

# The Era of Plant-Based Probiotics: An Overview of Potential Benefits and Future Aspects

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## Abstract

**Background and Objective:** Probiotics, defined as specific strains of live microorganisms, usually bacteria or yeast, play a crucial role in host health by enhancing digestive functions. Traditionally, these organisms were sourced from dairy-based fermented foods such as yogurt, cheese, and kefir; however, the rise in plant-based diets has spurred the popularity of plant-based probiotics, driven by factors such as veganism, lactose intolerance, and dairy allergies. Plant-based probiotics offer a valuable alternative that caters to diverse dietary requirements while also contributing to environmental sustainability through lower greenhouse gas emissions, reduced water consumption, and less land use. This review delves into the development, potential health benefits, future applications, and technological challenges related to the production and marketing of plant-based probiotics.

**Results and Conclusion:** Innovative approaches have led to the creation of functional foods that combine plant sources with robust probiotic strains capable of surviving in plant-based matrices. The integration of probiotics with prebiotic fibers such as chicory and acacia, has proven to enhance viability and performance. Furthermore, plant-based probiotic products are evolving beyond beverages to encompass snacks, ready-to-eat fruits, and nuts. Nonetheless, challenges persist regarding the viability of probiotic strains during storage, the costs associated with large-scale production, and the necessity of consumer education. Regulatory frameworks are being adapted to ensure health claims attributed to probiotic products that are backed by scientific evidence. As a promising frontier in sustainable functional foods, plant-based probiotics cater to a wide range of consumer needs. Future advancements are anticipated to focus on personalized formulations and broader applications within health and wellness, alongside improved techniques to enhance probiotic stability and efficacy.

**Keywords:** Functional foods, Non-dairy Probiotics, Plant-based probiotics, Sustainable nutrition, Vegan health, Gut microbiome, Eco-friendly foods

### What is “already known” on this topic:

- Probiotics, typically bacteria or yeast, enhance digestive health and are traditionally sourced from dairy products like yogurt, cheese, and kefir.
- The rise in veganism, lactose intolerance, and dairy allergies has increased demand for non-dairy and plant-based probiotic alternatives.
- Plant-based probiotics contribute to environmental sustainability by reducing resource consumption compared to dairy-based production.

### What this article adds:

- Introduces innovative functional foods that integrate plant-based probiotics with prebiotic fibers (e.g., chicory, acacia) to improve strain viability and performance.
- Highlights the diversification of plant-based probiotic products into snacks, ready-to-eat fruits, and nuts, beyond traditional beverages.
- Identifies challenges: maintaining probiotic viability during storage, high production costs, and the need for consumer education.
- Discusses evolving regulatory frameworks to ensure that health claims are supported by scientific evidence.
- Predicts future trends toward personalized probiotic formulations and advanced techniques for enhanced stability and broader health applications.

## 1. Introduction

Probiotics are live microorganisms that confer health benefits to the host when administered in adequate quantities [1]. These microorganisms exert beneficial effects via production of antimicrobial compounds, inhibition of pathogenic bacteria, and the generation of essential metabolites, including vitamins and short-chain fatty acids (SCFAs), thereby contributing to the overall well-being of the host [2]. The growing interest in probiotics is reflected in both scientific research and industry. Historically, dairy matrices have facilitated the growth and survival of probiotics, leading to their predominant use in products like yogurt, kefir, and cheese [3]. However, the reliance on dairy probiotics poses limitations that restrict their access to broader consumer groups.

Among the most well-known probiotic species are members of the lactic acid bacteria (LAB) group, comprising strains such as *Lactobacillus acidophilus*, *Lactocaseibacillus casei*, *Lactobacillus crispatus*, *Bacillus coagulans*, *Lactobacillus delbrueckii subsp. bulgaricus*, *Limosilactobacillus fermentum*, *Ligilactobacillus gasseri*, *Lactobacillus helveticus*, *Ligilactobacillus johnsonii*, *Lactococcus lactis*, *Lactocaseibacillus paracasei*, *Lactiplantibacillus plantarum*, *Limosilactobacillus reuteri*, *Lactocaseibacillus rhamnosus*[4].

Traditionally, these beneficial microorganisms are sourced from fermented dairy products, including kefir, yogurt, and curd. The growing demand for vegan foods, driven by health considerations, the prevalence of lactose intolerance, and increasing awareness of milk protein allergies, has fostered a shift toward non-dairy alternatives, notably in Asia and parts of Africa, where access to dairy products is limited [5]. Consumers are increasingly seeking sustainable probiotic delivery systems that align with ethical and environmental values [6]. Furthermore, eco-conscious consumers like to seek more sustainable probiotic delivery systems [7]. Figure 1 shows the classification of various probiotic foods.

Simultaneously, developments in fermentation technologies and food science have demonstrated the potential of plant-based matrices, such as cereals, legumes, fruits, vegetables, and plant-based milks, as efficient probiotic carriers. In addition to meeting dietary requirements, these substrates offer extra phytochemicals, dietary fiber, and bioactive compounds that could complement the effects of probiotics [8]. By offering unique tastes, textures, and health benefits, plant-based probiotic

formulations can appeal to a large market. Despite these promising trends, technological challenges remain unresolved. For example, probiotic viability, stability, sensory optimization, and regulatory frameworks for plant-based products are a few of them. Moreover, further research and developments are needed to confirm the efficacy of particular strains in plant-based matrices, with an emphasis on consumer demand, technological advancements, and health applications. This review aims to provide a comprehensive overview of the emerging field of plant-based probiotics, highlighting the drivers of consumer demand, technological innovations, and health applications while critically examining the current limitations and future directions.

