Food Materials Research

REVIEW

Open Access

https://doi.org/10.48130/fmr-0024-0029

Food Materials Research **2025**, 5: e001

Probiotics: microbes for human health and beyond

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Abstract

Probiotics are the good microbes naturally found in the human stomach that keep our digestive health balanced. Probiotics are significant because they have both an application in industrial product development and a favourable influence on human health. In this regard, probiotic microbes have been widely introduced to yogurts and other fermented milks, which are functional food leaders, accounting for nearly 65% of the global functional food market. This review paper explores the world of probiotics and their various roles in promoting health and well-being. Probiotics have been an area of keen interest in recent years for their unbeatable therapeutic applications. This paper empashizes current research findings and examines the impact of probiotics on human health, with a focus on, the immune system, and metabolic balance. The paper also evaluates challenges and considerations in probiotics research, including strain-specific effects, dosage optimization, and the influence of individual variations in the host microbiome. Through a comprehensive analysis of current literature, this review aims to provide an understanding of probiotics, offering insights into their therapeutic effects and future research directions. As the field of probiotics continues to evolve, this review paper serves as a valuable resource for researchers, clinicians, and health enthusiasts seeking a refined perspective on the promises and challenges of utilizing microbes for human health and more.

Citation: Thakur A, Sharma P, Sharma AJ, Sharma N, Singh S, et al. 2025. Probiotics: microbes for human health and beyond. *Food Materials Research* 5: e001 https://doi.org/10.48130/fmr-0024-0029

Introduction

Probiotics refer to live bacteria and yeast that confer health benefits when consumed in adequate amounts. These microscopic organisms are important for maintaining a balanced and healthy gut microbiota, promoting digestive well-being, and potentially offering various other health advantages. Research has shown that probiotics can positively impact immune function, alleviate gastrointestinal issues, and influence mental health. Probiotics are live non-pathogenic microorganisms that provide health benefits to the host. These microbes, primarily bacteria and yeast are like naturally occurring microbes in the human gut flora. Inside our bodies, these tiny helpers work to keep us healthy. The term probiotics came from the Greek phrase 'probios' which means 'for life' and was coined by Lilly & Stillwell in the early 1960s[1]. Due to the profound work of investigators later during the 20th century, it was suggested that the gut flora could be replaced with good microbes eliminating the harmful ones, which led to the concept of probiotics. However, the actual credit for the observation of bacteria is given to Metchnikoff[2]. He quoted: 'The dependence of the intestinal microbes on the food makes it possible to adopt measures to modify the flora in our bodies and to replace the harmful microbes with useful microbes'[3]. During this time, a paediatrician named Henry Tissier, observed that children suffering from diarrhoea had low numbers of bacteria in their stools but on the other hand, bacteria were abundantly found in healthy children[4]. Hence a suggestion was made that if these bacteria can be inserted into patients with diarrhoea, then it will help in the restoration of healthy gut flora. Slowly the concept of probiotics came to light and was defined around 1992 by Havenaar as, 'a viable mono or mixed culture of bacteria which, when applied to animal or man, beneficially affects the host by improving the properties of the indigenous flora'[5]. Not so recent but one more definition was proposed by Guarner & Schaafsma, around 1998 which states: 'live microorganisms, which when consumed in adequate amounts, confer a health effect on the host'[6]. These definitions point out the need to have adequate amounts of probiotic bacteria in the body to attain the desirable effects. These scientific observations proved to be so helpful that commercialization quickly took over and various types of probiotic products came into existence. The objective of this review is to comprehensively examine the potential of probiotics, highlighting their role in modulating gut microbiota, enhancing gut health, and alleviating gastrointestinal disorders. This review aims to analyse current research on the formulation, efficacy, and synergistic benefits of combining probiotics with fruit-derived bioactive compounds, as well as to identify gaps in the existing literature and propose directions for future studies to optimize these formulations for therapeutic use.

Materials and methods

This review draws upon a comprehensive collection of peer-reviewed articles, and reputed sources within the field of food science, microbiology, and nutrition to synthesize current knowledge on probiotic applications and advancements. The literature was sourced primarily from academic databases, including Pub Med, Science Direct, and Google Scholar, using specific keywords such as 'probiotics', 'gut health', 'fruit-based probiotic beverages', 'traditional fermented foods', and 'probiotic delivery systems'. Recent publications were also prioritized to ensure the inclusion of both foundational knowledge and recent advancements in the field.

The review employed a qualitative synthesis approach, focusing on summarizing and integrating findings from diverse studies. Methods included:

Literature search

Comprehensive searches were conducted across academic databases to identify relevant articles and studies. Specific keywords were used to refine search results.

Selection criteria

Inclusion criteria comprised peer-reviewed studies, and reviews, that addressed the role of probiotics, traditional uses, gut microbiota modulation, and non-dairy probiotic delivery systems.

Critical analysis

Each selected study was assessed for its methodology, results, and conclusions. Particular attention was given to research quality, sample size, and relevance to the topic.

This methodological framework ensured a thorough, evidence-based analysis of existing literature, presenting an informed perspective on the potential and challenges of using fruit-based probiotic formulations for enhancing gut health.

Traditional uses of probiotics

Probiotics have been used for centuries across various cultures for their health benefits, long before modern science identified their specific mechanisms of action. Traditional fermented foods, rich in probiotics, have been staples in diets worldwide and are valued for promoting gut health and overall well-being[7]. In ancient civilizations, fermented milk products like yogurt were consumed for their perceived ability to improve digestion and treat gastrointestinal disturbances. For instance, the health-promoting properties of fermented milk were known to be recognized as early as 6000 BCE in Mesopotamian and Middle Eastern cultures[8]. Other traditional probiotic-rich foods include sauerkraut, kimchi, kefir, and miso, which have been integral to European, Korean, Central Asian, and Japanese diets, respectively. These foods are created through natural fermentation processes that foster the growth of beneficial bacteria, particularly *Lactobacillus* and *Bifidobacterium* species, known for their positive impact on digestive and immune health[9]. The traditional use of such foods has been associated with maintaining a balanced gut microbiota and preventing the colonization of harmful pathogens, which can contribute to better overall health and reduced risk of certain diseases[10]. Fermented vegetables and beverages, such as kvass and kombucha, have also been consumed historically for their probiotic content. These fermented products are noted for enhancing nutrient bio availability and promoting antioxidant activity, thereby contributing to various health benefits, including improved gut barrier function and modulation of immune responses[11]. The incorporation of probiotics through traditional diets reflects an enduring practice aimed at bolstering gut health and promoting longevity across generations.

