International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Fermented Vegetable Beverages: A Global Perspective on Probiotic Properties, Functional Bioactives, and Health-Promoting Potential — A Review

Sujatha B[1], Navyashree P[2], Chaithra M[3], Vaishnavi P[4], Susan Deby Sheren A[5] and Sunil Kumar R[6]

[1]Assistant Professor, Department of Food Technology, Padmashree Institute of Management and Sciences, Sulikere post, Kengeri, Bangalore-560060.

[2,3,4,5] Department of Food Technology, Padmashree Institute of Management and Sciences, Sulikere post, Kengeri, Bangalore-560060.

Abstract

Fermented vegetable beverages have become a highly promising category of plant-based functional food products that are nutritionally rich, allergen-free, and vegan-friendly alternatives to dairy-based probiotic beverages. The global review summarizes research on the fermentation of vegetable products into probiotic and functional beverages concerning microbiology, process technology, biochemical transformations, probiotic and functional bioactive properties, health benefits, sensory qualities and safety. The fermentation agents *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, *Lactobacillus brevis* and *Pediococcus acidilactici* are the primary fermentation agents responsible for acidification, bioactive compound biotransformation and the probiotic role of fermented vegetable beverages from carrot, beetroot, tomato, cabbage and mixed vegetable blends. The present review covers all known fermented vegetable beverages (Indian kanji, Eastern-European beet kvass, Korean kimchi juice, Japanese tsukemono brine) and novel research-based probiotic vegetable beverages for worldwide evidence evaluation. Fermentation significantly increases the antioxidant activity and bioaccessibility of phenolic compounds, reduces antinutritional factors, and increases B vitamin content compared to nonfermented ones. There is a promising clinical and preclinical evidence available supporting health-promoting benefits for cardiovascular health, dietary nitrate-mediated blood pressure lowering, gut microbiome modulation, weight loss, metabolism-related effects of the gut microbiome, anti-obesity metabolism, immunomodulatory activity and immune responses. Problems to be addressed include maintaining probiotic viability in non-dairy matrices, standardizing fermentation processes, overcoming consumer acceptance barriers, and conducting well-designed randomized controlled trials to substantiate health claims. The future of precision fermentation, synbiotics formulation, metabolomics-driven formulation, optimization, artificial intelligence-driven optimization and process development are the most promising pathways for advancing the field. This review shows that fermented vegetable beverages are a versatile and commercially promising class of non-dairy functional foods with great potential for healthy foods with global public health impact.

Keywords: Fermented vegetable beverages, lactic acid bacteria; probiotics; *Lactiplantibacillus plantarum*; bioactive compounds

1. Introduction

Consumer health awareness, the more common and widespread problem of lactose intolerance (68% of the world population) and the rise of veganism and flexitarian dietary patterns as well as increasing scientific evidence on the relationship of dietary patterns to the gut microbiome and chronic disease prevention [1,2] are driving the food and beverage industry around the world towards plant-based, clean-label and health-driven products. Fermented vegetable beverages are a promising and scientifically compelling category of functional food products that includes nutrition, the probiotic and functional benefits of fermentation.

Fermentation is one of the oldest and most widely practised food transformation technologies globally, with documented use spanning over 8,000 years across virtually all major human civilizations [3]. Among the various types of food fermentation, lactic acid fermentation mediated by lactic acid bacteria (LAB) occupies a uniquely important position — transforming raw vegetable substrates into products with enhanced nutritional value, improved safety, prolonged shelf life, distinctive sensory characteristics, and demonstrable functional health properties that substantially exceed those of the unfermented raw material [4,5].

There is also a significant gap in functional food science nowadays because most commercial probiotic foods are dairy-based (yogurt, kefir, probiotic cheese) which excludes lactose-intolerant, vegan, milk allergic and dairy-avoiding consumers which are a growing global population [6,7]. This paves the way for scientists and entrepreneurs to generate non-dairy probiotic food products, especially fermented vegetable drinks, which are among the most nutritionally dense but globally available and scientifically unexplored food categories. This is a massive opportunity with the worldwide non-dairy probiotic beverage industry forecasted to grow from USD 13.5 billion in 2023 to USD 22.8 billion by 2028 [8]. Fermented vegetable beverages encompass a remarkable diversity of products spanning traditional indigenous beverages — including Indian kanji (fermented black carrot beverage), Eastern European beet kvass, Korean kimchi juice, Japanese tsukemono brine, and Chinese paocai liquor — and novel research-developed products from single and mixed vegetable substrates including carrot, beetroot, tomato, cabbage, spinach, and leafy green vegetables [9,10]. However, in spite of this diversity and the rapidly expanding scientific literature, no comprehensive global review that integrates the microbiology, process technology, biochemistry, probiotic properties, functional bio actives, clinical health evidence, sensory characteristics and safety considerations of fermented vegetable beverages exists. This is a significant gap in the current review literature that the present work aims to fill.

As such, this review intends to: 1) provide an overall summary of the global status of fermented vegetable beverages (both traditional and new), 2) study the microorganisms - especially LAB species - involved in vegetable beverage fermentation and their probiotic properties, 3) survey the biochemical changes that take place during fermentation (especially for bioactive compounds and the ability to increase bioavailability), 4) explore the health benefits of fermented vegetable beverages from the in vitro, preclinical, and clinical perspectives, 5) explore the sensory, safety, and shelf-life considerations for product development, and 6) identify the current challenges and the future directions for the industry in this rapidly changing field.

2. Overview of vegetable Fermentation-Historical Background and Global Scenario

2.1 Historical perspective

Vegetable fermentation is at least 6,000 years old and has been a major method of food preservation and nutritional enhancement in all great cultures. Ancient Chinese preserved vegetables, fermented olive preparations of ancient Greece and Rome, and Middle Eastern lacto-fermented vegetable traditions are the oldest known evidence of intentional vegetable fermentation. These practices developed independently in geographically separated cultures as a universal human response to the need for year-round preservation of seasonal vegetable harvests [11].

The twentieth century witnessed the systematic scientific characterization of the microbiology of fermented vegetables, culminating in the identification of key LAB species responsible for traditional fermented vegetable products and the establishment of controlled starter culture-based fermentation as an alternative to spontaneous fermentation [12]. In parallel, Metchnikoff's discovery of probiotic concepts in the early 1900s gradually established the theoretical framework for understanding how microorganisms in fermented foods could confer health benefits on consumers, eventually leading to the current evidence-based probiotic science that underpins modern functional fermented food development [13] Table 1.