## 2. Growing Demand Drivers

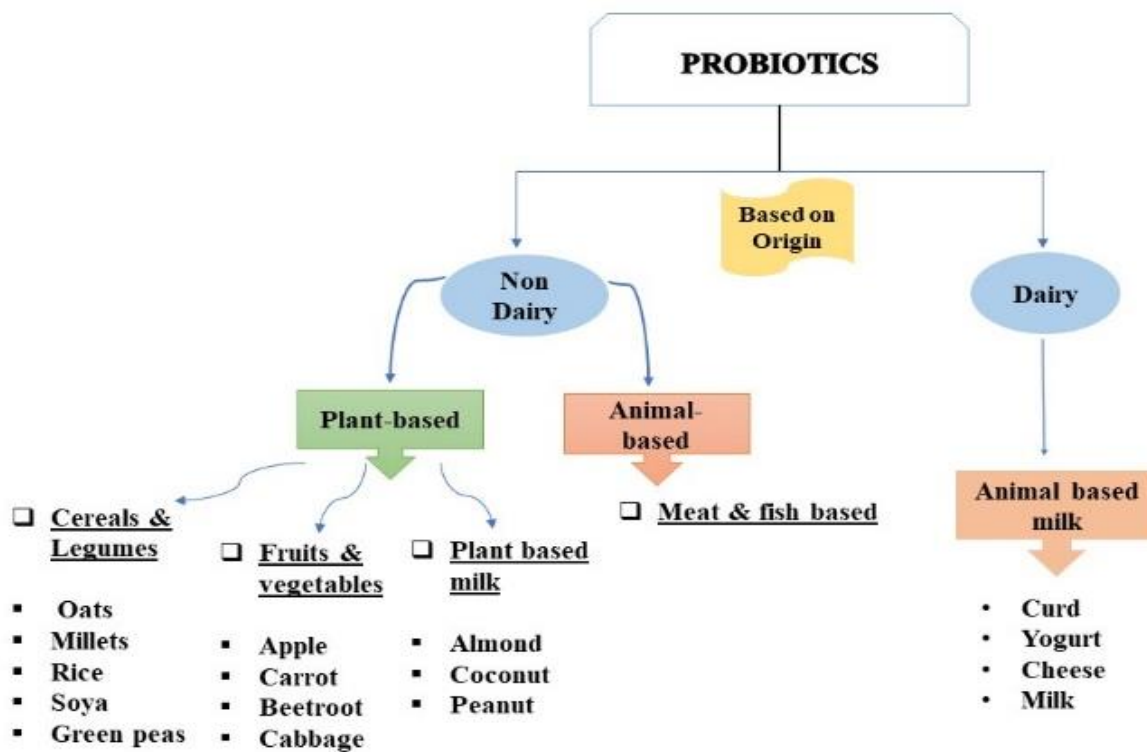
### 2.1. Vegan and dairy-free probiotic trends

The growing demand for lactose-free, cholesterol-free, and vegan foods has led to innovations in non-dairy probiotic systems. Researchers and industries are exploring plant-based alternatives like tree nuts, cereals, fruits, and vegetables as alternatives to traditional dairy substrates [9].

Due to their rich nutrient and prebiotic content, tree nuts such as almonds and cashews are emerging as promising fermentation substrates. Major challenges, such as emulsion stability and microbial viability, are being addressed using encapsulation techniques, natural stabilizers, and pH control [9]. For instance, traditional dairy products such as kefir, renowned for its health-promoting components like GABA (Gamma-aminobutyric acid), are now being reformulated using soy, rice, oat, and coconut bases. Although these alternatives may vary in taste and texture, they still provide metabolic advantages [10].

Recent advancements have introduced specific, well-characterized microbial strains specially designed for use with plant substrates, ensuring safety, functional efficiency, and reproducibility criteria. Targeted fermentation leveraging local agricultural resources can enhance the nutritional and therapeutic potential of plant-based probiotic foods [11]. Fruit- and vegetable-based probiotic beverages are gaining traction due to their nutritional variety and bioactive compounds that enhance shelf-life and functional value. Nevertheless, commercialization is still limited, necessitating further technological innovations [12].





**Figure 1.** Classification of Probiotic foods based on their origin

Fermented plant foods such as olives, vegetable juices, and pickled products, exhibit excellent potential as probiotic carriers due to their supportive matrices that enhance microbial adhesion and viability during controlled processing [10].

Nutritional evaluations indicate that vegan substitutes for dairy products like yogurt and cheese typically contain lower protein but higher fat and carbohydrate content. However, allergen risks from ingredients such as soy, nuts, and gluten pose challenges for product formulation. Clean labeling, improved protein profiles, and hypoallergenic options are vital for enhancing consumer acceptance [6]. Utilizing seasonal and regionally sourced substrates meets consumer demand for sustainable foods while also reducing production costs [13]. Transitioning from lab-scale innovation to industrial scalability necessitates multidisciplinary collaboration encompassing microbiological, technological, and economic expertise.

**2.2 Gut-health awareness**

The gut microbiome plays a pivotal role in maintaining health by supporting metabolic, immunological, and protective functions; however, awareness of its importance among the public remains limited, especially among children and adults [14] across many regions. An educational initiative conducted at a science fair in Kuala Lumpur, Malaysia, aimed to raise awareness about gut microbiota by engaging 324 participants aged 5 to 64

through quizzes and informational displays. Post-session, 77.9% of participants reported increased awareness of gut microbiota, with 85.3% expressing a willingness to incorporate more fruits and vegetables into their diets. Additionally, 60.5% indicated an intention to bring fruit for breaks in school or at work [14].

Research focusing on parental awareness of infant gut health uncovered significant gaps in knowledge provided by healthcare professionals. A survey of 933 parents, particularly those with preterm infants or those born via cesarean section, revealed a general lack of awareness concerning the connection between delivery mode and gut microbiome development [15]. Most parents did not receive adequate information on the significance of infant gut health, nor did they understand the roles of prebiotics and probiotics. This highlights the urgent need for targeted educational initiatives to inform parents about promoting their infant’s gut microbiome.

Alongside traditional fermented foods and probiotic supplements, there is growing recognition of the role of fruits and vegetables as prebiotics, representing a promising avenue for encouraging healthier gut microbiota [6]. These educational efforts underscore the critical importance of public health initiatives in facilitating long-term dietary changes and making gut health knowledge more accessible to wider populations.



### 2.3 Sustainability awareness among consumers

Heightened environmental concerns have significantly influenced consumer preferences within the food and beverage sectors. Plant-based dairy alternatives are gaining attraction, not only for their health benefits but also due to their reduced environmental footprint. Compared to conventional dairy production, plant-based alternatives typically use less land, water, and produce fewer greenhouse gases, marking them as a more sustainable choice [7]. This aligns with the values of eco-conscious consumers, particularly among younger demographics, who actively seek products that uphold ecological balance and mitigate climate impacts. As sustainability emerges as a driving force behind food innovation, the shift toward plant-based options reflects both ethical consumption trends and efforts to combat environmental degradation.

## 3. Emerging Sources and Innovations

Plant-based probiotics (PBPs) are sourced from various plant matrices serving as effective carriers for probiotic delivery. These products address the drawbacks of dairy-based options and are suitable for individuals with restrictive diets requiring probiotics. Major plant sources contributing to the development of non-dairy probiotics include cereals, legumes, fruits, vegetables, and plant-based milks [16].

