Journal Pre-proof

# Phytophagous Probiotic Foods: Exploring the Intersection of Characteristics, Quality Implications, Health Benefits, and Market Dynamics

Alaa Kareem Niamah, Shayma Thyab Gddoa Al-Sahlany, Hussein Katai Abdul-Sada, Pawan Prabhakar, Soubhagya Tripathy, Basant Kumar Dadrwal, Smita Singh, Deepak Kumar Verma, Alok Kumar Gupta, Rakesh Mohan Shukla, Mamta Thakur, Ami R. Patel, Gemilang Lara Utama, Mónica L. Chávez González, Prem Prakash Srivastav, Wissal Audah Hassan Alhilfi, José Sandoval-Cortés, Cristobal Noe Aguilar

PII: S0924-2244(24)00471-0

DOI: https://doi.org/10.1016/j.tifs.2024.104795

Reference: TIFS 104795

To appear in: *Trends in Food Science & Technology*

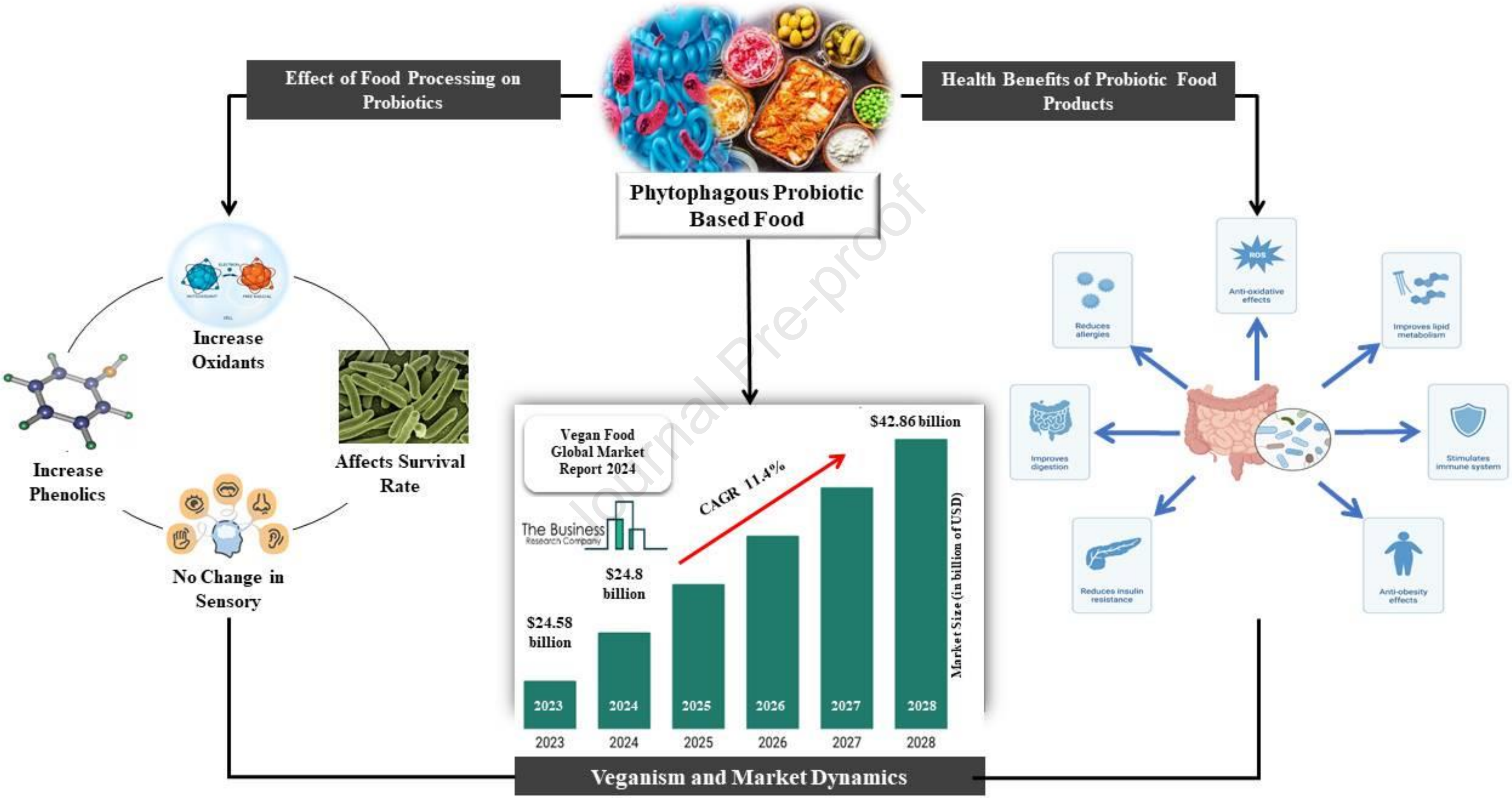
Received Date: 16 August 2024

Revised Date: 26 October 2024

Accepted Date: 16 November 2024

Please cite this article as: Niamah, A.K., Gddoa Al-Sahlany, S.T., Abdul-Sada, H.K., Prabhakar, P., Tripathy, S., Dadrwal, B.K., Singh, S., Verma, D.K., Gupta, A.K., Shukla, R.M., Thakur, M., Patel, A.R., Utama, G.L., Chávez González, M.L., Srivastav, P.P., Hassan Alhilfi, W.A., Sandoval-Cortés, J., Aguilar, C.N., Phytophagous Probiotic Foods: Exploring the Intersection of Characteristics, Quality Implications, Health Benefits, and Market Dynamics, *Trends in Food Science & Technology*, https://doi.org/10.1016/j.tifs.2024.104795.

## Graphical Abstract



# Phytophagous Probiotic Foods: Exploring the Intersection of Characteristics, Quality Implications, Health Benefits, and Market Dynamics

**Alaa Kareem Niamah[a], Shayma Thyab Gddoa Al-Sahlany[a], Hussein Katai Abdul-Sada[b], Pawan Prabhakar[c,d], Soubhagya Tripathy[e], Basant Kumar Dadrwal[f], Smita Singh[g], Deepak Kumar Verma[e]*, Alok Kumar Gupta[h], Rakesh Mohan Shukla[i], Mamta Thakur[j], Ami R. Patel[k], Gemilang Lara Utama[l,m], Mónica L. Chávez González[n], Prem Prakash Srivastav[e], Wissal Audah Hassan Alhilfi[o], José Sandoval-Cortés[n] and Cristobal Noe Aguilar[n]**

[a]*Department of Food Science, College of Agriculture, University of Basrah, Basra City, Iraq*

[b]*Al-Zahraa College of Medicine, University of Basrah, Basrah 61004, Iraq*

[c]*School of Business, Woxsen University, Hyderabad, Telangana, 502345, India*

[d]*Bio-Research Laboratory, Rajendra Mishra School of Engineering Entrepreneurship, Indian Institute of Technology Kharagpur, Kharagpur, 721 302, West Bengal, India*

[e]*Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur, Kharagpur 721302, West Bengal, India*