Types of probiotics

The first key probiotic is *Lactobacillus acidophilus* (1900s) which is identified as a probiotic that lives in the human intestine and is mainly found in fermented dairy products and supplements like yogurt and kefir[12]. It has been extensively studied for its potential in promoting digestive health, preventing infections, and supporting the immune system *L. acidophilus* helps maintain a balanced gut microbiota[13]. It supports the breakdown of food and the absorption of nutrients, thereby promoting optimal digestion[14]. Another species is *L. bulgaricus* (1905) which was discovered by Bulgarian doctor Stamen Grigorov and is a lactic acid bacteria commonly found in the digestive tract of humans[15]. Its significance lies in the contribution to the fermentation process particularly in the fermentation of yogurt. Beyond its role in dairy products, research suggests potential health benefits, such as supporting gut health and immune function[16]. Then we have *Saccharomyces boulardii* (1923) which is originally a yeast isolated from lychee and mangosteen fruit and known for its effectiveness in preventing and treating diarrhoea, especially antibiotic-associated diarrhoea[17]. This probiotic yeast has also been studied for its potential in managing inflammatory bowel diseases (IBD). Next, we have the second key probiotic which is *Bifidobacterium bifidum* (1950s) it plays a crucial role in the gut microbiota, especially found in the intestines of breastfed infants, and commonly used in probiotic formulations[18]. It is commonly included in probiotic formulations for its positive impact on gut health. We also have another species *Bifidobacterium breve* discovered around (1957) as a component of the human intestinal microbiota, *Bifidobacterium breve* is a probiotic species studied for its potential health-promoting effects. It is often included in probiotic supplements and has been associated with positive impacts on gut health, immune function, and the prevention of certain gastrointestinal issues[19]. Next, we also have *Lactobacillus casei* (1960s) identified for its role in dairy fermentation, *Lactobacillus casei* is a versatile probiotic species with strains that are heat-resistant and can survive the harsh conditions of the gastrointestinal tract[20]. Then there is *Bifidobacterium longum* (1970s), it is a common inhabitant of the human intestines. This probiotic species has been extensively researched for its role in maintaining gut health, supporting the immune system, and potentially alleviating symptoms of conditions such as irritable bowel syndrome (IBS)[18]. *Streptococcus thermophilus* (1974), is a probiotic bacterium that is extensively used in the production of yogurt and certain cheeses. Known for its ability to break down lactose, this probiotic contributes to the digestion of dairy products[19]. *Lactobacillus reuteri* (1980s), is a probiotic species naturally found in the human gut. Research suggests that it may have various health-promoting properties, including the ability to inhibit the growth of harmful bacteria, support oral health, and modulate the immune system[21]. *Lactobacillus rhamnosus* identified in 1983 for its ability to survive in the gastrointestinal tract, is a versatile probiotic species. It is commonly used in various probiotic formulations[20] (Table 1).

Table 1. List of some probiotic strains along with their discovery details.

Year	Probiotic	Discovery details	Ref.
1983	*Lactobacillus rhamnosus*	Known for its survival in the gastrointestinal tract	[12]
1980s	*Lactobacillus reuteri*	Discovered as a natural inhabitant of the gut	[21]
1974	*Streptococcus thermophilus*	Important in yogurt and certain cheese production	[19]
1970s	*Bifidobacterium longum*	Commonly found in the human intestines and feces	[18]
1960s	*Lactobacillus casei*	Identified for its role in dairy fermentation	[20]
1957	*Bifidobacterium breve*	Discovered as a part of the human intestine microbiota	[19]
1950s	*Bifidobacterium bifidum*	Recognized in the intestines of breastfed infants	[18]
1923	*Saccharomyces boulardii*	Isolated from lychee and mangosteen fruit	[16]
1905	*Lactobacillus bulgaricus*	Discovered by Stamen Grigorov in Bulgaria	[15]

Probiotic strains and their specific mechanisms of action

Probiotic strains vary widely in their properties and mechanisms of action, which contribute to their specific health benefits. This section compares some of the most studied probiotic strains and their roles in promoting gut health and managing various gastrointestinal conditions (Table 2).

Lactobacillus rhamnosus GG (LGG)

Lactobacillus rhamnosus GG commonly known as *LGG* was first isloated by Sherwood Gorbach and Barry Goldin and is known for its strong ability to adhere to the gut mucosa, enhancing the epithelial barrier and promoting mucin production. It also modulates the immune system by increasing anti-inflammatory cytokine production and reducing pro-inflammatory cytokines[22]. Widely used to prevent and treat diarrhoea, including antibiotic-associated diarrhoea and traveler's diarrhoea. It has also been studied for its role in reducing the severity of atopic dermatitis in children[23].

Bifidobacterium longum

This strain produces lactic acid, which lowers gut pH and inhibits the growth of pathogenic bacteria. It also helps in fermenting dietary fibers to produce short-chain fatty acids (SCFAs) like butyrate, which support gut barrier integrity[24]. Effective in alleviating symptoms of irritable bowel syndrome (IBS) and improving gut motility, it has also been linked to enhanced immune responses and decreased intestinal inflammation[25].

Lactobacillus acidophilus

Produces bacteriocins, which are antimicrobial peptides that help in inhibiting the growth of harmful bacteria. It also adheres well to the intestinal walls, preventing pathogenic colonization[26]. Commonly used for the prevention of vaginal infections, balancing the gut microbiota, and promoting lactose digestion, making it beneficial for individuals with lactose intolerance[27].

Saccharomyces boulardii

As a probiotic yeast, it prevents pathogenic bacteria from adhering to the intestinal lining and produces proteases that neutralize bacterial toxins. It also helps in the maintenance of tight junctions between intestinal cells[17]. Effective in treating acute diarrhoea and antibiotic-associated diarrhoea, and has been shown to reduce the recurrence of *Clostridium difficile* infections[28].

Lactobacillus reuteri

Modulates the gut environment by producing lactic acid and altering pH levels. It also promotes the growth of other beneficial bacteria and stimulates local immune responses[29]. Known for its role in improving digestion and alleviating constipation. It has also been studied for its potential in enhancing recovery from gastroenteritis[30].

Bifidobacterium bifidum

Produces acetic and lactic acid, creating a hostile environment for pathogens. It has strong anti-inflammatory properties and contributes to immune modulation[31]. Shown to improve symptoms of IBS and colitis. It is often used in combination with other probiotics for enhanced efficacy in treating inflammatory bowel diseases (IBD)[32].

Sources of probiotics

Dairy and non-dairy probiotics

Probiotics, defined as live microorganisms conferring health benefits, have gained substantial attention in the context of both dairy and non-dairy products. In the realm of dairy, fermented milk products such as yogurt and kefir have been traditional carriers of probiotics. These dairy-based probiotics primarily consist of strains belonging to *Lactobacillus* and *Bifidobacterium* genera, known for their resilience in the acidic environment of the stomach and their positive impact on gut health[33]. Several studies have highlighted the efficacy of dairy probiotics in promoting gastrointestinal well-being. For instance, a randomized controlled trial by Ouwehand et al. demonstrated that the consumption of a specific *Lactobacillus rhamnosus* strain in fermented milk positively influenced the gut microbiota composition and contributed to improved bowel habits[34]. Additionally, the symbiotic relationship between probiotics and dairy components, such as lactose, further enhances their bioavailability and potential health benefits[35]. The intake of probiotics have significant biological effects on the human body (Fig. 1).