#### a. Cereal-Based Products

Cereals are rich in protein, carbohydrates, vitamins, minerals, and fiber. Cereal grains such as maize, sorghum, millet, oats, barley, wheat, and rye are being utilized for the production of probiotic-rich foods, incorporating probiotic strains to enhance consumer health benefits.

#### b. Legume-Based Products:

Legumes (e.g., chickpeas, beans, lupins, soybeans) boast high levels of resistant starch and galactooligosaccharides, known for stimulating the growth and survival of probiotics.

#### c. Vegetable-Based Products:

Vegetables are abundant in carbohydrates, vitamins, minerals, and health-promoting compounds such as phytochemicals and phytonutrients. Commonly used substrates include carrots, cabbage, tomatoes, and beets, which are utilized to manufacture probiotic products employing LAB species like *L. acidophilus*, *L. plantarum*, and *B. longum*.

#### d. Fruit-Based Probiotic Products:

Fruit juices (e.g., apple, pineapple, mango, orange) serve as alternative vehicles for delivering probiotics. These juices offer health benefits and refreshing flavors enjoyed by diverse age groups, being rich in sugars and bioactive compounds that probiotics can utilize [8].

#### e. Non-Dairy milk substitutes:

Traditional milk products are increasingly being replaced by plant-based alternatives composed mainly of nuts and cereals, such as soy, almond, rice, and oat milks, each of which confer various health benefits [10]. These alternatives are regarded as functional foods, delivering essential nutrients that can aid in disease prevention [16].

### 3.1 Traditional sources of fermented plant foods

Fermentation stands as an age-old, cost-effective technique for preserving food, leveraging the growth and metabolic activities of microorganisms. Traditional fermented plant-based foods are valued across cultures for their flavor, health benefits, and natural preservative properties, and they serve as abundant sources of probiotics. Today, they are gaining recognition as effective non-dairy probiotic vehicles within vegan diets and functional food innovations [17]. Key examples of fermented foods and their functional benefits include:

Kimchi is a fermented vegetable dish prepared from vegetables, usually Chinese cabbage (Napa cabbage), Korean radish, and a variety of seasonings (ginger, garlic, salt, red chilli pepper, fish sauce/shrimps, etc.). This is a popular side dish in East Asian nations like Korea, Japan, and China. It acts as a probiotic vegetable food product that has rich nutritional qualities. Kimchi is also considered to be the source of LAB (*L. plantarum*, *L. brevis*). It helps to boost digestive health, improve immune system and mental health. Other beneficial properties of kimchi include cholesterol lowering activity, anti-obesity, anti-cancer, antioxidant, and anti-atherosclerotic properties [18].

Sauerkraut is a traditional fermented vegetable item prepared from cabbage. It is produced by spontaneous fermentation of cabbage that mainly involves heterofermentative LAB [19]. This is also known as German kraut and is very popular in European countries. Natural, unprocessed sauerkraut contains beneficial probiotic microorganisms like LAB (*L. plantarum*, *Leuconostoc mesenteroides*) [20]. From these foods, organic acids are produced by metabolizing sugars in the raw materials, altering flavors, prolonging its shelf life and producing B vitamins, such as folate (B<sub>9</sub>) riboflavin (B<sub>2</sub>), and other healthy components such as isothiocyanates and glycosylates. These compounds exhibit anti-inflammatory and anticancer properties which modulates specific cellular pathways and showing antioxidant activity which neutralizes the damaging effects of free radicals [8].

Tempeh is a nutrient-rich fermented legume food derived from soybeans and commonly consumed in Southeast Asia, especially in Indonesia and Malaysia. The fermentation process involves growth of mold, *Rhizopus* spp. which transforms soybeans into a white firm cake-like product as enzymes break down complex nutrients in soybeans into



simpler forms, enhancing the bioavailability of proteins, fiber, and other nutrients. Consumption of *Tempeh* has been linked to various health advantages including antidiabetic effects, reduced risk of cardiovascular diseases, cholesterol-lowering properties, improved cognitive function, antitumor and anticancer properties, anti-aging effects and improved gut health [21].

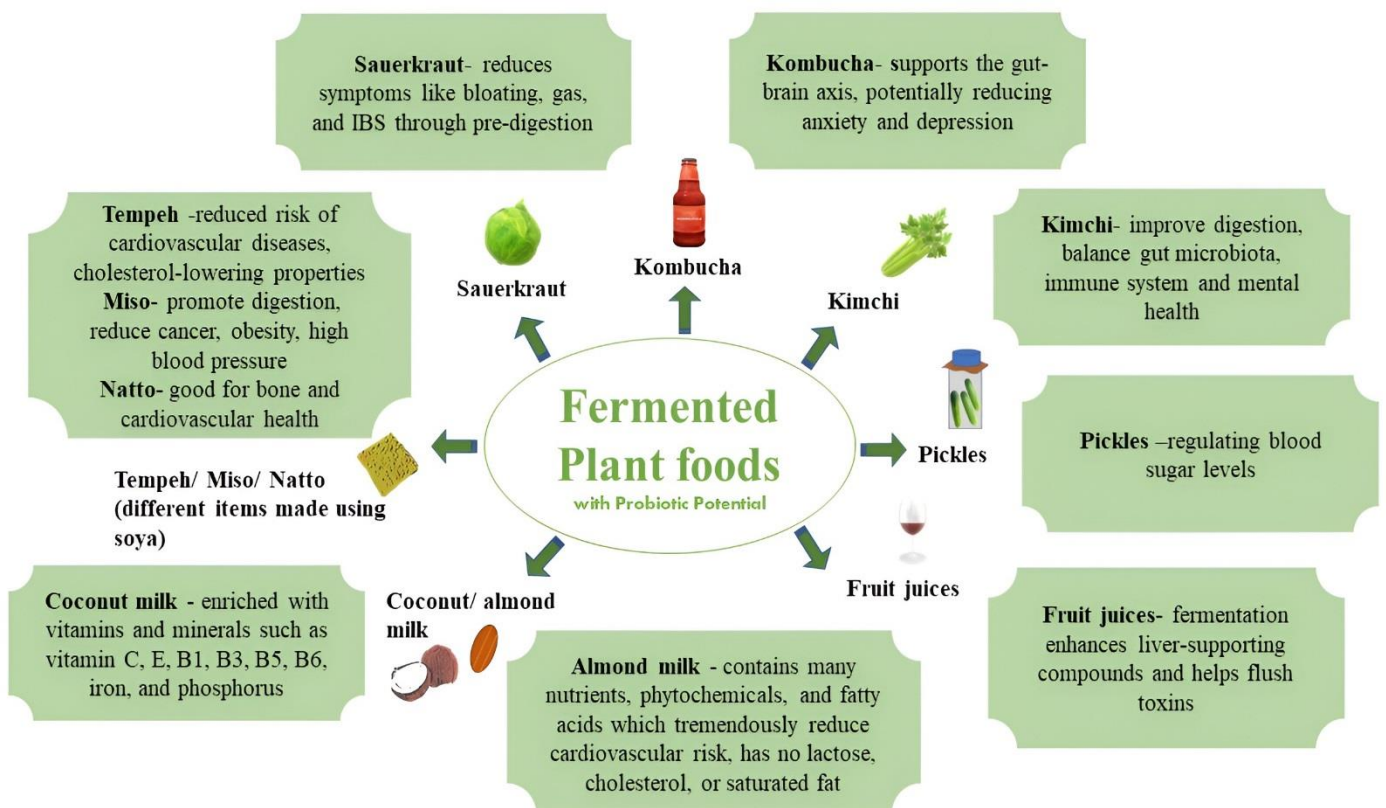
Miso is a Japanese salty and flavorful fermented paste made by fermenting soybeans with salt and a fungus *viz.*, *Aspergillus oryzae* (koji), *Lactobacillus sp.* along with soybeans and other ingredients such as barley, rice, and rye. It is typically salty and is considered as a good source of protein, fiber and vitamins (especially vitamin K), minerals, plant compounds, manganese, and copper. This helps to promote digestion, reduce cancer, obesity, high blood pressure and also helps regulate cholesterol levels [22].