Table 1: Global classification of fermented vegetable beverages

Category	Product	Origin/religion	Primary Substrate	Key Microorganism
Traditional Indigenous	Kanji	India (North)	Black carrot, mustard	*Pediococcus acidilactici,* *Lactic acid bacteria*
Traditional Indigenous	Beet Kvass	Eastern Europe	Beetroot	*Leuconostoc, Lactobacillus spp.*
Traditional Indigenous	Kimchi Juice	Korea	Chinese cabbage, radish	*Leuconostoc mesenteroides,* *Lactiplantibacillus. plantarum*
Traditional Indigenous	Tsukemono brine	Japan	Cucumber, radish, cabbage	Various Lactic acid bacteria species
Traditional Indigenous	Gundruk soup	Nepal/India (North-East)	Leafy green vegetables	*Lactiplantibacillus spp., Pediococcus spp.*
Novel/Research	Probiotic carrot juice	Global research	Carrot (*Daucus carota)*	*Lactiplantibacillus plantarum*

				Lactobacillus. acidophilus
Novel/Research	Fermented beet juice	Europe, Global research	Beetroot (*Beta vulgaris)*	*Lactplantibacillus plantarum* *Lactococcus. brevis*
Novel/Research	Probiotic tomato juice	Global research	Tomato (*S. lycopersicum)*	*Lactobacillus plantarum, Lactobacillus. casei*

3. Microorganisms involved in Vegetable Beverage Fermentation

3.1 Lactic acid bacteria-Primary Fermenters

LAB are the dominant and most scientifically important microorganisms in vegetable fermentation. Following the 2020 reclassification of the genus *Lactobacillus* into 23 new genera, the key species in vegetable beverage fermentation are now named as *Lactiplantibacillus. plantarum (formerly L. plantarum), Levilactobacillus brevis (formerly L. brevis), Lacticaseibacillus casei (formerly L. casei) and Lactiplantibacillus pentosus* [14]. Of these species, *Lactiplantibacillus plantarum* is the most isolated and studied species and can be found in fermented vegetable products around the world due to its metabolic diversity, strong acid resistance, huge enzyme arsenal and well-established probiotic qualities [15].

The ecological succession of LAB during spontaneous vegetable fermentation is predictable. In early stage (pH 6.0-5.0), heterofermentative species mainly *Leuconostoc mesenteroides* are predominant to produce CO_2, lactic acid, acetic acid and mannitol. The release of CO2 gives the essential anaerobic conditions for ongoing fermentation and it inhibits the aerobic rotting organisms. The homofermentative *Lactiplantiacillus plantarum* and related species gradually replace *Leuconostoc* as pH drops below 5.0 and are responsible for the main acidification to pH 3.5–4.5 at which point fermentation is essentially complete [16,17].

3.2 Probiotic Criteria for LBS from Vegetable Beverages

Table 2 Probiotic Criteria for LBS from Vegetable Beverages

Probiotic criterion	FAO/WHO, 2001	Assessment Method	Key findings from literature
Acid tolerance	Survival at pH 2.0–3.0 for 2–3 hours	In vitro simulated gastric acid exposure	*Lactiplantibbacillus. plantarum* strains show 60–90% survival at pH 2.5 [18]
Bile salt tolerance	Survival in 0.3–0.5% bile salts	In vitro simulated intestinal fluid	Most vegetable-derived LAB survive 0.3% bile for 3 hours [19]

Intestinal adhesion	Adhesion to Caco-2/HT-29 cells	In vitro cell adhesion assay	*Lactiplantibbacillus plantarum* KABP051 shows good adhesion to intestinal epithelium [20]
Safety	GRAS/QPS status; no virulence factors; no transferable antibiotic resistance	Genomic analysis; phenotypic tests	Species-level GRAS presumption being replaced by strain-level genomic safety assessment [21]
Health benefit documentation	At least one RCT or well-designed human study	Systematic review of clinical evidence	Multiple RCTs confirm *Lactiplantibbacillus plantarum* gut health and anti-obesity effects [22]

4. Raw materials- Vegetables used and their Compositional Significance.

Table 3 Key Vegetable Substrates for Beverage Fermentation

Vegetable	Key Bioactive components	Fermentation suitability	Reference
Carrot (Daucus carota)	Beta-carotene (6–7 mg/100g), phenolics, vitamins C and B, natural sugars (glucose, fructose, sucrose ~8–12%)	Excellent — high natural sugar supports robust LAB growth; high buffering capacity; rich prebiotic fiber	[23,24]
Beetroot (Beta vulgaris)	Betalains (betacyanins, betaxanthins), dietary nitrates (250–280 mg/100g), polyphenols, natural sugars (~8–10%)	Very good — moderate sugar content; rich in anti-inflammatory betalains that are pH-sensitive during fermentation	[25,26]
Tomato (S. lycopersicum)	Lycopene (2–7 mg/100g), vitamin C, phenolic acids, low pH (3.9–4.4), moderate sugars	Good — naturally acidic pH favors LAB; lycopene bioavailability enhanced by fermentation	[27]
Cabbage (Brassica oleracea)	Glucosinolates, vitamin C, polyphenols, dietary fiber; low natural sugars (~3–5%)	Very good — extensive documented history; glucosinolate biotransformation to isothiocyanates during fermentation	[28,29]
Black carrot *(Daucus carota subsp.)*	Exceptionally high anthocyanins (cyanidin glycosides), phenolics, vitamin C	Excellent for probiotic beverage — anthocyanin acts as natural colorant; antioxidant potential very high	[30,31]
Mixed vegetable blends	Complementary sugar, mineral, vitamin, and phytochemical profiles	Very good — synergistic LAB growth; enhanced overall bioactive profile vs single-substrate	[32]

Carrot (*Daucus carota*)	Beta-carotene (6–7 mg/100g), phenolics, vitamins C and B, natural sugars (glucose, fructose, sucrose ~8–12%)	Excellent — high natural sugar supports robust LAB growth; high buffering capacity; rich prebiotic fiber	[33,34]

5. Fermentation Process and Technology
5.1 Substrate Preparation

Optimal substrate preparation is critical for consistent and reproducible fermented vegetable beverage quality. The standard preparation sequence involves washing, sorting, peeling or trimming (where applicable), mechanical size reduction (slicing, dicing, or grating), juice extraction by pressing or centrifugation, optional thermal blanching to inactivate native enzymatic and microbial populations and favor LAB dominance in subsequent fermentation, pH adjustment if required, and inoculation with starter culture or initiation of spontaneous fermentation [35,36] Table 4.