On the other hand, the rise of non-dairy alternatives has prompted the exploration of plant-based and alternative sources for probiotics. Fermented products like tempeh, made from soybeans, and kimchi, a Korean dish of fermented vegetables, showcase the versatility of non-dairy probiotics. Non-dairy sources often embrace diverse strains, including beneficial yeast like *Saccharomyces boulardii*, providing a broader spectrum of microorganisms that can positively influence gut ecology[36]. Research in non-dairy probiotics is advancing, shedding light on their potential advantages for individuals with lactose intolerance or those seeking plant-based alternatives. A study by Marco et al. investigated the microbial communities in various non-dairy fermented foods, emphasizing the diversity of microorganisms that can thrive in these substrates[10]. Furthermore, the incorporation of probiotics into non-dairy desserts, snacks, and beverages offers innovative ways to deliver these beneficial microorganisms to a wider consumer base. The choice between dairy and non-dairy probiotics may depend on individual preferences, dietary restrictions, and health goals. Probiotics can be obtained from various natural food sources as well as through food supplements. The most well-known probiotic-rich food is yogurt.

Table 2. Probiotic strains and their mechanisms of action.

Probiotic	Mechanism of action	Health benefits	Sources	Ref.
Lactobacillus rhamnosus	Competitive elimination of pathogens, production of lactic acid and bacteriocins	Reduce prevalence of diarrhoea, enhances gut health	Yogurt, fermented foods	[22,23]
Bifidobacterium bifidum	Modulate immune response, improve intestinal barrier function	Reduce symptoms of IBS, support immune health	Probiotic supplements, dairy products	[31,32]
Lactobacillus acidophilus	Produce short-chain fatty acids (SCFAs), inhibit growth of harmful bacteria	Aid lactose digestion, improve vaginal health	Yogurt, kefir	[26,27]
Saccharomyces boulardii	Compete with pathogens for binding sites, produces antimicrobial compounds	Prevents antibiotic associated diarrhoea, restores gut flora	Probiotic supplements	[17,28]
Lactobacillus reuteri	Produce hydrogen peroxide, enhance mucosal immunity	Reduce gingivitis, improves skin health	Fermented milk products	[29,30]
Bifidobacterium longum	Ferments dietary fibres, produce SCFAs and vitamins	Supports digestive health, reduces inflammation	Probiotic supplements, yogurt	[24,25]

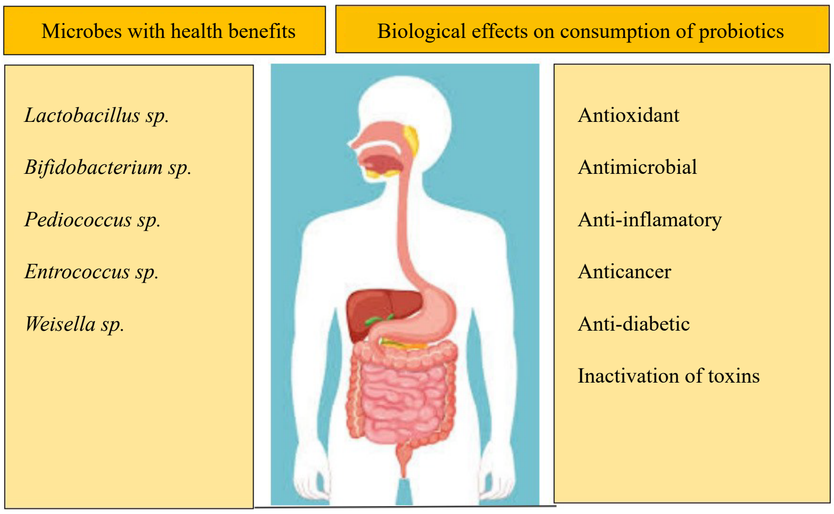

Fig. 1 Relationship of the intake of different probiotic species with their bioactive properties.

Kefir is a fermented milk drink that contains a variety of probiotic bacteria and yeast. Sauerkraut is a fermented cabbage that provides a natural source of probiotics. Kimchi is a fermented Korean dish made from seasoned vegetables. Miso is a traditional Japanese seasoning produced by fermenting soybeans or other grains with salt and koji (a type of fungus). There is a fermented soybean product originating from Indonesia commonly known as Tempeh whereas Natto is a Japanese dish. Pickles that are fermented in brine, not using vinegar. Traditional buttermilk is the liquid left behind after churning butter from cultured cream and contains live cultures. Some types of cheese, particularly those labelled as 'raw', 'aged', or 'fermented', contain live cultures, for example, Gouda, cheddar, and Swiss. Apart from these other fermented soy products like soy sauce and soy-based fermented condiments contain probiotics (Fig. 2). Probiotic supplements are also available in various forms, including capsules, tablets, powders, and liquids. These provide controlled and specific amounts of probiotic strains.

Sources of non-dairy probiotics

Fermented vegetables

Fermented vegetables are rich sources of non-dairy probiotics. The process involves the natural fermentation of vegetables, such as cabbage, carrots, and cucumbers, using lactic acid bacteria. These bacteria, predominantly belonging to the *Lactobacillus* genus, play a pivotal role in the fermentation process and contribute to the probiotic content of the final product. The work of Hugenholtz emphasizes the traditional use of fermentation in the preparation of foods and beverages, shedding light on the diverse microbial communities involved in these processes[37].

Non-dairy yogurts

Non-dairy yogurts have gained popularity as alternatives to traditional dairy-based yogurts. These products are often crafted from plant-based substrates such as coconut, almond, or soy milk. The fermentation of these substrates is achieved through the activity of specific probiotic strains, commonly *Bifidobacterium* and *Lactobacillus* species. These strains contribute not only to the characteristic tangy flavour but also to the potential health benefits of the final non-dairy yogurt product. Marco et al. discussed the consensus on fermented foods, underscoring the role of specific microbial strains in producing these products and their potential impact on gut health[38]. The rise of non-dairy yogurt aligns with the growing emphasis on sustainability and ethical consumption. Almond and soy-based yogurts, for instance, contribute to reduced environmental impact compared to traditional dairy farming[39].