[f]*Department of Plant Physiology, Sri Karan Narendra Agriculture University, Jobner Jaipur, 303 329, Rajesthan, India*

[g]*Department of Allied Health Sciences, Chitkara School of Health Sciences, Chitkara University, Punjab 140401, India*

[h]*Division of Post-harvest Management, ICAR-Central Institute for Subtropical Horticulture (Ministry of Agriculture and Farmers Welfare, Government. of India), Lucknow, UP, 226101, India*

[i]*Processing and Food Engineering Division, College of Agricultural Engineering and Technology (CoAE&T), Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, 190 025, Jammu and Kashmir, India*

[j]*Department of Food Processing Technology, College of Dairy and Food Technology (CDFT) (Rajasthan University of Veterinary & Animal Sciences, Bikaner), Bassi, Jaipur, Rajasthan, India*

[k]*Division of Dairy Microbiology, Mansinhbhai Institute of Dairy and Food Technology-MIDFT, Dudhsagar Dairy Campus, Mehsana-384 002, Gujarat, India*

[l]*Faculty of Agro-Industrial Technology, Universitas Padjadjaran, Sumedang 45363, Indonesia*

[m]*Center for Environment and Sustainability Science, Universitas Padjadjaran, Bandung 40132, Indonesia*

[n]*Bioprocesses and Bioproducts Group, Food Research Department, School of Chemistry. Autonomous University of Coahuila, Saltillo Campus. 25280. Coahuila, México*

[o]*Marine Science Center, University of Basrah, Basra City, Iraq*

***Corresponding author:**

**Dr. Deepak Kumar Verma**
Agricultural and Food Engineering Department,
Indian Institute of Technology Kharagpur,
Kharagpur 721302, West Bengal, India
**Tel.: +00-91-7407170260**
**E-mail:** rajadkv@rediffmail.com

# Phytophagous Probiotic Foods: Exploring the Intersection of Characteristics, Quality Implications, Health Benefits, and Market Dynamics

## Abstract

### *Background*

The development of novel food products with functional properties, particularly those that contain bioactive substances and probiotic microorganisms, is driving the rising demand for improved nutritional content. Phytophagous probiotic products assume significance in this manner. These are commonly known as biotechnological formulations comprising beneficial microorganisms with a primary nutritional preference for plant matter consumption. These beneficial microorganisms have been commonly utilized in non-dairy products due to their diverse and significant characteristics, which can influence not only food quality and safety parameters but also various aspects of human health.

