation itself is considered sustainable because it uses microbes to turn low-value raw materials into nutritious drinks[18]. As a result, the future growth of the fermented functional beverage industry is expected to rely heavily on sustainable processing and circular bioeconomy ideas.

Future prospects and research gaps

The nutritional composition, probiotic potential, and health benefits of fermented functional beverages have attracted increasing scholarly attention. Nevertheless, further research is necessary to address challenges such as product uniformity, probiotic stability, sensory quality, safety, and the scientific substantiation of health claims. Advances in food biotechnology and microbial engineering are expected to facilitate the development of future fermented beverages[1]. Precision fermentation, which utilizes controlled microbial cultures and optimized fermentation conditions to produce beverages with consistent quality and enhanced functional properties, represents a significant innovation[82]. To improve product quality and shelf stability, researchers are employing advanced technologies, including artificial intelligence, smart fermentation systems, and precision biotechnology to regulate variables such as temperature, pH, oxygen concentration, and microbial growth. Furthermore, new probiotic strains with superior antibacterial, antioxidant, and therapeutic properties are being explored[7]. Techniques such as metagenomics, metabolomics, and 16S rRNA sequencing have expanded understanding of microbial diversity and fermentation processes[83]. Collectively, these advancements have enabled the development of next-generation functional beverages with improved nutritional profiles, enhanced sensory attributes, and targeted health benefits.

Personalized nutrition has emerged as a significant trend, with consumers seeking beverages tailored to their specific lifestyles and health needs[84]. The incorporation of probiotics, prebiotics, vitamins, minerals, and bioactive compounds into fermented beverages has been associated with potential improvements in immunity, cardiovascular health, gastrointestinal function, and overall well-being[49,70]. Interest in the gut-brain axis and microbiome-based nutrition is further expanding opportunities in this sector[85]. However, additional human clinical trials are required to substantiate the health benefits and ensure the safety of fermented beverages, despite existing research indicating their therapeutic potential[4]. While traditional beverages such as Beetroot Kanji have demonstrated notable probiotic and antioxidant properties, their widespread commercialization and therapeutic acceptance remain limited by insufficient scientific standardization and clinical evidence. Future research should focus on comprehensive clinical validation, rigorous safety assessment, dosage standardization, and evaluation of long-term health effects to facilitate broader integration of these beverages into functional food systems. The key emerging technologies that have improved the efficiency, quality, safety, and functionality of fermented beverage production are summarized in Table 6.

Conclusions

For clear reasons, fermented drinks hold an important place in both the functional food industry and nutrition science. These beverages are usually rich in probiotics, bioactive compounds, vitamins, minerals, antioxidants, and phytochemicals that benefit human health. This is true whether they come from dairy, grains, fruits, vegetables, legumes, or other plant sources. Fermentation not only helps preserve food but also improves nutrient absorption, makes the beverages easier to digest, and boosts the

Table 6. Emerging technologies in fermented beverage production

Technology	Application	Advantages
Precision fermentation	Controlled production of bioactive compounds	Improved consistency and functionality
Metabolomics	Identification of fermentation metabolites	Better understanding of product quality
Metagenomics	Microbial community analysis	Selection of efficient starter cultures
Artificial Intelligence	Process optimization and quality prediction	Reduced processing time and improved consistency
Microencapsulation	Protection of probiotics	Enhanced viability and shelf life
Smart fermentation	Real-time process monitoring	Improved process control

stability and safety of the final product. Lactic acid bacteria and yeasts drive the creation of flavor, preservation, probiotic activity, and the production of metabolites that contribute to the drinks' benefits. Traditional fermented beverages made from dairy products remain popular and are here to stay. Their probiotic and nutritional importance is backed by decades of research. Fermented drinks made from grains are also important in traditional diets and food security in many regions. However, things are changing. Consumer views on sustainability and nutrition have shifted a lot. People are more aware of lactose intolerance, and it's harder to ignore the environmental problems tied to dairy farming. As a result, fermented plant-based drinks have become mainstream. Beverages made from fruits, vegetables, grains, legumes, nuts, and seeds are increasingly recognized as functional foods. They are not just dairy substitutes; they also offer benefits related to sustainability, probiotic potential, and antioxidant activity. Traditionally, drinks like Beetroot Kanji represent an overlooked source of nutraceutical and probiotic potential that food science is just beginning to study in depth. Advances in food microbiology, fermentation engineering, molecular biology, and biotechnology have started to create beverages with improved function, better taste, and longer shelf life. Issues like microbial safety, sensory consistency, standardization, probiotic survival during storage, and regulatory pathways remain unresolved. Furthermore, there are still relatively few solid human studies that clearly confirm the health benefits of many of these drinks, so the clinical evidence base needs to grow.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review paper.

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