Natto is another fermented soybean product, containing the bacterial strain- *B. subtilis*. It is typically mixed with rice and served with breakfast. It has a distinctive smell, slippery texture, and strong flavor, rich in protein, vitamin K2 and is good for bone and cardiovascular health [22].

Kombucha is a probiotic drink that originated in China which was made by fermenting sweet tea to produce a tangy and fizzy beverage. Known for its distinctive sour taste,

kombucha is believed to have detoxifying properties. D-glucaric acid in kombucha is linked to liver detoxification, helping bind and eliminate harmful compounds from the body. The drink also contains antioxidants, including ascorbic acid, gluconic acid, and polyphenols, which help combat reactive oxygen species, reduce oxidative stress, and may offer protective benefits against degenerative diseases such as atherosclerosis and Alzheimer's disease [8].

Pickles are an important dish, notably in India, US, Russia etc. Even though a variety of vegetables are used for pickling, cucumbers are considered as one of the most traditional options. The fermentation process for pickle production relies primarily on naturally occurring lactic acid bacteria, notably *L. plantarum* and *L. brevis*. As bacteria utilize the carbohydrates in cucumbers which help to generate lactic acid, it imparts a characteristic tangy flavor and inhibit the proliferation of pathogens and spoilage microorganisms. The probiotic content of pickles holds potential health benefits, such as regulating blood sugar levels and exhibiting anti-cancer properties [8]. The figure 2 shows the health benefits of fermented plant-based foods having probiotic potential.



**Figure 2.** Health benefits of fermented plant-based foods with probiotic potential



### 3.1.1 Microbial composition and fermentation mechanism

The microbial composition in fermented plant foods primarily includes bacteria, yeasts, and moulds, of which *Lactobacillus*, *Bifidobacterium*, *Acetobacter*, and *Saccharomyces* are the predominant species. These microorganisms play crucial roles in fermentation, influencing the characteristics of the food and metabolite production [23]. The action of enzymes and activity of microorganisms may induce changes in the nutritional properties and bioactive compound content, compared to the raw substrate [24]. Fermentation mechanisms are key to developing flavor, texture, nutritional value, and probiotic functionality. Some types of fermentation involved include:

(1) Lactic acid fermentation, which is involved in the formation of kimchi, sauerkraut and pickles. Some of the strains include *Lactobacillus*, *Leuconostoc*, *Pediococcus*, and *Weissella*. The mechanism involves conversion of glucose to pyruvate to lactic acid, which inhibits pathogens, and preserves the food.

(2) Alcoholic Fermentation, which is involved in the formation of kombucha and certain vegetable-based beverages, is carried out using *Saccharomyces cerevisiae*. The mechanism involves conversion of sugars into ethanol and carbon dioxide. In kombucha, a synbiotic culture of bacteria and yeast (SCOBY) are used for its production.

(3) Acetic acid fermentation that is also involved in kombucha formation (utilizing the strain *Komagataeibacter xylinus*) the oxidation of ethanol to acetic acid occurs under aerobic conditions [25].

### 3.1.2 Challenges associated with probiotic viability

The growing market for vegan probiotics faces several major challenges, including environmental factors (pH, temperature, oxygen level, and the presence of secondary metabolites) and manufacturing processes (including heat treatment and storage conditions) that may affect probiotic viability [26]. Strategies to ensure proper viability include selecting resilient strains, implementing encapsulation, enriching substrates with prebiotics (synbiotics), managing controlled fermentation, and adhering to strict packaging and cold-chain processes [27].

### 3.2 Novel strains being optimized for plant matrices

In functional food production, a critical consideration is given to the food matrix, which serve as the carrier for probiotic microorganisms, and provide a supportive environment for their growth and survival. The food matrix should also protect viable probiotic cells to ensure survival during passage through the gastrointestinal (GI) tract, thus allowing the appropriate gut colonization. These steps are essential for achieving the intended probiotic health benefits for the host [28]. GABA is a non-protein amino acid, which plays a significant role as an inhibitory neurotransmitter in

the mammalian central nervous system. It is been reported that GABA is associated with mammalian behavior by regulating stress and anxiety, modulating cognitive and brain functions, promoting sleep, and enhancing mood [29]. A novel probiotic GABA drink was created using brown rice as the main base ingredient, incorporating *L. pentosus* 9D3, a GABA-producing strain derived from Thai pickled weed [29]. *L. plantarum* ITM21B (LMG P-22033) and *L. paracasei* IMPC2.1 (also quoted as LMG-P22043) survived on brined artichokes for at least 90 days and the anchorage of bacterial strains on the vegetable tissues improved their survival in a simulation of GI digestion [30]. Probiotic drink was developed by combining extracts of medicinal plants which provide significant health benefits. A study reported by Eksiri et al 2017 showed that the produced probiotic drink containing apple juice, *Pussy willow* and *Echium amoenum*, glucose and whey powder which was a favorable medium for the growth of *L. casei* and *L. rhamnosusto* [31].