### *Scope and approach*

This present study has conducted an assessment of phytophagous probiotic products, providing a thorough examination of both commercially accessible and scientifically investigated products, along with their associated health-promoting advantages.

### *Key findings and conclusions*

The information presented in this article will be of great value to researchers and professionals in the industry, as it will help guide future research efforts that should focus on investigating key factors related to vegan food. These factors include consumer preferences, with the ultimate goal of promoting widespread global adoption of veganism. Moving forward, it is recommended that short-term marketing strategies incorporate not only the vegan demographic but also individuals who aim to reduce their consumption of animal-derived products while actively seeking innovative non-animal-derived alternatives.

**Keywords:** phytophagous products, probiotics, prebiotics, plant food, functional foods; human health; industrial application

## 1. An Introduction of Phytophagous Probiotic Foods

Plant-based food products possess the capacity to enhance human well-being and concurrently mitigate the ecological repercussions associated with excessive consumption of animal-derived food stuff such as meat and dairy products.  When compared to the production of foods derived from animals, the production of plant-based foods, such as grains, legumes, fruits and vegetables, nuts, and seeds, results in fewer emissions of greenhouse gases **(Springmann et al., 2018)**. The adoption of vegetarianism is experiencing a surge in popularity, leading to increased consumer demand for products that possess superior nutritional and functional attributes. The scientific community has prioritized the significance of a nutritionally balanced diet for optimal health and the efficacy of specific food products in mitigating the likelihood of developing diseases. This has led to a surge in research and development efforts focused on exploring and synthesizing innovative natural compounds, primarily derived from plant-based materials and commodities. These endeavors primarily target the development of functional products, thereby generating new opportunities within niche markets **(Khalil et al., 2022)**. Based on a recent survey, it is projected that the worldwide market for plant-based food will experience a threefold increase, growing from US$ 11.3 billion in 2023 to US$ 35.9 billion by 2033 **(FMI, 2023)**. The upward trajectory of vegetarian or vegan dietary practices and the increasing demand for dairy and meat substitutes are pivotal drivers of the plant-based food products market. In addition to the dietary trend, various health concerns such as milk protein allergies, lactose intolerance, and dyslipidemia, as well as factors like economic considerations related to dairy-based probiotic products, including the need for refrigeration, contribute significantly to the increasing popularity of non-dairy probiotic foods **(Küçükgöz et al., 2022)**. Non-dairy fermented substances are foods or drinks made from ingredients other than milk or milk products. Fermentation is a process in which microorganisms break down food, converting it into new products with different flavors, textures, and nutritional properties. Examples of non-dairy fermented substances include sauerkraut, kimchi, tempeh, and kombucha. These substances are also known for their health benefits, such as improved digestion and immunity. Fermentation also preserves food, allowing it to last longer. Fermentation also produces beneficial enzymes and probiotics, which can provide additional health benefits **(Küçükgöz et al., 2022)**. A growing number of consumers are actively searching for alternatives to traditional dairy milk, driven by various factors such as environmental sustainability, personal health considerations, lifestyle choices, and nutritional preferences. This demand has prompted the emergence of a range of plant-based milk substitutes, derived from sources such as nuts, seeds, and legumes **(Niamah et al., 2017)**. Veganism is a dietary paradigm characterized by the exclusive consumption of plant-derived foods, such as wheat, rice, maize, barley, and sorghum **(Kumar et al., 2022)**. Veganism is a lifestyle that aims to minimize, to the greatest extent possible and practical, the utilization of animals for food, clothing, cosmetics, or any other purpose, as stated on the Vegan Society's official website. Therefore, in a comprehensive manner, veganism can be delineated as a specific dietary paradigm characterized by the exclusive ingestion of botanical-derived sustenance and the deliberate abstention from any form of animal-derived substances **(Miguel et al., 2021)**.