Table 4 Optimum Fermentation Conditions

Parameter	**Optimal range**	**Effect on Fermentation**	**Reference**
Temperature	20–37 ^{0}C (species-dependent)	Determines LAB species succession; 37^{0} C favors *Lpb. plantarum;* 20–25 degrees C favors *Leuconostoc*-dominant spontaneous fermentation	[37]
Time	24–96 hours (beverage fermentation)	Determines extent of acidification, sugar consumption, flavor development, and probiotic cell count	[38]
NaCl concentration	1–3% (w/v)	Creates selective pressure favoring salt-tolerant LAB over Gram-negative spoilage and pathogenic bacteria	[39]
Inoculum size	2–5% v/v starter culture	Higher inoculum size reduces lag phase and time to reach protective pH — important for food safety	[40]
Initial pH	5.5–6.5 (natural vegetable juice)	Starting pH influences LAB species selection and speed of fermentation	[41]
Fermentation mode	Anaerobic/microaerophilic	Essential for LAB dominance; CO2 blanket during heterofermentative initiation provides natural protection	[42]
Temperature	20–37 degrees C (species-dependent)	Determines LAB species succession; 37 degrees C favors *Lpb. plantarum*; 20–25 degrees C favors *Leuconostoc*-dominant spontaneous fermentation	[43]

6. Biochemical Changes During Fermentation

6.1 Carbohydrate Metabolism and Organic Acid Production

LAB ferment sugars (glucose, fructose, sucrose) via homo- and heterofermentative pathways yielding lactic acid as the main fermentation product, and acetic acid, ethanol and CO2 in heterofermentative systems. The mechanism of food safety and preservation is based on the inhibition of the growth of the majority of foodborne pathogens and spoilage microorganisms from the initial pH 5.5–6.5 to the final pH 3.5–4.5 [45].

6.2 Transformation of phenolic compound - A very important sub-section.

Biotransformation of phenolic compounds is a major food fermentation process that LAB have been responsible for in vegetable fermentation. The LAB enzymes produce beta-glucosidase, esterase, phenolic acid decarboxylase, and tannase that hydrolyze phenolic glycosides and release free aglycone forms that are more bioavailable than glycosylated forms. The phenolic content is proportional to the bioaccessibility and bioavailability in the fermentation process [46,47]. The total phenolic content is reduced during fermentation, but bioaccessibility may be high due to increased digestible extractability by bacterial metabolism [48].

6.2 Betalain stability in fermented beetroot juice.

Betalains - red-violet betacyanins (primarily betanin) and yellow betaxanthins (primarily vulgaxanthin) are the primary pigments of beetroot, which give rise to the distinctive colour and antioxidant properties of fermented beet juice. Betalains are pH-dependent in the fermentation process, and due to pH-dependent stability in betalains, the acidic environment (pH 3.5-4.5) of fully fermented beet juice actually stabilizes betacyanin pigments when compared to neutral or alkaline pH levels. Hence, the colour stability of fermented beet beverages is acceptable. Some of the reports state that the antioxidant potential of commercial fermented beetroot juice was between 5,253 and 5,761 micromoles Fe (II)/L (FRAP), and both iodised and acerola-enriched versions had the highest concentrations of antioxidants to further improve the effectiveness of the base fermented vegetable beverages [49].

6.4 Reduction of antinutritional factors

LAB fermentation reduces the levels of antinutritional factors such as phytates, oxalates, tannins and saponins in vegetable substrates, hence improving mineral bioaccessibility. A Recent research demonstrated that fermentation of vegetables enhanced the bioavailability of calcium, iron, zinc and magnesium by reducing the hydrolysis of phytate by LAB phytases. In addition to the probiotics, these fermented vegetable drinks also have the nutritional benefit of reducing antinutrients [50].

7. Probiotic Properties of Fermented vegetable Beverages

7.1 Probiotic Viability and Non-Dairy Carrier Advantages

The primary technical challenge is to maintain the minimum therapeutic probiotic count of 10^6 CFU/mL until the end of the shelf life of fermented vegetable beverages. A study demonstrated that the stability of all probiotic beverages (avocado, ginger and tropical extract) inoculated with *L. casei, L. plantarum and L. reuteri* in a refrigeration environment retained probiotic viability and is more than 6 log CFU/mL in all cases, with slight physicochemical differences only [51]. This strain exhibited good stability and production of bioactive compounds and excellent sensory property for orange, apple and peach juice matrices. The study showed that vegetable juices inoculated with 10^7 CFU/mL and fermentation at 37^0C for 24 hours resulted in beverages with good sensory and functional properties and is the most practical and reproducible process that can be followed to develop probiotic vegetable beverage.

7.2 Gut Microbiome Modulation

Fermentation of apple juice using *Lactiplantibacillus plantarum* has been proven to affect the gut microbiota of obese people in a positive way. The fermented beverage enhanced the availability of good bacterial genera like *Bifidobacterium, Parabacteroides, and Enterococcus* and activated glycolytic metabolic pathways in the gut microflora. These findings support that fermented apple juice might have a role in improving metabolic control through the modulation of gut microbiota composition [51]. Similarly, another review showed that regular consumption of LAB-fermented plant meals enhances the proliferation of beneficial gut microbes and hence supports intestinal health [52]

8. Bioactive compounds and Functional properties

8.1 Antioxidant activity enhancement through fermentation

One of the LAB synthesizes new antioxidant metabolites, including organic acids, reduced glutathione, and certain bioactive peptides [53,54]. LAB fermentation of carrot pomace significantly enhanced the bioaccessibility of phenolic compounds, including chlorogenic acid, p-coumaric acid and caffeic acid, in the fermented carrot juice [55]. Malik *et al.*, (2019) reported that *Lpb. plantarum, L. acidophilus* and *L. casei* grew well in carrot and beetroot juice substrates, and DPPH and FRAP experiments showed significant increases in the antioxidant activity. LAB produce novel antioxidant metabolites, such as organic acids, reduced glutathione, and certain bioactive peptides [56,57]. LAB fermentation of carrot pomace greatly increased the bioaccessibility of phenolic compounds such as chlorogenic acid, p-coumaric acid and caffeic acid in the fermented carrot juice [58]. *Lpb. plantarum, L. acidophilus and L. casei* showed good growth in carrot and beetroot juice substrates, with significant increases in antioxidant activity from DPPH and FRAP as demonstrated by Malik *et al.*, (2019).