Probiotic supplements

Non-dairy probiotic supplements offer a convenient means of incorporating probiotics into a dairy-free diet. Available in various forms, including capsules and powders, these supplements often feature a diverse array of probiotic strains. Notable genera include *Lactobacillus* and *Bifidobacterium,* known for their positive effects on gut microbiota and overall well-being. The work of Hill et al. provides a consensus statement on the appropriate use of the term 'probiotic', and underscores the significance of these microorganisms in supporting human health[33].

Fermented non-dairy beverages

Fermented non-dairy beverages, such as kombucha (fermented tea) and water kefir, offer a refreshing and probiotic-rich alternative. The fermentation process involves a symbiotic culture of bacteria

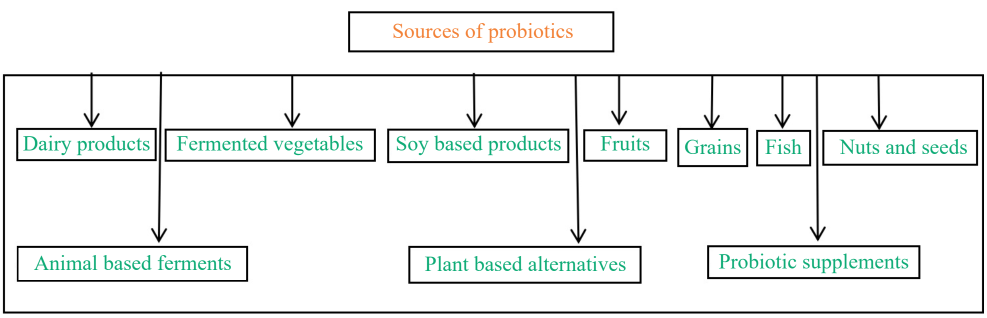

Fig. 2 Classification of sources of probiotics.

and yeast (SCOBY), contributing to the diverse microbial composition of these beverages. The microbial diversity may include various bacterial and yeast strains, each potentially offering unique health benefits. Marsh provides insights into the microbial composition of kefir grains and highlights the potential health-promoting attributes of fermented beverages[40].

Preparation of probiotics from various sources

Fermented grains and cereals

Fermentation of grains and cereals is a time-honoured method of producing probiotic-rich foods. Grains like rice, quinoa, and millet can be fermented using lactic acid bacteria, *bifidobacteria*, or yeast. The process not only enhances the nutritional profile of these staples but also introduces probiotics into the final product. In his seminal work, Steinkraus comprehensively explores the diverse world of indigenous fermented foods, shedding light on the various methods and microorganisms involved in the fermentation of grains and cereals[41]. The fermentation of wheat or rye flour with *lactobacilli* and wild yeast cultures results in sourdough bread, providing a unique flavour and potential probiotic benefits[42].

Fermented vegetables

Fermented vegetables are notable sources of non-dairy probiotics. Fermented vegetables, such as sauerkraut and kimchi, stand out as notable sources of non-dairy probiotics. Common vegetables like cabbage, carrots, and radishes undergo lactic acid fermentation facilitated by strains of *Lactobacillus*. This not only imparts distinct flavours to these vegetables but also introduces beneficial microorganisms into the digestive system. Marco et al. delve into the health benefits of fermented foods, elucidating the role of microbiota in promoting overall well-being[43]. Finely shredded cabbage undergoes lactic acid fermentation, primarily facilitated by *Lactobacillus* species, resulting in sauerkraut, a tangy fermented cabbage dish[44].

Fermented fruits

While less common than vegetable fermentation, fruits can also serve as substrates for probiotic fermentation. Examples include fruit kvass, a fermented beverage, and probiotic-rich jams. The process involves the activity of lactic acid bacteria, contributing to the preservation of fruits and the introduction of beneficial microorganisms. Rezac comprehensively reviewed fermented food sources and their health benefits, providing insights into the diverse array of fermented products, including those derived from fruits[45]. Various fruits, such as berries or tropical fruits, can be fermented to create probiotic-rich beverages (Fig. 3). Lactic acid bacteria and yeast strains contribute to fermentation, adding both flavour and potential health benefits[43]. The process of formation of probiotic juice from fresh fruits require very simple steps (Fig. 4).

Dairy alternatives

Non-dairy sources, such as soy, almond, and coconut milk, can be fermented to produce probiotic-rich alternatives to traditional dairy products. *Lactic acid* bacteria and *Bifidobacterium* strains are commonly used to ferment these substrates, resulting in non-dairy yogurts and kefir. Farnworth contributes to the understanding of fermented functional foods, encompassing various non-dairy alternatives and their potential health benefits[46]. Fermentation of plant-based milk with probiotic strains like *Lactobacillus bulgaricus* and *Streptococcus thermophilus* yields non-dairy yogurt with a similar texture and taste profile[47].

Legumes and pulses

Legumes and pulses, including beans and lentils, can be fermented to create probiotic-rich dishes. The fermentation process not only improves digestibility but also enhances the nutrient profile of these plant-based protein sources. Strains of lactic acid bacteria and *Bacillus* are often involved in legume fermentation. Adebo & Medina-Meza investigate the impact of fermentation on the nutritional quality and functional properties of infant formula produced from different legumes and cereals, shedding light on the benefits of fermentation in diverse food products[48]. Fermented soybeans, bound by *Rhizopus oligosporusmold,* create tempeh, a protein-rich, probiotic-rich food with a distinct nutty flavour[49].

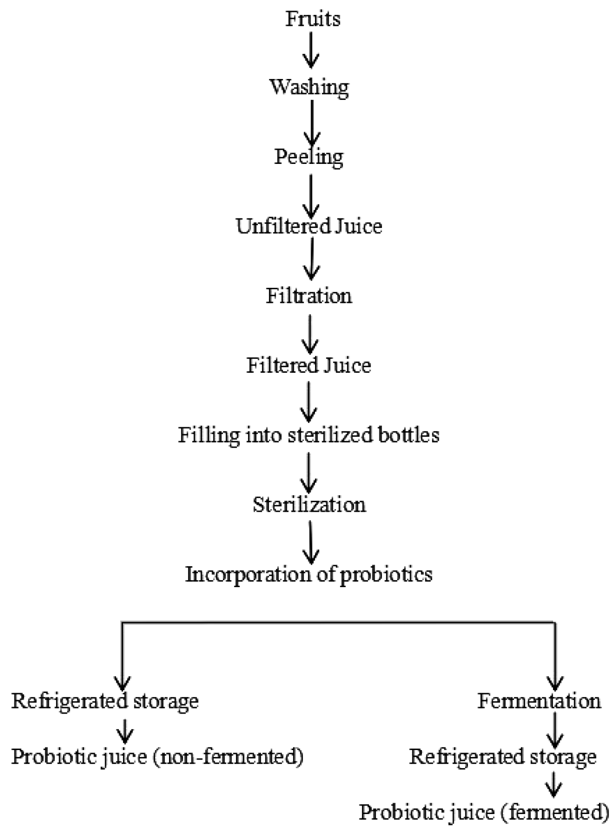

Fig. 4 Formation of probiotics enriched fermented and non-fermented fruit juice.