Furthermore, this specific dietary selection exhibits a multitude of facets and is characterized by a high level of energy. Consequently, individuals' dietary patterns and selections are shaped by sociocultural influences, subjective inclinations, and ecological determinants. Therefore, it is evident that individuals depend on an established identity that provides guidance on dietary practices. The examination of attitudes toward veganism can be approached by analyzing three pivotal factors that impact daily behaviors: attitudes, subjective standards, and perceived control **(Sobal et al., 2014)**. In this context, the development of nutritionally balanced and/or value-added products is notable for their pragmatic usefulness. Due to their high efficacy and proven health benefits, along with the ability of probiotic cultures to adapt to diverse dietary compositions, it is imperative to advocate for the promotion of probiotic products **(Subhashree & Kavita, 2019; Niamah, 2019; Jayarathna et al., 2021)**. Nutritionally balanced and/or added-value products demonstrate practicality and efficiency, while probiotic products exhibit benefits owing to their adaptability to diverse dietary matrices. Individuals adhering to a vegan dietary pattern, specifically, must incorporate supplementary measures into their nutritional regimen to guarantee adequate intake of essential nutrients such as iron (Fe), calcium (Ca), vitamin B12, and vitamin D. These nutrients can be sourced from fermented cereal products enriched with probiotic bacteria. The process of fermenting plant matrices results in the synthesis of various vitamins, essential amino acids, minerals, prebiotics, and probiotic microflora. Additionally, it facilitates the breakdown of anti-nutritional compounds such as tannins, phytic acid, and polyphenols. The presence of probiotics in fermented products not only enhances their energy contents and nutritional properties, but also improves their therapeutic potentials to a certain extent **(Ray et al., 2016)**. The efficacy of probiotics is associated with their viability in food products, and several factors have been implicated in reducing it. Consequently, a multitude of strategies are employed to enhance and sustain the survival of microbial cells, encompassing the meticulous choice of probiotics and the utilization of suitable dietary matrices. An alternative approach to promote the growth of probiotics involves the formulation of synbiotic compositions **(Pimentel et al., 2021)**.

The objectives of the review have to examine phytophagous probiotic products, offering a comprehensive analysis of both commercially available and scientifically researched products, along with their corresponding health-enhancing benefits. The study has also examined the effects of probiotics on industrial and sensory characteristics, as well as the factors that affect the survival of probiotics and the main challenges and trends in this market segment. The information provided in the present article will be valuable for researchers and industry professionals in facilitating communication with consumers to enhance the utilization of phytophagous food products. It will also serve as a starting point for discussing the phytophagous probiotics industry, focusing on limitations related to the sources of strains and regulatory requirements for labeling such food products.

## 2. Key Characteristics of Phytophagous Probiotic Food

The increasing need for enhanced nutritional value has prompted the development of innovative food products that possess functional attributes, specifically those containing bioactive compounds and probiotic microorganisms. Probiotics refer to living microorganisms, such as bacteria and yeasts that can provide advantageous effects on the health of the host organism when consumed in sufficient amounts. However, dormant bacteria and their components can also exhibit probiotic characteristics. *Bifidobacterium* and multiple strains of lactic acid bacteria (LAB) are frequently employed as probiotic bacteria and can be found in various functional ingredients and dietary supplements **(Niamah, 2017; Plaza-Diaz et al., 2019)**. The burgeoning probiotic industry on a global scale has garnered considerable interest from food corporations, prompting them to develop novel products that incorporate probiotic microorganisms. Furthermore, scientists are currently conducting investigations into the precise characteristics of probiotics and their impact on the overall well-being of the general population. However, within the context of a swiftly growing global probiotic industry, end-users face difficulties in discerning between probiotics of superior and inferior quality. The presence of uncertainty poses a significant threat to the confidence and reliance that consumers and healthcare providers place in probiotic products. To address this issue, it is advised that companies acquire third-party certification for the quality and accuracy of their probiotic products **(Jackson et al., 2019)**.