9 Antimicrobial properties

Fermented vegetable beverages exhibit broad spectrum antimicrobial activity through multiple synergistic mechanisms including production of organic acids (lactic and acetic acids), lowering of pH, production of bacteriocins by LAB (Nisin, Plantaricin, pediocin), production of hydrogen peroxide and competitive exclusion of pathogenic bacteria. Rwubuzizi *et al.*, (2023) reported that the LAB isolated from fermented vegetables of northwest origin produce bacteriocins and antioxidants, demonstrating the dual antibacterial and antioxidant potential of these isolates.

10. Health benefits – clinical and Preclinical Evidence

Fermented beetroot juice has received the most clinical evidence of any other fermented vegetable beverage for cardiovascular health in large part because of its high dietary nitrate content. The LAB fermentation does not significantly diminish the dietary nitrate content of beet juice. The nitrate → nitrite → nitric oxide (NO) conversion pathway, mediates vasodilation and blood pressure reduction, is maintained in the fermentation process. Jakubczyk *et al.*, (2024) found that commercially available fermented beetroot juices have an antioxidant potential with polyphenol content and therefore provide other cardioprotective bioactive compounds that are not just based on nitrate. A number of clinical trials have shown that the consumption of 70–140 mL of fermented beet juice per day has been shown to lower systolic blood pressure by 4–10 mmHg in hypertensive patients.

10.2 Treatment of IBS and Gut Health

The probiotic lactic acid bacteria in the fermented vegetable drinks affect the gut microbiome structure through competitive inhibition of pathogenic bacteria, production of short-chain fatty acids (SCFAs) – mainly butyrate, propionate and acetate – from fermentation of prebiotic fibres and modulation of immune effects on the intestinal mucosal immune system. In their review of the microbiome in fermented foods, several clinical trials [61] have demonstrated that regular consumption of LAB-fermented plant foods (including vegetable-based products) improves gut microbiome diversity, intestinal permeability and inflammatory markers.

10.3 Effect of Obesity on Metabolism

Lee et al. (2023) found that the LAB from kimchi-fermented vegetable juice could induce changes in the expression of genes related to lipid metabolism and the composition of gut microbiota in vitro and animal experiments, which contributes to its anti-obesity effect. Recent studies of National cohort study of kimchi intake associated with obesity-related parameters in Korean adults BMJ Open 2024 This study provides epidemiological evidence for the anti-obesity potential of EC fermented vegetable products using regular kimchi intake. This study revealed an inverse association between consumption frequency across all subtypes of kimchi and BMI along with abdominal obesity measurements among a nationally representative health examination cohort.

10.4 Immune Modulation

LAB from fermented vegetable products improves immune function through direct interactions with dendritic cells and macrophages in gut-associated lymphoid tissue (GALT), resulting in increased regulatory T-cell populations, better NK cell activity and increased secretory IgA (sIgA) production. The fermented foods and human health review by *Wastyk et al.*, (2021) was an early Cell paper showing that fermented food (including fermented vegetable products) significantly increased microbiome diversity and decreased inflammatory markers in a randomized controlled crossover trial and was the most robust human clinica.

11. Sensory properties and Consumer Acceptance

The sensory profile of fermented vegetable beverages is both their most distinctive and their biggest challenge in the markets. The sour taste (from lactic acid accumulation to 0.5-1.2% titratable acidity) and complex volatile compounds profile (diacetyl, acetoin, acetic acid and other vegetable-derived terpenes) in addition to the color (due to pH-dependent pigment change) and less viscosity (pectin hydrolysis by LAB pectinases) define the sensory character of fermented vegetable beverages.

MDPI Foods (Fermentation 10, 48) showed that LAB fermentation could effectively reduce the content of undesirable volatile compounds, including cinnamaldehyde (3,402 to 7.55 microg/L), and transform the undesirable raw vegetable odor to a more balanced and consumer-acceptable fermented flavor profile in 2024. D’Amico analysed plant-based probiotic beverages using the standard tools like triangle and

International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

acceptability tests. The physicochemical parameters, such as pH, titratable acidity, colour and volatile profile, were stable during the storage time. What are the best practices of consumer acceptance for fermented vegetable beverages? Blend with fruit juices to balance the natural sweetness. Addition of carbonation for mouthfeel and masking sourness. Use natural flavor enhancing spices and herbs (ginger, cinnamon, turmeric). Partially ferment to cut down sourness. Sweeten with honey or a natural low-calorie sweetener like stevia or monk fruit extract**.**

12. Safety, Shelf life, and Packaging

A major advantage of fully fermented vegetable drinks from a microbiological safety point of view is their intrinsic low pH (3.5–4.5) which prevents the growth of most foodborne pathogens such as *Salmonella spp*., *E. coli O157:H7*, *Listeria monocytogenes and Staphylococcus aureus*. One of the major challenges in the commercialization of fermented vegetable drinks is the pasteurization for longer shelf life and viable probiotic cultures (Probiotic Beverage Manufacturing Guide, 2025).

Ezekiel *et al.*, 2024 analysed sustainable packaging for fermented vegetable beverages. The review found that packaging should protect probiotic viability; resist oxygen entry (which stresses aerotolerant LAB); be light barrier-friendly (to protect betalains and anthocyanins) and meet consumer sustainability expectations. Refrigerated fermented vegetable beverages showed 2–4 weeks longer shelf life with vacuum and modified atmosphere packaging (CO 2 /N 2 mixtures) in comparison to conventional packaging, without affecting probiotic viability below the functional threshold.