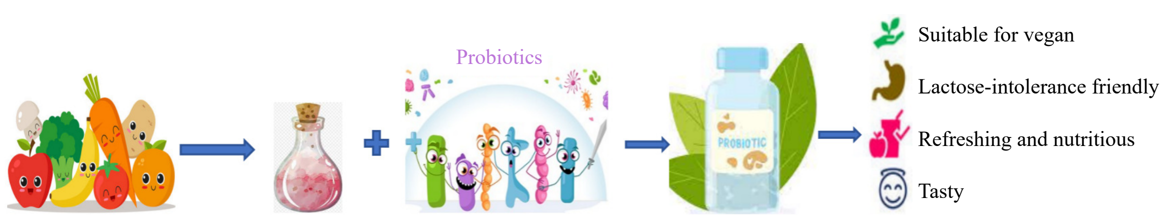

Fig. 3 Stages in probiotication of fruits and vegetables juice.

Miscellaneous sources

Beyond the more commonly recognized sources, various other food items undergo fermentation, introducing probiotics into the diet. Various other food sources, such as pickles, tempeh, and miso, also undergo fermentation, introducing probiotics into the diet. Each of these products involves unique microbial communities and fermentation processes that contribute to the diversity of available probiotic-rich foods. Tamang & Kailasapathy provide a global perspective on fermented foods and beverages, exploring traditional and innovative products from around the world[50]. A traditional Korean dish 'Kimchi' made from fermented vegetables, primarily cabbage, and radishes, seasoned with chili peppers and other flavourful ingredients[51].

Probiotics and their health benefits

Gut health

One of the primary areas where probiotics exert their beneficial effects is in maintaining gut health (Fig. 5). Probiotics help to balance the intestinal microbiota, promoting the growth of beneficial bacteria and inhibiting the proliferation of harmful pathogens. This balance is crucial for proper digestion, nutrient absorption, and overall gastrointestinal well-being[52].

Immune system modulation

Probiotics play a pivotal role in modulating the immune system. They stimulate the production of antibodies, enhance the activity of immune cells, and contribute to the overall resilience of the immune response. Regular consumption of probiotics has been associated with a reduced risk of infections and may be beneficial in managing immune-related conditions[53].

Gastrointestinal disorders

Probiotics have shown promise in alleviating symptoms associated with various gastrointestinal disorders. Conditions such as irritable bowel syndrome (IBS), inflammatory bowel disease (IBD), and antibiotic-associated diarrhoea have been targeted with specific strains of probiotics, providing relief and improving overall gut function[54].

Mental health

Emerging research suggests a connection between gut health and mental well-being, often referred to as the 'gut-brain axis'. Probiotics may have a role in promoting mental health by influencing the gut microbiota and, in turn, impacting neural pathways. There is evidence to support the potential use of probiotics in managing conditions such as anxiety and depression[55].

Metabolic health

Probiotics have been investigated for their potential in improving metabolic health. Some studies suggest that certain strains may help in managing obesity, insulin resistance, and lipid profiles. The mechanisms behind these effects are complex and involve interactions between gut microbiota and host metabolic pathways[56].

Skin health

Probiotics have gained significant attention for their potential to improve skin health, with growing evidence suggesting their beneficial impact on various dermatological conditions. The mechanisms by which probiotics exert their skin-enhancing effects include modulating the skin microbiome, enhancing skin barrier function, and reducing inflammation. *Lactobacillus acidophilus* and *Bifidobacterium bifidum* have been found to reduce acne severity by controlling inflammation and decreasing the colonization of *Propionibacterium acnes*, the bacteria associated with acne[57]. Probiotics

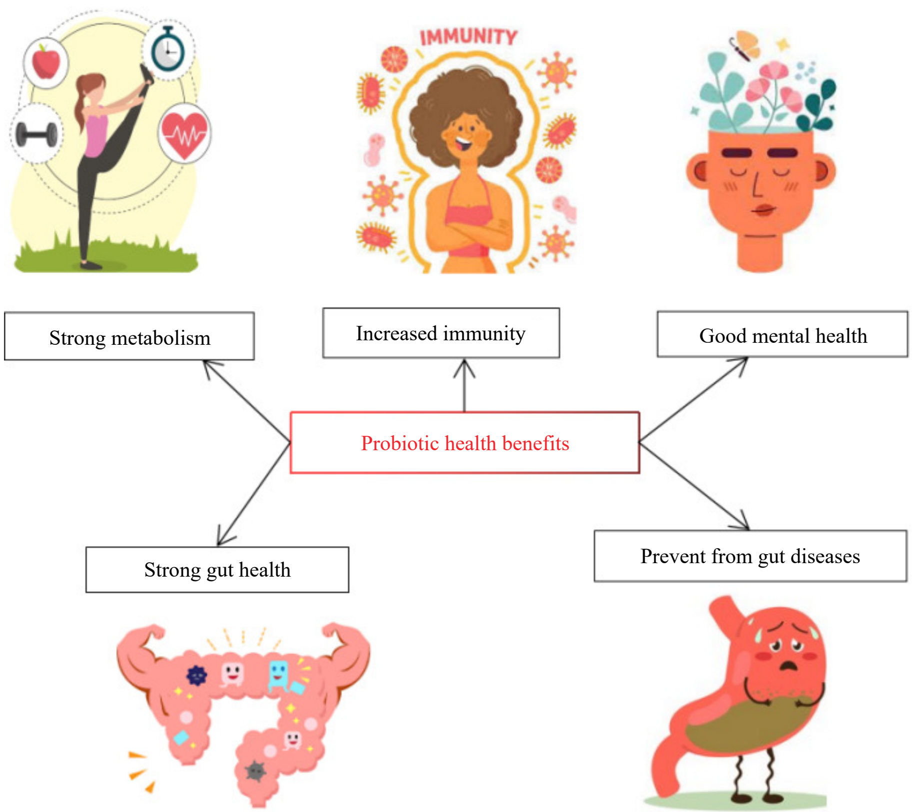

Fig. 5 Health benefits of consuming probiotics.

influence systemic inflammation and immune responses that impact skin conditions. They may produce antimicrobial peptides that inhibit harmful bacteria on the skin's surface and support the growth of beneficial microbes.

Nutrients present in fruits and their contribution to health

Polyphenols

Polyphenols are antioxidants found in various fruits. They play a crucial role in gut health by promoting the growth of beneficial gut bacteria and reducing inflammation in the gut lining. Additionally, polyphenols have been associated with improved immunity by modulating immune cell function and reducing oxidative stress[58]. Polyphenols possess antioxidant capabilities, which are believed to confer beneficial effects. Studies have shown positive effects of polyphenol supplementation in heart disease patients, such as improved inflammatory and fibrinolytic status, reduced blood pressure, inhibition of platelet aggregation, and positive effects on vasomotor function. Diets rich in polyphenols have been associated with better cardiovascular health in various clinical and epidemiological studies[59].