For an extended period, the dairy industry has exerted significant control over the probiotic market, primarily through the prevalence of products like yogurt, kefir, and other fermented dairy products that have enjoyed a dominant position within the market. However, as a consequence of the escalating population of individuals adhering to vegan diets, experiencing lactose intolerance, and/or exhibiting high cholesterol levels, it became imperative to alter this prevailing pattern **(Küçükgöz et al., 2022)**. Consequently, a range of plant-derived alternatives, including vegetables, fruits, and seed matrices, have been proposed as potential vehicles for probiotics **(Cosme et al., 2022)**. In response to consumer demand, the agricultural industry has undertaken efforts to identify alternative options to milk. One prominent strategy involves promoting the utilization of water-soluble extracts derived from a range of plant sources such as walnuts, coconuts, beans, oats, rice, and soybeans (as outlined in **Table-1**). Numerous fermented vegetables, including olives, cabbage, mustard cucumbers, pickles, and kimchi, exhibit a rich presence of LAB species across diverse geographical regions. Kimchi, a culturally significant Korean culinary preparation, is produced through the fermentation of vegetables, with a particular emphasis on Baechu, also known as cabbage (scientific name: *Brassica rapa*). This traditional dish has garnered widespread acclaim on a global scale owing to its unique flavor profile, as well as its functional attributes and nutritional advantages, with kimchi constituting more than 70 % of its composition **(Ashaolu et al. 2020; Lee et al., 2020)**.

Fermented non-dairy beverages originating from diverse regions across the globe, including Boza, Pozol, Bushera, Mahewu, Togwa, and others, are abundant in probiotics and prebiotics. This is attributed to their raw materials, which consist of grains, cereal grains, beans, vegetables, and fruits. Boza, for example, is a cereal-derived beverage that undergoes fermentation using whole grains such as wheat and maize, as well as flour. This exhibits significant popularity within various nations, including Turkey, Uzbekistan, Kazakhstan, Albania, Croatia, Greece, Montenegro, Bosnia and Herzegovina, as well as select regions of Romania and Serbia. Similar beverages are also produced in Eastern European countries, such as braga or brascha, as well as in the Balkans (busa) and Egypt (bouza) **(Ucak et al., 2022)**. The predominant strains of LAB commonly found in these products are *Limosilactobacillus fermentum* and *Lactiplantibacillus plantarum*. In India, one of the alcoholic beverages known as sura (wine or beer), which was produced by the fermentation of cooked rice or barley, is documented in the literature as having been consumed since ancient times. In addition to this, some of the most well-known beverages to originate from India are *asava* (beer made from sugarcane), *medaka* (beer made from spiced rice), *prasanna* (beer made from spicy wheat or barley), etc. Several probiotic bacteria have been extracted and characterized from traditionally fermented nondairy beverages **(Borah et al., 2019; Ilango et al., 2016)**. These strains were obtained through isolating and fermenting the beverages. Furthermore, **Das et al. (2019)** reported the existence of prebiotics in addition to probiotics. They also found evidence of the presence of nutraceutical chemicals such as carotene, thiocoumarine, oxazolidine-2-one, and acetyl tyrosine in the sample. It is evident that a significant proportion of products labeled as "probiotics" in the consumer market do not meet the prescribed criteria, including the specified composition, adequate bacterial viability until the end of the product's shelf life, and substantiated indications of positive effects on health (**Figure-1**). Consequently, probiotic plant food exhibits two significant limitations: (1) the origin of the probiotic strains is primarily derived from animal sources or animal-derived products, as observed in the majority of commercially accessible strains; while, (2) The vegan nature of probiotic supplements is compromised due to the utilization of animal-derived sources or dairy constituents during the processing of numerous probiotic strains.

Supplements may contain animal components in the form of inactive substances, such as artificial binders or fillers. Hence, it is imperative to thoroughly examine the compendium of active and inactive constituents in particular merchandise in order to verify their adherence to vegan principles. Choosing plant-based food options as probiotic sources, such as fermented beverages and kefirs derived from soy, almond, or coconut, along with vegan-friendly fermented vegetables like sauerkraut, kimchi, pickles, miso, natto, tempeh, kombucha, and fermented rice, presents a more enticing and viable alternative. An alternative approach would involve conducting a search for widely recognized probiotic capsules that are compatible with a vegan diet, possess superior standards in terms of quality, purity, and potency, and offer convenient administration. Rice and soy extracts, along with fruits and vegetables, have emerged as the most auspicious reservoirs of probiotic microorganisms for plant-based food products, exhibiting substantial research prospects **(Samedi et al., 2019; Rasika et al., 2021)**.