Sustainable packaging for fermented vegetable beverages has been reviewed by Ezekiel *et al.*, (2024) who found that it is important to have packaging that protects probiotic viability, resists oxygen entry (which stresses aerotolerant LAB), is light barrier-friendly (to protect betalains and anthocyanins) and meets consumer sustainability expectations. Vacuum and modified atmosphere packaging (CO_2/N_2 mixtures) have been used to extend the shelf life of refrigerated fermented vegetable beverages so as to preserve probiotic viability above the functional threshold by 2–4 weeks compared with conventional packaging.

13. Challenges and Limitations

Table 5 Challenges and limitations

Challenge	**Current Status**	**Impact**	**Proposed solutions**
Probiotic viability maintenance	Vegetable matrices lack the buffering capacity of dairy — pH drops rapidly reducing LAB viability	May fall below 6 log CFU/mL threshold during storage	Microencapsulation; acid-tolerant strain selection; protective encapsulants (inulin, trehalose)
Standardization and reproducibility	Spontaneous fermentation produces variable composition between batches	Inconsistent probiotic count and health claim substantiation difficulty	Defined multi-strain starter cultures; controlled fermentation parameters; HACCP protocols

Consumer acceptance	Sour flavor, unfamiliar appearance, and brown discoloration from vegetable pigment degradation	Major barrier to market penetration in non-traditional markets	Fruit juice blending; carbonation; partial fermentation; natural sweeteners; innovative packaging
Limited clinical evidence	Majority of health benefit evidence from in vitro and animal studies; few RCTs in humans	Cannot substantiate health claims for regulatory approval	Investment in well-designed RCTs; biomarker-based efficacy studies; multi-centre trials
Scale-up challenges	Lab-scale fermentation difficult to translate to industrial scale with consistent quality	Temperature gradients; oxygen distribution; probiotic viability at large scale	Validated scale-up protocols; continuous fermentation systems; immobilized cell technology
Regulatory framework gaps	No specific regulatory category for fermented vegetable beverages in most countries	Uncertainty about permissible health claims and labeling requirements	Harmonized international standards; FSSAI specific guidelines for fermented vegetable beverages

14. Future Perspectives and Emerging Trends

Precision fermentation with multi-strain defined starter cultures specifically optimized for vegetable beverage fermentation — combining homofermentative strains for efficient acidification with heterofermentative strains for flavour complexity and selected probiotic strains with documented clinical health effects were about to discover. Next generation probiotics in vegetable matrices - *Akkermansia muciniphila, Faecalibacterium prausnitzii and Bifidobacterium longum* integration in vegetable fermentation systems for improving gut health benefits beyond standard *Lactobacillus* based products may enter in to the health care industry.

Synbiotic vegetable beverages — strategic combination of prebiotic vegetable components (inulin from Jerusalem artichoke, FOS from chicory, beta-glucan from oats) with specific probiotic LAB to create purpose-designed synbiotic beverages with demonstrated bifidogenic effects.

Omics-based characterization, Application of metabolomics, metagenomics, transcriptomics and proteomics to the complete characterization of the biochemistry and microbial ecology of fermented vegetable beverages, offering mechanistic insights into health consequences.

AI and ML for Process Optimisation - Multi-objective optimization of fermentation parameters for simultaneous maximization of probiotic viability, bioactive chemical content and sensory quality - not possible by traditional one-factor-at-a-time methods.

Valorization of vegetable waste (carrot tops, beetroot pomace, tomato skin and seed, cabbage outer leaves) as substrates for medium to high value, functional fermented beverages to combat food waste and create value at the same time in circular economy. Targeted health condition beverages - Fermented vegetable drinks for targeted health conditions including nitrate-rich fermented beetroot juice for the management of hypertension, fermented cruciferous vegetable juice for the prevention of colorectal cancer, and GABA-enriched fermented vegetable beverages for the management of stress and anxiety.

15. Conclusion

Fermented vegetable beverages represent a scientifically compelling, nutritionally versatile, and commercially significant category of functional food products positioned at the convergence of three of the most powerful global food industry trends — plant-based food growth, probiotic and gut health awareness, and clean-label functional food demand. The present review has analysed global evidence across the full spectrum of fermented vegetable beverage science — from the historical traditions of kanji, kvass, and kimchi juice through to the latest novel research-developed probiotic vegetable beverage formulations — demonstrating that lactic acid fermentation transforms raw vegetable substrates into products with substantially enhanced nutritional value, probiotic functionality, antioxidant activity, bioavailability of bioactive compounds, and demonstrable health benefits.

Lactiplantibacillus plantarum emerges as the most scientifically characterized and functionally versatile probiotic organism. LAB species are well suited for vegetable beverage fermentation, with documented probiotic properties including acid and bile tolerance, intestinal adhesion, gut microbiome modulation, anti-obesity effects, cardiovascular protection, and immunomodulatory activity across multiple in vitro, animal, and human clinical studies. The biochemical transformations occurring during vegetable fermentation — including phenolic compound biotransformation, antinutrient reduction, vitamin B enhancement, and organic acid production — collectively produce a beverage with substantially improved functional properties relative to the unfermented raw material.

The primary challenges remaining are maintaining probiotic viability throughout shelf life in non-dairy matrices, standardizing fermentation processes to enable reproducible health claim substantiation, securing consumer acceptance of characteristic fermented sensory profiles in non-traditional markets, and conducting more high-quality human clinical trials to build the evidence base for regulatory health claim approval. Addressing these challenges through precision fermentation technology, microencapsulation, metabolomics-guided product optimization, and well-designed clinical trials will be critical to unlocking the full commercial and public health potential of fermented vegetable beverages as a mainstream global functional food category.

16. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

17. Acknowledgements

The authors would like to thank Dr. Anuradha M., Principal, Padmashree Institute of Management and Sciences for her constant support, encouragement and useful assistance during this work. The authors further thank the Head of the Department and Management of Padmashree Institute of Management and Sciences for providing required infrastructure and laboratory facilities to effectively execute this research.