A combination of emerging strains such as *Akkermansia muciniphila* with polyphenol rich plant matrices (grapes, berries) enhance growth of the organism and has demonstrated to improve colonic inflammation and metabolic disorders and some other diseases in animal models [32]. Another study revealed that patients treated with *Faecalibacterium prausnitzii* exhibited a reduction in non-alcoholic fatty liver disease, hyperlipidaemia, prediabetes, inflammatory bowel disease and type 2 diabetes, positioning it as a potential Next generation probiotic (NGP) strain [32]. A variety of plant-based matrices (food products) for probiotic delivery are currently being explored. The survival of probiotic cultures is dependent on the processing steps, pH, food matrix, probiotic strain and the method of incorporation into the matrix, storage conditions /packing, and addition of prebiotic components [33]. Vegan probiotics impact the properties of food by extended shelf life, improved nutritional value, sensory changes [33].

### 3.3 Plant-based synbiotics

Plant-based matrices are rich sources of nutrients essential for probiotic growth, including complex carbohydrates, simple sugars, and plant proteins, in addition to non-nutritive bioactive compounds like fibers, vitamins, minerals, and secondary plant metabolites. These components exert antioxidant and antimicrobial properties, reduce dysbiosis, and reinforce intestinal integrity [34]. Many bioactive elements impact gut microbiota, supporting a balanced microbiome and improving overall health. Prebiotics—non-digestible compounds promoting beneficial microorganisms—contribute to alleviating gastrointestinal symptoms, immunomodulation, and preventing metabolic disorders [34]. Synbiotic products



combining probiotics and prebiotics are formulated using isolated or concentrated prebiotics to ensure effectiveness.

Prebiotics of plant-based matrices are a source of essential nutrients and, can support probiotic survival in food environments as well as in the digestive tract. They also would moderate probiotic bioactivity [28]. The safe usage of *L. plantarum* MBTU-HK1 (probiotic) and acacia gum (prebiotic), either individually or together as a synbiotic was clearly documented [35]. When taken together, this synbiotic demonstrated a range of health benefits, such as reduced blood lipid levels, improved immune regulation, and decreased activity of enzymes linked to carcinogen release. Maintaining a healthy gut microbiota through the combined use of prebiotics and probiotics offers a promising approach to enhancing overall well-being and preventing disease. Similarly, a study revealed that the extraction and purification of inulin from chicory roots act as a prebiotic and that can be used along with probiotics exhibiting various health benefits [36]. A study conducted by Chaturvedi et al. 2022 investigated on optimization of extraction process of legume-based symbiotic beverages from red kidney and mung bean blends fermented with *L. casei* which revealed that the fermentation significantly reduced antinutrients in the beverages. Therefore, the formulated beverages under standardized fermentation conditions, have the potential to serve as a functional food in non-dairy industry which offer improved health benefits and newer flavor profiles [37]. A study conducted screened the combinations of commercial probiotic strains (e.g., *L. rhamnosus* GG, *B. lactis*) with six different dietary fibers (prebiotics) to access its synergistic role in producing SCFAs, which are key metabolic products linked to gut health, and the work concludes that the prebiotic combinations with different probiotic strains that may be useful for developing effective synbiotic blends [38].

## 4. Future Trends

### 4.1 Functional foods and beverages

Heightened consumer awareness regarding nutrition, coupled with the World Health Organization's endorsement of functional foods, has spurred the global demand for functional beverages enriched with bioactive compounds from plant, animal, or microbial origins, including phenolics, vitamins, peptides, and unsaturated fatty acids. The functional beverage market is experiencing a surge in the popularity of probiotic/prebiotic drinks, products tailored for immunological and cognitive health, and those with enhanced aesthetic appeal. Technological advancements such as encapsulation, emulsification, and

high-pressure homogenization are employed to boost ingredient stability and bioavailability [39]. Nonetheless, challenges persist around maximizing sustainability, safety, and bioavailability [40]. Continuous innovation in formulation, storage, and sensory appeal remains crucial for ensuring long-term market viability and consumer acceptance [40]. Table 1 represents a selection of recently developed probiotic food products formulated using novel plant-based or non-traditional substrates, probiotic strains used, viable counts, and associated health benefits.

### 4.2 Pharmaceutical and cosmetic applications

Non-dairy probiotics are increasingly relevant in pharmaceutical applications driven by the consumer interest in health-promoting vegan products and the need for potent alternatives to dairy-derived probiotics. They are being investigated for therapeutic potential across various health conditions, particularly in supporting gut health, enhancing immune function, and promoting well-being. The future development of next-generation probiotics is likely to employ innovative strategies aimed at reinventing probiotic therapies [50]. Additionally, non-dairy probiotics are gaining traction in the beauty and skincare industry for their ability to support skin health. Probiotics are being integrated into cosmetic formulations to confer benefits such as anti-aging, anti-inflammatory, and hydrating effects. A study conducted using the non-dairy probiotic *Micrococcus luteus* Q24 demonstrated its capacity for improving skin condition following application. Notably, this application reduced pore size and wrinkles while remarkably increasing hydration levels, indicating the potential for probiotics as valuable ingredients in the beauty sector focused on enhancing skin texture and health [51]. Further, probiotics in both oral and topical forms can treat skin disorders by augmenting the skin's microbiome, enhancing barrier function, and targeting inflammation [52].

### 4.3 Regulation and labeling

The development of comprehensive regulatory frameworks and labeling policies for probiotics and probiotic-based foods encompasses safety, efficacy, quality control, and health claims regulations [53]. Given the marketing of probiotics as food, dietary supplements, or nutraceuticals, compliance with legal standards for product labeling is required, including specifics such as product name, scientific strain identification, viable count in colony-forming units (CFUs), approved health benefits, recommended daily dosage, storage requirements, expiration date, allergy information, and company contacts for adverse effect reporting [54].



**Table 1:** This table presents a selection of recently developed probiotic food products formulated using novel plant-based or non-traditional substrates, probiotic strains, viable counts, and associated health benefits.