## 3. Quality Implications of Probiotic Integration in Phytophagous Foods

The viability of probiotic starter bacteria and their impact on the quality of food products can be influenced by various factors, including the food matrix, processing stages, probiotic strain, method of addition, storage conditions, and prebiotic components. Numerous scientific investigations have examined the effects of incorporating probiotic bacteria into plant-based products. The researchers assessed the viability, physicochemical characteristics, as well as techno-functional and sensory attributes of the samples. Hence, the advantageous protective effects are significantly impacted by the botanical composition of plants, including fruits, vegetables, and seeds, as well as their distinct constituents. In relation to the viability of probiotics, table olives and artichokes have demonstrated higher rates of survival during storage and under laboratory conditions that simulate the gastrointestinal (GI) environment. These rates are comparable to, and in some cases superior to, those observed in probiotic dairy products. The coarse microstructure of these vegetables potentially acts as a protective barrier for the probiotic in an acidic environment, while the presence of prebiotic compounds may enhance bacterial survival by supplying nutrients that are released from the vegetables **(Koh et al., 2018; Wang et al., 2019)**.

### *3.1. Technological and Physicochemical Attributes of Probiotic-enhanced Vegan Foods*

The incorporation of probiotic microorganisms has minimal impact on the chemical composition of food products, including moisture, protein, lipids, ash, fiber, and carbohydrate content **(Rafiq et al., 2016)**. Conversely, a scientific investigation revealed alterations in the concentrations of protein, carbohydrates, and fat within probiotic-infused carrot juice **(Rafiq et al., 2016)**. The probiotic carrot juice, which includes *Lactobacillus acidophilus*, *Lactiplantibacillus plantarum*, *Lacticaseibacillus casei*, and *Bifidobacterium longum*, exhibited elevated protein content (1.12%) and ash content (0.34%) in comparison to the fresh product. However, it demonstrated reduced fat content (0.79%) and carbohydrate content (7.94%) when compared to the fresh product, with values of 0.76%, 0.95%, 8.10%, and 0.23% for protein, fat, carbohydrates, and ash content, respectively **(Rafiq et al., 2016)**. The observed elevation in protein levels can be ascribed to the existence of probiotic microorganisms and their metabolic byproducts. Furthermore, the incorporation of soybean and Brazil-nut water solubility extraction in the production of fermented beverages resulted in improved technical characteristics **(Barbosa et al., 2020)**. This suggests that the combination of multiple plant-based beverages can enhance the physicochemical and technological properties of the final product. The inclusion of either papaya or mango pulp at a concentration of 20% in a probiotic rice beverage resulted in comparable outcomes, with significantly elevated viscosities observed **(Atwaa et al.,**

**2019)**. The addition of probiotic bacteria to a product has been observed to result in a decrease in the overall concentration of soluble solids (TSS) and sucrose. This phenomenon can be attributed to the metabolic activity of probiotic cultures, wherein they enzymatically degrade complex carbohydrates and subsequently generate organic acids, including lactic acid and acetic acid. This phenomenon is commonly observed in fermented beverages, although it may vary depending on the specific probiotic strain and food composition in alternative products.

In a study conducted by **Pimentel et al. (2015)**, it was observed that the addition of probiotic *Lacticaseibacillus paracasei* to fermented apple juice and oligofructose probiotic juice did not result in any significant alterations in their chemical composition, density, consumer acceptance, or purchase intent when compared to non-supplemented products. Nevertheless, it resulted in an elevation of acidity levels, turbidity, and the manifestation of a red hue. In the meantime, adding oligofructose as a supplement did not have any effect on the physicochemical characteristics, attractiveness, or buy intent of the products; however, it did enhance the probiotic's shelf life while it was being stored. Furthermore, the application of microencapsulation technique to *Lactiplantibacillus plantarum* 33 probiotic cultures and their incorporation into olive pastes resulted in enhanced color properties **(Alves et al., 2015)**. This was achieved by effectively maintaining the brightness of the product during storage, surpassing the performance of using probiotic cells in their free form.