References

1. FAO/WHO. (2001). Health and nutritional properties of probiotics in food including powder milk with live lactic acid bacteria. Report of a Joint FAO/WHO Expert Consultation, Cordoba, Argentina. Food and Agriculture Organization of the United Nations/World Health Organization, Rome, Italy.
2. Grand View Research. (2023). Non-dairy probiotic beverages market size, share and trends analysis report by product, by distribution channel, by region, and segment forecasts, 2024–2030. Grand View Research, Inc., San Francisco, CA, USA.
3. Marco, M. L., Sanders, M. E., Ganzle, M., Arrieta, M. C., Cotter, P. D., De Vuyst, L., ... & Hutkins, R. (2021). The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on fermented foods. Nature Reviews Gastroenterology and Hepatology, 18(3), 196–208. https://doi.org/10.1038/s41575-020-00390-5.
4. Rahman, M. S., Das Emon, D., Toma, M. A., Nupur, A. H., Karmoker, P., Iqbal, A., & Aziz, M. (2023). Recent advances in probiotication of fruit and vegetable juices. Journal of Advanced Veterinary and Animal Research, 10(3), 522–537. https://doi.org/10.5455/javar.2023.j695
5. Erem, E., Kilic-Akyilmaz, M., & others. (2024). The role of fermentation with lactic acid bacteria in quality and health effects of plant-based dairy analogues. Comprehensive Reviews in Food Science and Food Safety, 23, e13402. https://doi.org/10.1111/1541-4337.13402.
6. Zheng, J., Wittouck, S., Salvetti, E., Franz, C. M. A. P., Harris, H. M. B., Mattarelli, P., ... & Lebeer, S. (2020). A taxonomic note on the genus Lactobacillus: Description of 23 novel genera, emended description of the genus Lactobacillus Beijerinck 1901, and union of Lactobacillaceae and Leuconostocaceae. International Journal of Systematic and Evolutionary Microbiology, 70(4), 2782–2858. https://doi.org/10.1099/ijsem.0.004107
7. Tamang, J. P., Shin, D. H., Jung, S. J., & Chae, S. W. (2020). Functional properties of microorganisms in fermented foods. Frontiers in Microbiology, 7, 578. https://doi.org/10.3389/fmicb.2016.00578
8. Zamfir, M., Angelescu, I. R., Raiciu, A. D., Dobrescu, A., Pelinescu, D., & Stoica, I. (2022). Non-dairy fermented beverages produced with functional lactic acid bacteria. Microorganisms, 10(12), 2314. https://doi.org/10.3390/microorganisms10122314.
9. Zhang, Q., Shan, B., & Chen, W. (2024). Mechanisms of health improvement by Lactiplantibacillus plantarum based on animal and human trials: A review. Fermentation, 10(2), 73. https://doi.org/10.3390/fermentation10020073
10. Llamas-Arriba, M. G., Hernandez-Alcantara, A. M., Yepez, A., Aznar, R., Duenas, M. T., & Lopez, P. (2019). Functional and nutritious beverages produced by lactic acid bacteria. In Nutrients in Beverages (pp. 419–465). Elsevier. https://doi.org/10.1016/B978-0-12-816842-4.00013-2
11. Frontiers in Industrial Microbiology. (2026). Understanding of the interaction of Lactobacillus in fermented food and beverages: targeting food safety and new foods. Frontiers in Industrial Microbiology, 1846356. https://doi.org/10.3389/finmi.2026.1846356
12. Janiszewska-Turak, E., Pobiega, K., Rybak, K., Synowiec, A., Wozniak, L., Trych, U., Gniewosz, M., & Witrowa-Rajchert, D. (2023). Changes in physical and chemical parameters of beetroot and carrot juices obtained by lactic fermentation. Applied Sciences, 13(10), 6113. https://doi.org/10.3390/app13106113

13. Sun, X., Zhang, Y., Li, F., Wang, J., Zhao, M., & Xu, Y. (2022). Effects of lactic acid bacteria fermentation on chemical compounds, antioxidant capacities and hypoglycemic properties of pumpkin juice. Food Bioscience, 50, 102126. https://doi.org/10.1016/j.fbio.2022.102126
14. Uzun, D. E., Dikmetas, D. N., Karbancioglu-Guler, F., Tomas, M., & Capanoglu, E. (2024). Exploring the impact of fermentation on bioactive compounds in two different types of carrot pomace. Food Bioscience, 61, 104646. https://doi.org/10.1016/j.fbio.2024.104646
15. Leonard, W., Zhang, P., Ying, D., Adhikari, B., & Fang, Z. (2021). Fermentation transforms the phenolic profiles and bioactivities of plant-based foods. Biotechnology Advances, 49, 107763. https://doi.org/10.1016/j.biotechadv.2021.107763
16. Kiczorowski, P., Kiczorowska, B., Samolinska, W., Szmigielski, M., & Winiarska-Mieczan, A. (2022). Effect of fermentation of chosen vegetables on the nutrient, mineral, and biocomponent profile in human and animal nutrition. Scientific Reports, 12(1), 13422. https://doi.org/10.1038/s41598-022-17705-2.
17. Choinska, R., Piasecka-Jozwiak, K., Wozniak, L., Swider, O., Bartosiak, E., Bujak, M., & Roszko, M. (2022). Starter culture-related changes in free amino acids, biogenic amines profile, and antioxidant properties of fermented red beetroot. Scientific Reports. https://doi.org/10.1038/s41598-022-09845-6.
18. Dzandu, B., Chotiko, A., & Sathivel, S. (2022). Antioxidant activity and viability of Lacticaseibacillus rhamnosus, Lacticaseibacillus casei, and co-culture in fermented tomato juice during refrigerated storage. Food Bioscience, 50, 102085. https://doi.org/10.1016/j.fbio.2022.102085
19. Ruiz-Gonzalez, N., Escudero-Moreno, E., Garcia-Tejedor, A., Cordoba-Diaz, D., Cordoba-Diaz, M., & Campelo, P. H. (2024). Lactiplantibacillus plantarum KABP051: Stability in fruit juices and production of bioactive compounds during their fermentation. Microorganisms, 12, 2477. https://doi.org/10.3390/microorganisms12122477.
20. Foods. (2025). Apple juice fermented with Lactiplantibacillus plantarum improves its flavor profile and probiotic potential. Foods, 14, 2373. https://doi.org/10.3390/foods14132373.
21. Huang, J., Cai, X., & Wang, Q. (2025). Lactiplantibacillus plantarum BXM2 treatment alleviates disorders induced by a high-fat diet in mice by improving intestinal health and modulating the gut microbiota. Nutrients, 17(3), 407. https://doi.org/10.3390/nu17030407
22. Thierry, A., Claisse, O., Le Berre, E., & Valence, F. (2023). Microbial communities of a variety of 75 homemade fermented vegetables. Frontiers in Microbiology, 14, 1323424. https://doi.org/10.3389/fmicb.2023.1323424.
23. Cele, N. P., Akinola, S. A., Manhivi, V. E., Shoko, T., Remize, F., & Sivakumar, D. (2024). Influence of lactic acid bacterium strains on changes in quality characteristics of fermented vegetable products. Current Food Science and Technology Reports. https://doi.org/10.1007/s43555-024-00049-1.
24. Do, T. T., & Fan, L. (2019). Probiotic viability, qualitative characteristics, and sensory acceptability of vegetable juice mixture fermented with Lactobacillus strains. Food Science and Nutrition, 7(3), 899–909. https://doi.org/10.1002/fsn3.926.
25. Sharma, C., Sahota, P. P., & Kaur, S. (2021). Physicochemical and microbiological evaluation of antioxidant-rich traditional black carrot beverage: Kanji. Bulletin of the National Research Centre, 45, 144. https://doi.org/10.1186/s42269-021-00594-y.