Vitamins and minerals

Fruits are rich in vitamins (such as vitamin C) and minerals (such as potassium and magnesium) which support overall immunity and gut health. These nutrients are essential for the proper functioning of immune cells and help maintain the integrity of the gastrointestinal tract[60]. Vitamins are indispensable for good human health, serving as essential coenzymes and cofactors in various metabolic processes, including energy production. For instance, vitamin B1 (thiamine), B2 (riboflavin), B3 (niacin), B5 (pantothenic acid), B6 (pyridoxine), B7 (biotin), B9 (folate), and B12 (cobalamin) play crucial roles in energy metabolism, facilitating the conversion of dietary energy sources into cellular energy adenosin tri phospahate (ATP). Deficiencies in these vitamins can lead to impaired energy production, affecting overall health and vitality. Additionally, vitamins B6, B12, and folate regulate mitochondrial enzymes, significantly impacting mitochondrial energy metabolism. Similarly, minerals are vital components for maintaining good health, particularly in energy metabolism and performance. Minerals like magnesium, zinc, and chromium serve as essential co-factors for enzymes involved in energy production pathways. Deficiencies in these minerals can result in increased energy needs, compromised cardiovascular function, and impaired exercise performance. Thus, ensuring adequate intake of these minerals is crucial for efficient energy metabolism and overall well-being[61].

Dietary fibre

Fruits are excellent sources of dietary fibre, which aids in digestion, prevents constipation, and promotes the growth of beneficial gut bacteria. Fibre also helps regulate blood sugar levels and reduces the risk of gastrointestinal diseases such as diverticulitis and colon cancer[62]. Dietary fibre from fruits offers numerous health benefits. Rich in nutrients and phytochemicals, fibre aids in weight management by promoting satiety, reducing energy absorption, and modifying metabolism. Soluble fibre induces satiety hormones and lowers metabolizable energy, while insoluble fibre speeds up digestion, reducing nutrient absorption. In diabetes prevention, especially type two, insoluble fibre demonstrates a strong inverse relationship with risk. It enhances glucose disposal, stimulates hormone secretion, and reduces post-meal glucose spikes. Increased magnesium intake from fibre sources further aids in diabetes prevention. Despite some research inconsistencies, increasing dietary fibre intake presents a promising approach to metabolic health[63].

Carbohydrates

Carbohydrates from fruits provide a readily available source of energy for the body and support metabolic functions. They are also important for maintaining healthy gut microbiota by serving as fuel for beneficial bacteria[64]. Carbohydrates are fermented by gut bacteria in the colon, leading to the production of SCFAs such as acetate, propionate, and butyrate. SCFAs serve as an energy source for colonocytes, promote intestinal epithelial integrity, modulate immune function, and regulate inflammation in the gut[65].

Organic acids

Organic acids present in fruits contribute to their characteristic taste and play a role in maintaining the pH balance of the gastrointestinal tract. This is important for proper digestion and absorption of nutrients[66]. Organic acids, such as those found in fermented foods like yogurt and kefir, contribute to maintaining the acidic pH of the gut environment, which helps inhibit the growth of pathogenic bacteria while promoting the growth of beneficial bacteria[67].

Amino acids

Amino acids are the building blocks of proteins and are essential for various physiological processes, including immune function and neurotransmitter synthesis. Consuming fruits rich in amino acids supports overall health and mental well-being[68]. Amino acids are crucial for maintaining gut barrier function and supporting the repair and regeneration of intestinal epithelial cells. They also serve as precursors for the synthesis of antimicrobial peptides and other immune mediators in the gut[69].

Phytochemicals and phytosterols

Phytochemicals and phytosterols found in fruits have antioxidant and anti-inflammatory properties, which contribute to their beneficial effects on gut health, immunity, and metabolic health[70]. Phytochemicals, found abundantly in fruits, vegetables, herbs, and spices, possess various bioactive properties that contribute to gut health. They exhibit antioxidant, anti-inflammatory, antimicrobial, and prebiotic effects, thereby supporting a healthy gut microbiota and reducing the risk of gastrointestinal diseases. Phytosterols, plant-derived compounds structurally similar to cholesterol, play a role in modulating cholesterol absorption in the gut. They compete with cholesterol for absorption, thereby reducing circulating cholesterol levels and lowering the risk of cardiovascular diseases[71].

Antioxidants

Antioxidants present in fruits help neutralize harmful free radicals in the body, thereby protecting cells from oxidative damage. This can help reduce the risk of chronic diseases and support overall health[72]. Antioxidants help neutralize harmful free radicals in the gut, protecting against oxidative stress and inflammation. They contribute to gut health by maintaining the balance of gut microbiota and preserving intestinal barrier function[73].

Enzymes

While fresh fruits contain enzymes that aid in digestion, these enzymes are typically destroyed during cooking or processing. However, consuming fresh fruits may still provide some enzymatic activity, which can support digestion and nutrient absorption[74]. Enzymes play a vital role in breaking down dietary components into absorbable forms, facilitating nutrient absorption in the gut. They also contribute to the digestion of complex carbohydrates, proteins, and fats, thereby promoting gut health[75].

Lipids

Fruits contain small amounts of lipids, mainly in the form of healthy unsaturated fats. These fats are important for cellular function, hormone production, and brain health. Consuming fruits rich in healthy fats can support overall metabolic health and cognitive function[76]. Lipid metabolism is vital for energy storage, hormone regulation, and nutrient transportation. Lipids are dense energy sources, storing about 100,000 kcal in the body, sustaining functions for weeks without food intake. They protect organs and are crucial for various metabolic cycles. The liver is central to lipid metabolism, storing excess fat and distributing lipids throughout the body. Fatty acids are oxidized for energy, yielding ATP and reactive oxygen species. Glycerolipids, synthesized mainly in the liver and adipose tissue, play key roles. Understanding lipid metabolism aids in comprehending metabolic disorders[77].

Emerging applications of probiotics

The field of probiotics is rapidly expanding, with new applications emerging beyond traditional gastrointestinal health. Understanding the mechanistic actions behind these applications and addressing the associated challenges are crucial for their successful integration into broader therapeutic and wellness strategies (Table 3).

Food industry

Probiotics are revolutionizing the food industry by enhancing product functionality and appealing to consumers interested in gut health and immunity. In fermented foods, probiotics add health value and create unique flavor profiles. Dairy products like yogurt and kefir have long contained beneficial probiotics, but there is now a strong push towards including probiotics in non-dairy foods like plant-based yogurts, beverages, cereals, and snacks[78].