LAB were employed to enhance the quality of olives and decrease the duration of debittering in the process of table olive fermentation **(Lanza et al., 2020)**. The fermentation process was observed to measure multiple parameters, including pH, titratable acidity, NaCl concentration, bio-phenol breakdown, and the increase of hydroxytyrosol and tyrosol in the olive flesh, oil, and brine. The jars that were inoculated exhibited accelerated degradation of secoiridoid glucosides compared to the jars that underwent spontaneous fermentation. This was accompanied by an increase in the synthesis of hydroxytyrosol and ligstroside aglycon **(Lanza et al., 2020)**. This observation suggests the complete breakdown of oleuropein and the partial breakdown of ligstroside. The incorporation of diverse inocula facilitated the achievement of thorough debittering and the potential development of probiotic properties. The inclusion of *Lactiplantibacillus plantarum* B1 and B124 as fermentation inoculants led to the production of a final product exhibiting enhanced quality characterized by an optimal trajectory of de-bittering and fermentation parameters. *Lactiplantibacillus plantarum* B51 exhibits promising characteristics that make it a viable candidate for utilization as a probiotic alternative in the development of entirely plant-derived probiotic food products **(Lanza et al., 2020)**. No significant differences ($p > 0.05$) were observed in the pH (4.0) and total acidity (0.47–0.50 g expressed in citric acid/100 g) between the mixture of fruit juice (juçara, banana, and strawberry pulps) containing probiotics (*Bifidobacterium animalis*, *Lactobacillus acidophilus*, *Lacticaseibacillus casei*, and *Lactiplantibacillus plantarum*) and the control beverage **(de Oliveira Ribeiro et al., 2020)**.

### *3.2. Food Processing and Its Effects on Probiotic-infused Vegan Foods*

Various food processing methods can influence the viability of probiotics in food products **(Pimentel et al., 2015; de Oliveira Ribeiro et al., 2020)**. The inclusion of a fermentation phase has the potential to augment the probiotic count in the end product. However, it is worth noting that both fermented and non-fermented products can possess sufficient quantities of probiotics **(Pimentel et al., 2015; Calinoiu et al., 2016)**. The process of microencapsulation involves the encapsulation of probiotic bacteria within a protective microenvironment. This microenvironment serves to maintain the bacteria's metabolic activity and enhance their viability throughout food processing **(Ilango et al., 2016; Niamah et al., 2021)**. The microencapsulation carrier refers to a controlled microenvironment that serves as a habitat for bacteria or yeast. This carrier enables the controlled release of these microorganisms in targeted regions of the small intestine, both during processing and storage. Encapsulation has been scientifically demonstrated as the optimal method for preserving probiotics and ensuring their stability and viability throughout the production, processing, and storage of probiotic food products **(Niamah et al., 2021)**. The viability of probiotics in both food products and the small intestine can be influenced by various storage conditions, including temperature and duration (**Pimentel et al., 2015; de Oliveira Ribeiro et al., 2020; Calinoiu et al., 2016)**. In addition, the presence of oxygen can potentially harm various probiotic cells, leading to reduced cell viability throughout the entire storage period **(Calinoiu et al., 2016)**. Consequently, the proper storage and packaging of food products are crucial factors to consider.

Fruit juices exhibit a high carbohydrate content, comprising prebiotic compounds that facilitate the proliferation of probiotic microorganisms **(Valero-Cases et al., 2017;**

**Fonteles & Rodrigues, 2018)**. Moreover, fruit and vegetable juices exhibit elevated levels of vitamins and antioxidants **(Fonteles & Rodrigues, 2018)**. According to **de Oliveira Ribeiro et al. (2020)**, *Lacticaseibacillus casei* BGP93 and *Lactiplantibacillus plantarum* demonstrated survival in *in vitro* simulations of the small intestine. It has been observed that the tolerance of both cultures to the conditions of the small intestine decreased over the storage period of the beverages (90 days). The viability of probiotic cells is compromised by the low pH environment of the gastric phase, as evidenced by previous studies **(Miranda et al., 2020)**. Consequently, the impacts of storage and GI tract conditions may exhibit associations with the food matrix composition and probiotic strain.

### *3.3. Assessing Probiotic Strain Viability in Phytophagous Food Products*

The requisite population size of probiotics in food prior to ingestion, in order to confer health advantages, is a minimum of 6 log CFU/mL or g of food. Numerous plant-derived food products, such as fruit and vegetable juices or beverages, have been observed to retain adequate levels of probiotics throughout the storage period, as indicated in **Table-2**. Furthermore, an assessment was conducted on the feasibility of microencapsulated *Lactobacillus pentosus* on the external layer of olives over a duration of one month. The count of viable cells was found to be equal to or greater than 6 log CFU/g **(Elvan et al., 2021)**. As a result, the microencapsulation of *Lactobacillus pentosus* within the xylan-WPC complex was successfully achieved, leveraging its antibiotic and digestion fluid resistance properties, along with its antioxidant properties. Hence, it can be deduced that table olives possess the necessary attributes to serve as an appropriate medium for hosting advantageous microorganisms that adhere to the regulatory criteria for functional foods **(Elvan et al., 2021)**. Therefore, the technique of microencapsulation can be utilized in various other products to augment the viability of probiotics, facilitate controlled release, and extend the duration of their effects.