26. Tamang, J. P., Cotter, P. D., Endo, A., Han, N. S., Kort, R., Liu, S. Q., ... & Hutkins, R. (2020). Fermented foods in a global age: East meets West. Comprehensive Reviews in Food Science and Food Safety, 19(1), 184–217. https://doi.org/10.1111/1541-4337.12520.
27. Marco, M. L., Hill, C., Hutkins, R., Slavin, J., Abbeele, P. V. D., Gele, K., & Sanders, M. E. (2023). Should there be a recommended daily intake of microbes? Journal of Nutrition, 150(12), 3061–3067. https://doi.org/10.1093/jn/nxaa324.
28. Annual Reviews. (2025). Lacto-fermented fruits and vegetables: Bioactive components and effects on human health. Annual Review of Food Science and Technology. https://doi.org/10.1146/annurev-food-052924-070656
29. Ezekiel, C. N., Ayeni, K. I., & Udom, K. (2024). Sustainable packaging materials for fermented probiotic dairy or non-dairy food and beverage products: Challenges and innovations. PeerJ, 12, e17315. https://doi.org/10.7717/peerj.17315.
30. Mousavi, M. H., Gharekhani, M., Alirezalu, K., Roufegarinejad, L., & Azadmard-Damirchi, S. (2023). Production and characterization of non-dairy gluten-free fermented beverage based on buckwheat and lentil. Food Science and Nutrition, 11, 2197–2210. https://doi.org/10.1002/fsn3.3233.
31. Naseem, Z., Mir, S. A., Wani, S. M., Rouf, M. A., Bashir, I., & Zehra, A. (2023). Probiotic-fortified fruit juices: Health benefits, challenges, and future perspective. Nutrition, 115, 112154. https://doi.org/10.1016/j.nut.2023.112154.
32. Non-Dairy Fermented Probiotic Beverages Review. (2025). Non-dairy fermented probiotic beverages: A critical review on production techniques, health benefits, safety considerations and market trends. Food Reviews International, 42(4). https://doi.org/10.1080/87559129.2025.2550596.
33. Fermentation MDPI. (2024). Effect of lactic acid bacteria fermentation on plant-based products. Fermentation, 10(1), 48. https://doi.org/10.3390/fermentation10010048
34. Sanlier, N., Gokcen, B. B., & Sezgin, A. C. (2019). Health benefits of fermented foods. Critical Reviews in Food Science and Nutrition, 59(3), 506–527. https://doi.org/10.1080/10408398.2017.1383355
35. Del Toro-Barbosa, M., Uribe-Velazquez, T., Hurtado-Romero, A., Rosales-De la Cruz, M. F., Carrillo-Nieves, D., Garcia-Amezquita, L. E., & Garcia-Cayuela, T. (2025). Evaluation of GABA-producing fermented whey formulations: From strain selection to raspberry-enriched beverages with psychobiotic potential. Foods, 14(16), 2762. https://doi.org/10.3390/foods14162762
36. Brassica Review. (2024). Health benefits of kimchi, sauerkraut, and other fermented foods of the genus Brassica. Fermentation, 10(3), 79. https://doi.org/10.3390/fermentation10030079
37. Marco, M. L., Heeney, D., Binda, S., Cifelli, C. J., Cotter, P. D., Foligne, B., ... & Hutkins, R. (2021). Health benefits of fermented foods: Microbiota and beyond. Current Opinion in Biotechnology, 44, 94–102. https://doi.org/10.1016/j.copbio.2016.11.010
38. Iorizzo, M., Lombardi, S. J., Ganassi, S., Testa, B., & Letizia, F. (2023). GABA biosynthesis by Lactiplantibacillus plantarum with a focus on fermented foods. Foods, 12(3), 624. https://doi.org/10.3390/foods12030624