Study	Probiotic strains	Probiotic concentrations	Health benefits and applications	Reference
Probiotic infused Quiona snacks	<i>Bacillus coagulans</i>	3% to 0.35%	Supports gut health, exhibit antimicrobial activity	[41]
Probiotic chocolate	<i>Lactiplantibacillus plantarum</i>	Free Probiotic Chocolate- $5.8 \times 10^7$ Microencapsulated Probiotic Chocolate- $2.1 \times 10^7$ $2.4 \times 10^5$	Improved probiotic activity in children	[42]
Probiotic Millet Biscuits	<i>Lactobacillus acidophilus</i>	5.02–5.38 log CFU/g	Provide stable probiotics for gut health, Contribute for the development of probiotic enriched functional foods	[43]
Probiotic Rich pineapple with <i>L.plantarum</i> and <i>L.casie</i>	<i>Lactiplantibacillus plantarum</i> , <i>Lacticaseibacillus casei</i>	<i>L. plantarum</i> : $8.54 \pm 0.04$ log CFU/g <i>L. casei</i> : $8.55 \pm 0.05$ log CFU/g	Enhances immune function and digestive health	[44]
Fortifying vegetable matrices with iron and <i>Lactobacillus casei</i>	<i>Lactobacillus casei</i>	$>10^7$ CFU/g	Improved bioaccessibility, probiotic viability	[45]
Ready to eat Blueberries as probiotic carriers	<i>Lacticaseibacillus casei</i> <i>Bifidobacterium animalis</i>	$>10^6$ CFU/g	Probiotic delivery. Biocontrol of pathogens, functional food	[46]
Probiotic infused apple and banana snack	<i>Lactobacillus plantarum</i> <i>Lactobacillus casei</i>	5–5.5 log CFU/g	Probiotic enrichment in fruits, improving gut health	[47]
Probiotic apple juice	<i>Lactobacillus plantarum</i> , <i>Bifidobacterium bifidum</i>	Encapsulated <i>L. plantarum</i> : = $8.73$ log CFU/mL Encapsulated <i>B. bifidum</i> : = $8.50$ log CFU/mL	Enhanced probiotic survival and sensory properties; gut health	[48]
Fermented soy-based food for probiotic benefits	<i>Lactiplantibacillus paracasei</i> BGPI, <i>Lactiplantibacillus plantarum</i> CIDCA 8327	8.41 to 8.71 log CFU/ml	Gut health improvement potential anti-inflammatory effects	[49]

## 5. Challenges in the Development of Plant-Based Probiotics

Despite the rising consumer interest, several obstacles hinder the full realization of plant-based probiotics.

### 5.1 Consumer awareness and acceptance

While there is an increasing demand for plant-based alternatives, particularly among vegans and lactose-intolerant individuals, a significant gap exists in consumer knowledge regarding these products. Many potential consumers remain unaware of the sensory qualities, efficacy, and health benefits associated with plant-based probiotics, creating a barrier to market penetration. Factors such as sensory acceptability, taste, and texture, along with skepticism about their probiotic efficacy, further impede acceptance [55].

### 5.2 Innovation in non-dairy functional beverages: synbiotic vegan juices

The diversification of probiotic food products into vegan, non-dairy formats has garnered attention as a means to satisfy the nutritional needs and preferences of health-conscious consumers. A study by Valero-Cases et al. explored the development of synbiotic carrot-orange juices fermented with *Lactiplantibacillus plantarum* and enriched with inulin [56]. Their research demonstrated that fermentation markedly enhanced the antioxidant capacity (AOC), primarily attributed to the  $\beta$ -carotene content. Inulin improved the survival of *L. plantarum* over a 21-day period while enhancing the sensory profile, with 2% inulin receiving the highest consumer acceptance due to its improved sweetness and orange flavor. The growing interest in plant-based functional foods is also supported by emerging trends in food biotechnology. Arwanto et al. discussed innovative techniques such as fermentation, high moisture extrusion cooking, and shear cell technology, which restructure plant proteins into realistic meat-like



textures. These advancements cater to the increasing consumer demand for healthier plant-based diets, which have been linked to lower disease risk, stress reduction, and better weight maintenance. Furthermore, the authors emphasized the market potential for plant-based products, particularly in regions like Indonesia, underscoring the significant opportunities for global expansion in this arena [57].

### 5.3 Consumer perspectives on plant-based dairy alternatives

The acceptability of plant-based dairy substitutes has spurred additional research into consumer perceptions. Adamczyk et al. identified health concerns, curiosity, and social influences as key motivators for accepting these alternatives, while barriers such as taste, texture, and familiarity remained pronounced [58]. A comprehensive study conducted across focus groups in Poland, Germany, and France revealed that attitudes toward plant-based dairy substitutes vary significantly by country, reflecting the deep-rooted significance of dairy in diverse culinary traditions.

This variability highlights the necessity for tailored marketing strategies that acknowledge local preferences and cultural contexts. The rise in popularity of plant-based beverages has spurred market developments, including the proliferation of probiotic drinks and various functional beverages. Kellersohn's overview of the probiotic beverage market elaborated on consumer demographics, market size, and increasing demand among health-conscious individuals seeking to enhance digestive health and immunity [59]. Notably, the demographics for probiotic beverages also shifted toward younger, educated consumers, reinforcing the need for products that resonate with contemporary health trends.

Emerging innovations in the sector include adaptogens (plant-derived compounds that assist the body in managing stress) and postbiotics, which are metabolic byproducts of fermented probiotics. Additionally, non-digestible fibers known as prebiotics nourish beneficial gut bacteria, while psychobiotics (microorganisms or compounds that influence mental health via the gut-brain axis) are gaining attraction for their potential health benefits [59].

Moss et al. revealed that consumer attitudes towards plant-based milk alternatives (PBAs) in Canada were influenced by health benefits, sustainability, and sensory attributes [60]. The popularity of oat, almond, and pea milk rose significantly, particularly when flavored with chocolate or vanilla. The study emphasized that the sensory characteristics of creaminess and smoothness significantly enhance the acceptability of PBAs. These insights reinforce the need for continued research focused on improving flavor and sensory attributes to bolster consumer appeal and acceptance.

### 5.4 Safety and strain-specificity, cost, investment, and scalability

While PBP hold promising health benefits, it is essential to recognize that these effects are not universally applicable across all strains. Selecting and clinically validating specific strains for target health benefits is critical [3]. Consideration of dose-dependency is also pertinent, with effective doses typically ranging from  $10^8$ – $10^9$  CFU/day in human studies [61].

Safety is another significant consideration, as adverse effects such as bacteremia or sepsis have been documented, particularly in immunocompromised individuals, despite most probiotics being classified as Generally Recognized as Safe (GRAS) [50]. Hence, thorough safety evaluations and regulatory oversight are crucial in the development of plant-based probiotic products.

The advancement of high-end biotechnological methods and specialized fermentation techniques is vital for creating stable and functional PBP, though these developments can increase manufacturing costs. Different plant substrates can introduce variability, complicating the smooth scaling of production. Addressing these challenges will require substantial research funding and robust public-private partnerships. Despite the undeniably substantial health and sustainability advantages offered by PBP, consumer awareness and perceptions remain critical hurdles that demand attention.