Functional foods

Functional foods, which offer health benefits beyond basic nutrition, are increasingly incorporating probiotics as core ingredients. These foods target specific health outcomes, such as enhanced immunity, improved digestion, and reduced inflammation. Functional probiotic foods can include fortified beverages, dietary supplements, and enhanced snacks that deliver live, beneficial bacteria to the gut[27].

Pharmaceuticals

The pharmaceutical industry is increasingly adjunct focusing on probiotics for their therapeutic applications, which have shown promise as treatments for various diseases. Probiotics are being studied as co-therapies for antibiotic-associated diarrhoea, irritable bowel syndrome (IBS), and certain inflammatory conditions. Specific strains are being tailored for targeted health outcomes; for example, *Lactobacillus reuteri* is known for its role in reducing gastrointestinal inflammation and preventing antibiotic-related complications[79].

Next-generation probiotics

Next-generation probiotics represent a more advanced stage of probiotic development, involving genetically engineered or specially selected strains that offer enhanced or targeted health benefits. These probiotics include bacterial strains with unique health effects or genetically modified strains capable of producing therapeutic compounds. For instance, *Faecalibacterium prausnitzii* and *Akkermansia muciniphila* are next-generation probiotics with strong potential for anti-inflammatory and gut barrier-enhancing effects[80].

Table 3. Emerging applications of probiotics.

Application	Mechanism of action	Potential health benefits	Relevant probiotic strains	Examples	Ref.
Food industry	Enhance gut microbiota, improves food safety through pathogen inhibition	Supports digestive health, increases food preservation	*Lactobacillus acidophilus*, *Lactobacillus casei*, *Lactobacillus plantarum*	Yogurt, kefir, drinks, etc.	[78]
Functional foods	Modulateimmune response, producebioactive compounds	Reduceinflammation, enhance nutrient absorption	*Lactobacillus acidophilus*, *Lactobacillus casei*, *Streptococcus thermophilus*	Probiotic fortified juices, probiotic enhanced snack bars, etc.	[27]
Pharmaceuticals	Delivertherapeutic molecules, Compete with pathogens	Treat gastrointestinal diseases, support mucosal health	*Lactobacillus rhamnosus GG*, *Saccharomyces boulardii*	Florastor, align, culturelle, etc.	[79]
Next generation probiotics	Utilize non-conventional strains, enhanceviability through encapsulation techniques	Targets metabolic syndromes, improve gut barrier function	*Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, *Clostridium butyricum*	Evolus, BIO-tract, etc.	[80]
Disease prevention	Competitive exclusion of pathogens, detoxify environmental pollutants	Prevents antibiotic-associated diarrhoea, reduce risk of IBD and obesity	*Bifidobacterium lactis BB-12*, *Saccharomyces boulardii*	Align *(Bifidobacterium 35624)*, etc.	[81]
Gut health restoration	Improve intestinal barrier integrity, modulate gut-brain axis	Alleviatesymptoms of anxiety and depression, enhance nutrient metabolism	*Lactobacillus rhamnosus GG*, *Saccharomyces boulardii*	Garden of Life RAW Probiotics, etc.	[82]
Mental health and gut-brain axis	Modulate gut microbiota composition, produce neurotransmitters, influence the hypothalamic-pituitary-adrenal (HPA) axis	Reduce anxiety and depression symptoms, enhancemood	*Lactobacillus rhamnosus*, *Bifidobacterium longum*	VSL#3 (a high-potency probiotic blend), etc.	[83,84]
Metabolic health and obesity	Regulate energy metabolism, modulate lipid metabolism, produces short-chain fatty acids (SCFAs)	Aids weight management, improve insulin sensitivity	*Akkermansiamuciniphila*, *Lactobacillus gasseri*	Activia, LG2055, etc.	[85,86]
Immune modulation and allergies	Balance Th1/Th2 immune response, enhance regulatory T cell (Treg) function, produces anti-inflammatory cytokines	Reduces allergic reactions, improves immune tolerance	*Lactobacillus reuteri*, *Bifidobacterium bifidum*	Align, flostor, etc.	[87]
Cancer prevention and adjunctive therapy	Enhance anti-tumor immunity, modulate gut microbiota to inhibit carcinogenesis, produce bioactive compounds that may have anti-cancer properties	Reduces cancer risk,supportconventional cancer treatments	*Lactobacillus acidophilus*, *Bifidobacterium longum*	VSL#3, *LGG*, etc.	[88,89]

Disease prevention

Probiotics are being actively researched for their role in disease prevention, particularly in reducing the risk of chronic diseases and metabolic disorders. For example, probiotics have been shown to influence cholesterol levels, blood sugar regulation, and immune function, reducing the risk of cardiovascular disease, diabetes, and certain infections[81].

Gut health restoration

Restoring gut health is one of the most well-researched established applications of probiotics. Disruptions in gut microbiota balance, or dysbiosis, are associated with digestive disorders, immune dysfunction, and even mood changes. Probiotics help restore this balance by replenishing beneficial bacteria and supporting gut barrier integrity, crucial for digestive health and nutrient absorption[82].

Mental health and the gut-brain axis

The relationship between the gut microbiota and brain function, known as the gut-brain axis, has led to the exploration of probiotics as potential therapeutic agents for mental health disorders. Probiotic strains such as *Lactobacillus* and *Bifidobacterium* have been shown to influence neurotransmitter production, including gamma-aminobutyric acid (GABA) and serotonin, which play roles in mood regulation[83]. Mechanistic studies suggest that probiotics can modulate the hypothalamic-pituitary-adrenal (HPA) axis and reduce stress-induced inflammation, contributing to improved mental health outcomes[84].

Metabolic health and obesity

Probiotics are being researched for their potential in managing metabolic disorders, including obesity and type 2 diabetes. Strains like *Lactobacillus gasseri* have shown promise in reducing body fat mass and regulating lipid metabolism[85]. The underlying mechanisms involve the modulation of gut microbiota composition, increased production of short-chain fatty acids (SCFAs), and the regulation of metabolic pathways related to glucose and lipid homeostasis[86].

Immune modulation and allergies

Probiotics have shown the potential to modulate immune responses and reduce the incidence and severity of allergic reactions. Strains such as *Bifidobacterium bifidum* and *Lactobacillus rhamnosus* promote the balance between pro-inflammatory and anti-inflammatory cytokines, enhancing immune tolerance[87]. These mechanisms can reduce allergic inflammation and improve conditions like atopic dermatitis and allergic rhinitis.

Cancer prevention and adjunctive therapy

Preliminary studies indicate that certain probiotic strains may help reduce cancer risk or serve as adjuvants in cancer therapy. Probiotics may exert anticancer effects through the production of metabolites such as butyrate, which induces apoptosis in cancer cells and enhances gut barrier function[88]. Additionally, probiotics can modulate the immune system to help detect and eliminate tumor cells more effectively[89].