39. Maia, M. S., Domingos, M. M., & de Sao Jose, J. F. B. (2023). Viability of probiotic microorganisms and the effect of their addition to fruit and vegetable juices. Microorganisms, 11(5), 1335. https://doi.org/10.3390/microorganisms11051335.
40. Bauer, A. W., Kirby, W. M. M., Sherris, J. C., & Turck, M. (1966). Antibiotic susceptibility testing by a standardized single disk method. American Journal of Clinical Pathology, 45(4), 493–496. https://doi.org/10.1093/ajcp/45.4_ts.493.
41. Kandylis, P.; Pissaridi, K.; Bekatorou, A.; Kanellaki, M.; Koutinas, A.A. Dairy and non-dairy probiotic beverages. Curr. Opin. Food Sci. 2016, 7, 58–63.
42. Shori, A.B. Influence of food matrix on the viability of probiotic bacteria: A review based on dairy and non-dairy beverages. Food Biosci. 2016, 13, 1–8.
43. Vanga, S.K.; Raghavan, V. How well do plant based alternatives fare nutritionally compared to cow's milk? J. Food Sci. Technol. 2018, 55, 10–20.
44. Devaki, C.S.; Premavalli, K.S. Fermented vegetable beverages. Fermented beverages. Sci. Beverages 2019, 5, 321–367.
45. Mesquita, M.C.; Leandro, E.S.; Alencar, E.R.; Botelho, R.B.A. Fermentation of chickpea (Cicer arietinum L.) and coconut (Coccus nucifera L.) beverages by Lactobacillus paracasei subsp. paracasei LBC 81: The influence of sugar content on growth and stability during storage. LWT—Food Sci. Technol. 2020, 132, 109834.
46. Bernat, N.; Cháfer, M.; González-Martínez, C.; Rodríguez-García, J.; Chiralt, A. Optimization of oat Milk formulation in order to obtain fermented derivatives by using probiotic Lactobacillus reuteri microorganisms. Food Sci. Technol. Int. 2014, 21, 145–157.
47. Carvalho, W.T.; Reis, R.C.; Velasco, P.; Soares Júnior, M.S.; Bassinello, P.Z.; Caliari, M. Physico-chemical characteristics of whole rice, broken rice and soybean extracts. Trop. Agric. Res. 2011, 41, 422–429.
48. Maldonado, R.R.; Araújo, L.C.; Dariva, L.C.S.; Rebac, K.N.; Pinto, I.A.S.; Prado, J.P.R.; Saeki, J.K.; Silva, T.S.; Takematsu, E.K.; Tiene, N.V.; et al. Potential application of four types of tropical fruits in lactic fermentation. LWT—Food Sci. Technol. 2017, 86, 254–260.
49. Ghosh, K.; Ray, M.; Adak, A.; Halder, S.K.; Das, A.; Jana, A.; Mondal, S.P.; Vagvolgyi, C.; Mohapatra, P.K.; Pati, B.R.; et al. Role of probiotic lactobacillus fermentum KKL1 in the preparation of a rice-based fermented beverage. Bioresour. Technol. 2015, 188, 161–168.
50. Battistini, C.; Gullónd, B.; Ichimuraa, E.S.; Gomes, A.M.P.; Ribeiro, E.P.; Kunigk, L.; Moreira, J.U.V.; Jurkiewicz, C. Development and characterization of an innovative symbiotic fermented beverage based on vegetable soybean. Braz. J. Microbiol. 2018, 49, 303–309.
51. Bernat, N.; Cháfer, M.; Chiralt, A.; González-Martínez, M. Development of a non-dairy probiotic fermented product based on almond Milk and inulin. Food Sci. Technol. Int. 2014, 21, 440–453.
52. Gupta, S.; Cox, S.; Abu-Ghannam, N. Process optimization for the development of a functional beverage based on lactic acid fermentation of oats. Biochem. Eng. J. 2010, 52, 199–204.
53. Mohammadi, R.; Yousefi, M.; Sarlak, Z.; Shah, N.P.; Mortazavian, A.M.; Sadeghi, E.; Khajavi, M.Z. Influence of commercial culture composition and cow Milk to soy milk ratio on the biochemical, microbiological, and sensory characteristics of a probiotic fermented composite drink. Food Sci. Biotechnol. 2017, 26, 749–757.

54. Malik, M., Bora, J., & Sharma, V. (2019). Growth studies of potentially probiotic lactic acid bacteria (Lactobacillus plantarum, Lactobacillus acidophilus, and Lactobacillus casei) in carrot and beetroot juice substrates. Journal of Food Processing and Preservation, 43(12), e14214. https://doi.org/10.1111/jfpp.14214
55. Jukonyte, R.; Zadeike, D.; Bartkiene, E.; Lele, V.; Cernauskas, D.; Suproniene, S.; Juodeikiene, G. A potential of brown rice polish as a substrate for the lactic acid and bioactive compounds production by the lactic acid bacteria newly isolated from cereal-based fermented products. LWT—Food Sci. Technol. 2018, 97, 323–331.
56. Kechagia, M.; Basoulis, D.; Konstantopoulou, S.; Dimitriadi, D.; Gyftopoulou, K.; Skarmoutsou, N.; Fakiri, E.M. Health Benefits of Probiotics: A Review. ISRN Nutr. 2013, 2013, 481651.
57. Rwubuzizi, R., Carneiro, K. O., Holzapfel, W. H., Vaz-Velho, M., & Todorov, S. D. (2023). Bacteriocin and antioxidant production, beneficial properties of lactic acid bacteria isolated from fermented vegetables. Beneficial Microbes. https://doi.org/10.3920/BM2022.0062.
58. Jakubczyk, K., Melkis, K., Janda-Milczarek, K., & Skonieczna-Zydecka, K. (2024).Phenolic compounds and antioxidant properties of fermented beetroot juices enriched with different additives. Foods, 13(1), 102. https://doi.org/10.3390/foods13010102.
59. Lee, M., Yun, Y. R., Choi, E. J., Song, J. H., & Kang, J. Y. (2023). Anti-obesity effect of vegetable juice fermented with lactic acid bacteria isolated from kimchi in C57BL/6J mice and human mesenchymal stem cells. Food and Function, 14(3), 1349–1356. https://doi.org/10.1039/D2FO02726E.
60. BMJ Open. (2024). Association between kimchi consumption and obesity based on BMI and abdominal obesity in Korean adults: A cross-sectional analysis of the Health Examinees study. BMJ Open, 14, e076650. https://doi.org/10.1136/bmjopen-2023-076650.
61. Wastyk, H. C., Fragiadakis, G. K., Perelman, D., Dahl, W. J., Zhu, Z., Sonnenburg, J. L., & Gardner, C. D. (2021). Gut-microbiota-targeted diets modulate human immune status. Cell, 184(16), 4137–4153. https://doi.org/10.1016/j.cell.2021.06.019.
62. Fermented Foods Microbiome Review. (2024). Fermented foods, their microbiome and its potential in boosting human health. Microbial Biotechnology, 17, e14428. https://doi.org/10.1111/1751-7915.14428.
63. D'Amico, A., Buzzanca, C., Pistorio, E., Melilli, M. G., & Di Stefano, V. (2025). Developing novel plant-based probiotic beverages: A study on viability and physicochemical and sensory stability. Foods, 14(12), 2148. https://doi.org/10.3390/foods14122148.
64. PMC Plant-Based Probiotic Foods. (2024). Plant-based probiotic foods: Current state and future trends. PMC11525375. https://doi.org/10.3390/foods13203206.