Prevalent misconceptions regarding the efficacy of plant-based probiotics, together with unfamiliarity and sensory challenges compared to traditional dairy products, currently limit their widespread adoption. For example, a study involving Danish consumers based on the Theory of Planned Behavior revealed that positive attitudes, perceived sensory quality, and self-efficacy significantly influenced intentions to choose plant-based yogurt alternatives [62]. In contrast, social norms and objective knowledge appeared to have minimal impacts on consumer decisions. This suggests that enhancing sensory appeal and bolstering consumer confidence are more effective strategies than merely providing additional information.

In South Korea, Lee et al. examined consumption patterns and pairing behaviors associated with cow's milk versus plant-based milk [63]. Their findings indicated that plant-based milk consumers generally tended to be older adults, women, and urban residents. Notably, these consumers were inclined to pair plant-based milk with various foods, such as bananas, eggs, nuts, and sweet potatoes, reflecting distinct consumption habits compared to traditional dairy consumers.

An intriguing experiment comparing consumer perceptions of "vegan latte" versus "plant-based latte" labels revealed that both labels performed comparably regarding purchase intentions. However, there was a slight preference



for the “plant-based” label. This study indicated that, even among non-vegans, curiosity about food and a desire for diverse options served as strong motivators for adoption, pointing to the effectiveness of good labeling and messaging in broadening demographics [63].

These findings highlight the necessity to promote plant-based probiotics as credible alternatives through a multifaceted approach focusing not only on health benefits but also on consumer psychology, compatibility with lifestyle choices, and appealing food pairings.

## 6. Health Benefits and Mechanisms of Action of Plant-Based Probiotics

PBP offer a diverse range of health benefits; however, these effects are highly strain-specific, often dose-dependent, and possess well-characterized mechanisms of action. A critical understanding of these factors is essential to validate and optimize the efficacy of PBP. Some of the health benefits of plant-based probiotics are depicted in figure 3.

### a. Gut Health and Barrier Function

One of the most consistently observed benefits of probiotics is the improvement of gut health through intestinal microbiome modulation, promoting gut barrier integrity, and anti-inflammatory effects. *Lactiplantibacillus plantarum*, commonly used in plant matrices such as brined artichokes [30], has showed the ability to improve gut barrier function and survive GI passage. The production of SCFAs, such as butyrate, which support epithelial integrity and have local anti-inflammatory effects, has also been demonstrated to modulate the intestinal microbiome and promote gut barrier integrity in *Lactiplantibacillus plantarum* strains used in co-culture for the development of functional plant-based fermented beverages [64].

### b. Modulation of Immune Responses

Probiotic strains can positively influence immune function through various mechanisms, including enhancing mucosal immunity (e.g., immunoglobulin A, IgA secretion), modulating cytokine production, and interacting with gut-associated lymphoid tissue (GALT). For instance,

*Lactiplantibacillus plantarum* MBTU-HK1 combined with acacia gum showed improved immune regulation in a synbiotic formulation [34]. *Lactiplantibacillus plantarum* and *Lacticaseibacillus casei*, used in fortified cut pineapple matrices, also contributed to enhanced immune responses and gut health [44].

### c. Cholesterol-lowering and Metabolic Effects

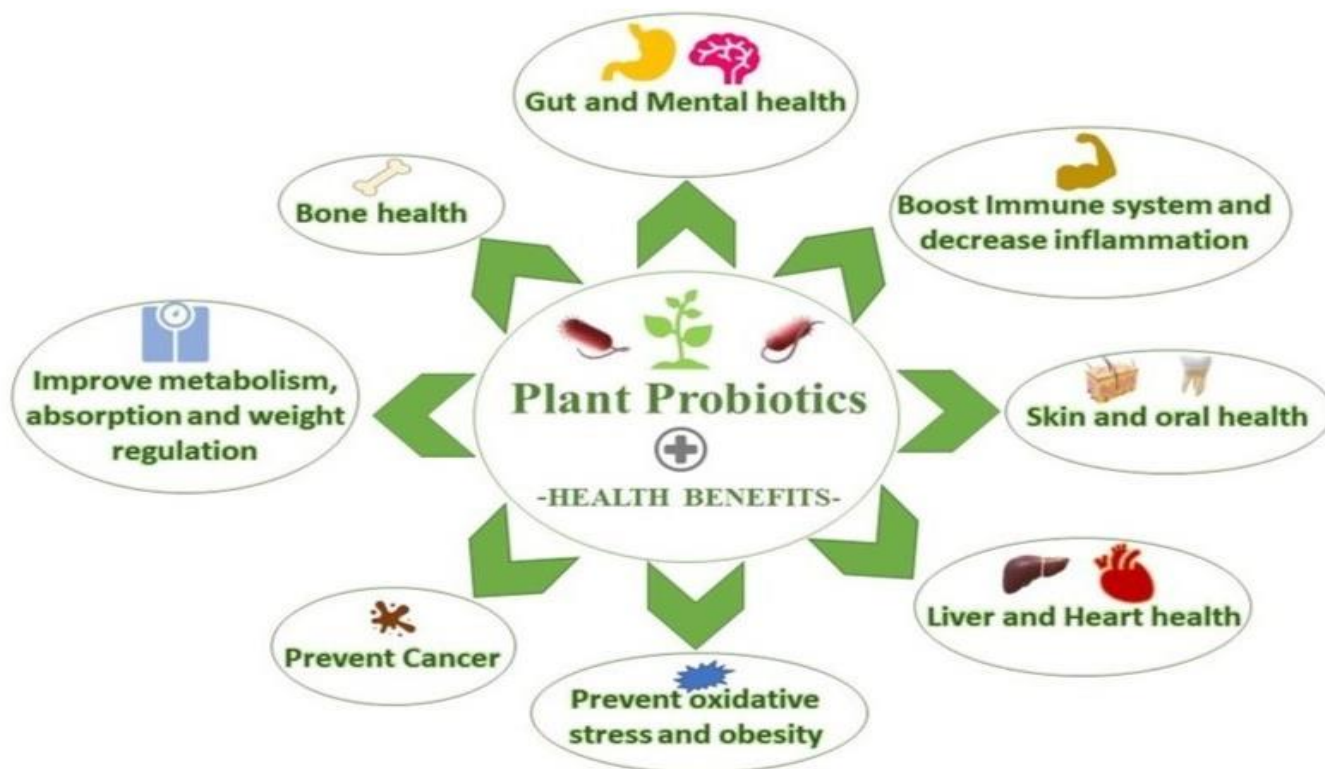
Certain probiotic strains contribute to cholesterol-lowering effects through bile salt hydrolase activity and modulation of lipid metabolism. For example, *B. coagulans*, when incorporated into quinoa snacks, has been observed to lower serum cholesterol levels while exhibiting antimicrobial activity [41]. In addition, *L. pentosus* isolated from Thai pickled weed produces GABA when fermented in brown rice drink, which is associated with reduced stress levels, improved cognitive functions, and potential blood pressure modulation [29].