Negative effects of probiotics on human health

While probiotics are generally considered safe and beneficial, it is essential to recognize that their consumption can sometimes lead to negative effects too, particularly in vulnerable populations. These negative impacts are often related to the strain of probiotic used, the dosage, and the individual's underlying health condition[90]. Understanding these potential risks helps to ensure that probiotics are used safely and effectively.

Gastrointestinal symptoms

Some individuals may experience mild gastrointestinal side effects such as bloating, gas, and diarrhoea when starting probiotic supplementation. These symptoms are typically due to the body's adjustment to the introduction of new microbial species into the gut[91]. Although these side effects are usually temporary, they can be more pronounced in sensitive individuals or those with underlying gastrointestinal conditions.

Risk of infections

For individuals with compromised immune systems, such as those undergoing chemotherapy, post-surgical patients, or those with severe illnesses, probiotics can pose a risk of systemic infections. Case reports have documented instances of bacteremia and fungemia (infections of the bloodstream) linked to certain probiotic strains like *Lactobacillus* and *Saccharomyces* in immuno-compromised patients[92]. While rare, these cases underscore the importance of careful probiotic strain selection and monitoring in clinical settings.

Potential for antibiotic resistance transfer

The horizontal transfer of antibiotic-resistance genes from probiotic strains to pathogenic bacteria is a concern raised by some studies. While probiotics themselves may not pose a direct threat, the possibility that they could act as vectors for resistance genes necessitates further investigation to ensure their safe use[93].

Interactions with medications

Probiotics may interact with medications, particularly immunosuppressive drugs and certain antibiotics. For instance, probiotics can potentially diminish the effectiveness of antibiotics by competing for similar binding sites in the gut[94]. Conversely, antibiotics may also decrease the effectiveness of probiotics by killing the beneficial bacteria they introduce.

Adverse reactions in individuals with underlying conditions

Some conditions, such as short bowel syndrome or intestinal permeability disorders, may exacerbate the risk of adverse reactions. The colonization of probiotics in such patients could lead to complications like sepsis or excessive bacterial translocation[95]. These reactions emphasize the need for personalized medical advice before starting probiotic therapy.

Market trends and challenges

Understanding consumer preferences for non-dairy probiotics is essential for product development and market success. Consumer studies have highlighted a growing interest in plant-based and non-dairy alternatives, driven by factors such as lactose intolerance, veganism, and a desire for diverse dietary options[8]. The market for non-dairy probiotic products has witnessed significant growth. Plant-based yogurts, kefirs, and fermented non-dairy beverages have become mainstream. Market trends indicate a surge in demand for products that cater to specific dietary needs, emphasizing the need for innovation in formulation and marketing strategies[96]. While non-dairy probiotics offer diverse options, challenges exist. The stability and viability of probiotic strains in non-dairy matrices, such as plant-based milks or fermented vegetables, can be affected by processing methods and storage conditions. Ensuring the survival of probiotics until consumption is a critical consideration[97]. Also, taste is a crucial factor influencing consumer acceptance. Non-dairy probiotic products must not only deliver health benefits but also meet taste expectations. Balancing the characteristic tanginess of probiotics with the flavour profile of non-dairy bases is a delicate consideration in product development[98]. Future research in non-dairy probiotics should focus on the identification and characterization of novel probiotic strains suitable for non-dairy matrices. Understanding the interactions between specific non-dairy substrates and probiotic strains can enhance product development and efficacy[33]. Advancements in encapsulation technologies, microencapsulation, and protective matrices can improve the stability and viability of probiotics in non-dairy products. Innovations in fermentation processes and the use of prebiotics to enhance probiotic survival and functionality present exciting avenues for exploration[10]. Some of the main challenges includes issues such as:

Stability of probiotic formulations

One of the significant challenges in the development and application of probiotics is ensuring the stability of the products. Probiotic strains can be sensitive to temperature, humidity, and oxygen exposure, which can compromise their viability. Research is ongoing to improve formulation strategies, such as microencapsulation and the use of cryo-protectants, to enhance the shelf-life and stability of probiotic products[99].

Safety concerns

While probiotics are generally considered safe, their administration, especially to vulnerable populations such as the immuno compromised or those with critical illnesses, poses potential risks. Issues like bacteremia, endocarditis, and the horizontal transfer of antibiotic resistance genes have been reported[92]. Ensuring strain-specific safety through rigorous clinical trials and monitoring is crucial for minimizing these risks.

Regulatory issues

The regulatory landscape for probiotics is complex and varies across regions. Unlike pharmaceuticals, probiotics often face fewer rigid regulations, which can lead to variations in product quality and efficacy. The need for standardization in terms of strain identification, dosage, and clinical validation is a significant challenge in ensuring that probiotic products meet safety and efficacy standards[14]. Addressing these regulatory gaps would require international consensus and clearer guidelines from regulatory authorities.

Conclusions

In conclusion, non-dairy probiotics align with evolving consumer preferences for diverse, plant-based, and health-conscious dietary choices. Market trends underscore the increasing demand for non-dairy probiotic products. However, challenges related to stability, viability, and taste need to be addressed for sustained success. Future research directions should focus on the development of novel probiotic strains and innovative technologies to enhance product quality and efficacy. The importance of non-dairy probiotics in promoting overall health and catering to varied dietary needs cannot be overstated, making them a crucial component of the contemporary food landscape. The development of plant-based probiotic drinks is important in promoting healthier alternatives to dairy-based drinks. A thorough grasp of the range of plant fermentable sugars, as well as the critical quality indicators of fermented products, aids in the production of high-quality functional beverages. The difficulties in maintaining the high viability of probiotics in fruit-and-vegetable-based drinks impose challenges to meet the increasing demand by consumers. The commercialization of non-dairy probiotic drinks creates a variety of taste options and promotes healthier lifestyles for consumers.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Thakur A, Sharma P, Sharma JA; data collection: Thakur A, Sharma A; analysis and interpretation of results: Thakur A, Sharma P, Sharma JA, Sharma N; draft manuscript preparation: Thakur A, Sharma P, Sharma JA, Sharma N, Singh S, Chamoli N, Kumar R. All authors reviewed the results and approved the final version of the manuscript.

Data availability

All data generated or analyzed during this study are included in this published article.

Acknowledgments

The authors would like to express their sincere gratitude to Career Point University, Hamirpur, for providing the resources and support necessary to complete this review. We also acknowledge the invaluable input from our peers and colleagues, whose feedback has greatly improved the quality of this work.

Conflict of interest

The authors declare that they have no conflict of interest.

Dates

Received 9 October 2024; Revised 17 November 2024; Accepted 4 December 2024; Published online 23 January 2025

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