The spectrum of health benefits provided by plant-based probiotics is wide-ranging and promising, marking improvements in gut barrier functionality, immune modulation, metabolic regulation, and antimicrobial protection. However, determining the exact health benefits is heavily reliant on the specific probiotic strains, their formulations, and dosing conditions. Hence, future research endeavors should prioritize strain-specific clinical validations, synergistic synbiotic combinations, and address regulatory standards that facilitate the complete realization of PBP in functional food applications.

## 6.1. Health impacts and functional properties of plant-based alternatives

Toribio-Mateas et al. (2021) investigated the microbiome changes associated with partial replacement of animal meat with plant-based meat alternatives (PBMA) [65]. Their findings indicated that such dietary transitions led to beneficial shifts in the gut microbiome, including an increase in butyrate-producing bacteria and enhanced metabolic potential related to gut health. This underscores the potential of PBMA in fostering dietary shifts toward flexitarianism or a predominantly plant-based diet.





**Figure. 3.** Health Benefits of probiotics

## 7. Conclusion

The advent of plant-based probiotics marks a significant evolution in the realm of functional foods and gut microbiome research. The convergence of consumer interest in vegan diets, lactose intolerance issues, environmental sustainability, and the emergence of plant-derived probiotics culminate in a robust alternative to conventional dairy formulations. Advancements in strain selection, fermentation technologies, and prebiotic incorporation have facilitated the creation of functional foods and beverages that cater to diverse dietary preferences and offer multiple health benefits, including gut health promotion, immune enhancement, and reduction of metabolic disorders such as obesity, diabetes, and hyperlipidemia.

Furthermore, the integration of plant-based probiotics and synbiotics into innovative functional food and beverage formulations resonates with ongoing preventive healthcare and lifestyle wellness trends. However, key challenges such as strain viability, large-scale production, and enhancing consumer awareness need to be addressed to solidify efficacy and foster market success. Future research endeavors should concentrate on personalized nutrition, next-generation probiotic strains, and regulatory frameworks that embrace innovation while ensuring product integrity. In conclusion, plant-based probiotics possess tremendous potential for advancing human health, aligning

with sustainable practices, and fulfilling the evolving demands of health-conscious consumers. Continued research that interweaves food science, microbiology, biotechnology, and nutrition is essential to overcome existing barriers and unlock the full potential of plant-derived probiotics.

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## 9. Declaration of competing interest

The authors report no conflicts of interest.

## 10. Authors' Contributions

Formal analysis, investigation, writing—original draft preparation- ASN, AS.; Conceptualization, Supervision, Review and editing – RRP, SS.

## 11. Using Artificial Intelligent Chatbots

No AI chat bots were used in the preparation of this manuscript.



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## دوران پروبیوتیک‌های گیاهی - مروری بر مزایای بالقوه و جنبه‌های آینده

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### تاریخچه مقاله

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چاپ ۱۱ اوت ۲۰۲۵

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### چکیده

**سابقه و هدف:** پروبیوتیک‌ها، که به عنوان گونه‌های خاصی از میکروارگانیسم‌های زنده، معمولاً باکتری یا مخمر، تعریف می‌شوند، با افزایش عملکرد گوارشی نقش مهمی در سلامت میزبان ایفا می‌کنند. به طور سنتی، این ارگانیسم‌ها از غذاهای تخمیری مبتنی بر لبنیات مانند ماست، پنیر و کفیر تهیه می‌شدند. با این حال، افزایش رژیم‌های غذایی گیاهی، محبوبیت پروبیوتیک‌های گیاهی را افزایش داده است که ناشی از عواملی مانند وگان‌سیسم، عدم تحمل لاکتوز و آلرژی به لبنیات است. پروبیوتیک‌های گیاهی جایگزین ارزشمندی ارائه می‌دهند که نیازهای غذایی متنوع را برآورده می‌کند و در عین حال از طریق کاهش انتشار گازهای گلخانه‌ای، کاهش مصرف آب و استفاده کمتر از زمین به پایداری محیط زیست نیز کمک می‌کند. این بررسی به بررسی توسعه، مزایای بالقوه سلامتی، کاربردهای آینده و چالش‌های فناوری مربوط به تولید و بازاریابی پروبیوتیک‌های گیاهی می‌پردازد.

**یافته‌ها و نتیجه‌گیری:** رویکردهای نوآورانه منجر به ایجاد غذاهای کاربردی شده‌اند که منابع گیاهی را با گونه‌های پروبیوتیک قوی که قادر به زنده ماندن در ماتریس‌های گیاهی هستند، ترکیب می‌کنند. ادغام پروبیوتیک‌ها با فیبرهای پری‌بیوتیک، مانند کاسنی و اقاچیا، باعث افزایش قابلیت حیات و عملکرد شده است. علاوه بر این، محصولات پروبیوتیک گیاهی در حال تکامل فراتر از نوشیدنی‌ها هستند و شامل میان وعده‌ها، میوه‌های آماده مصرف و آجیل نیز می‌شوند. با این وجود، چالش‌هایی در مورد قابلیت حیات گونه‌های پروبیوتیک در طول نگهداری، هزینه‌های مرتبط با تولید در مقیاس بزرگ و ضرورت آموزش مصرف‌کننده همچنان وجود دارد. چارچوب‌های نظارتی در حال تطبیق هستند تا اطمینان حاصل شود که ادعاهای سلامتی نسبت داده شده به محصولات پروبیوتیک توسط شواهد علمی پشتیبانی می‌شوند. پروبیوتیک‌های گیاهی به عنوان یک رمز امیدوارکننده در غذاهای کاربردی پایدار، طیف وسیعی از نیازهای مصرف‌کننده را برآورده می‌کنند. پیش‌بینی می‌شود پیشرفت‌های آینده بر فرمولاسیون‌های شخصی‌سازی شده و کاربردهای گسترده‌تر در حوزه سلامت و تندرستی، در کنار تکنیک‌های بهبود یافته برای افزایش پایداری و اثربخشی پروبیوتیک‌ها، متمرکز شوند.

**واژگان کلیدی:** غذاهای عملکردی، پروبیوتیک‌های غیرلبنی، پروبیوتیک‌های گیاهی، تغذیه پایدار، سلامت افراد گیاه‌خوار، میکروبیوم روده، غذاهای دوست‌دار محیط زیست