### *3.4. Sensory Evaluation of Probiotic-enriched Vegan Foods*

Plant-based foods often exhibit nutritional imbalances and possess restricted gustatory appeal **(FMI, 2023)**. Numerous scientific investigations have consistently demonstrated that the process of probiotic fermentation has the potential to significantly improve the sensory acceptance of food products when compared to their non-fermented counterparts **(Pereira et al., 2017; Tomar et al., 2019; Hashemi et al., 2020; Khalil et al., 2022)**. The incorporation of probiotic cultures into the fermentation process enhances the sensory attributes of the food **(Tomar et al., 2019)**. This improvement can be attributed primarily to the synthesis of lactic acid, acetic acid, and aromatic compounds. The sensory characteristics of probiotic plant-based foods can be modulated by the botanical species employed, the probiotic strains employed, and the fermentation methodology employed (**Table-3**). **Table-4** discusse some prevalent sensory attributes associated with probiotic plant-based foods.

The principal incentive for the consumption of probiotic products comes from their potential health advantages. Nevertheless, it is imperative to uphold the sensory palatability of these products to a degree that is commensurate with conventional products. Consumers exhibit a tendency to refrain from consuming functional foods that emit atypical odors or flavors **(Min et al., 2019)**. Frequently, it has been noted that fermented dairy products derived from animal milk and containing probiotics can exhibit the emergence of medicinal aromas or atypical olfactory characteristics. Moreover, this phenomenon could potentially be influenced by the milk's origin, specifically whether it is derived from a bovine, bubalus, caprine, ovine, or camelid species.

In a prior investigation, it was observed that probiotic carrot juice, produced with probiotic starters such as *Lactobacillus acidophillus*, *Lactiplantibacillus plantarum*, *Lacticaseibacillus casei*, and *Bifidobacterium longum*, exhibited diminished levels of acceptability in comparison to freshly prepared carrot juice **(Rafiq et al., 2016)**. Consequently, it is imperative to evaluate the impact of probiotic supplementation on the sensory acceptability of the product, taking into account the specific food matrix and probiotic strain involved. In a study conducted by **Ryan et al. (2020)**, it was observed that the incorporation of 10% mango juice resulted in enhanced viability of probiotics, as indicated by their research findings. Furthermore, upon exposure to *in vitro* GI  digestion, this particular formulation exhibited an enhanced capacity to withstand probiotic tolerance. Based on the findings of the sensory analysis, it was observed that an increase in the mango juice concentration from 20% to 40% in the beverage resulted in enhanced sensory ratings **(Ryan et al., 2020)**. The process of microencapsulation of probiotic cultures has the potential to assist in preserving the sensory acceptability of probiotic food products at a level that is similar to the control group, as demonstrated by previously published studies **(Niamah et al., 2021)**. The inclusion of encapsulated *Lacticaseibacillus casei* in fruit juices can elicite both positive and negative response from consumers. This is primarily attributed to the aesthetic appearance of the product.

## 4. Health Benefits of Probiotic-enriched Phytophagous Foods

Recent scientific investigations have explored the physiological and health implications of different botanical substances when combined with probiotics, both in controlled laboratory conditions (*in vitro*) and in living organisms (*in vivo*). The presence of probiotic bacteria in plant-based foods may also exhibit potential health advantages (**Figure-2**). *Pediococcus pentosaceus* and *Levilactobacillus brevis* were isolated from traditional Korean fermented foods, specifically radish kimchi. The HT-29 cells, specifically human colon adenocarcinoma cells, exhibited adhesion rates of 4.45% and 6.30%, as reported in reference **(Koh et al., 2010)**. Furthermore, two strains of *Lactococcus lactis* were isolated from whole-grain rice and subjected to probiotic characterization and antimicrobial activity against various pathogenic strains. The pathogenic strains, namely *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Enterococcus faecalis*, exhibited varying responses to the isolates at different concentrations. It is hypothesized that these isolates have the potential to serve as biotherapeutic agents for the treatment of bacterial infections, as an alternative to antibiotics **(Soundharrajan et al., 2021)**. *Lactiplantibacillus paraplantarum* and *Saccharomyces cerevisiae* were isolated from Jangajji, a traditional Korean fermented food product, through extraction procedures. This suggests that Jangajji may possess functional applications in the development of food and pharmaceutical products, owing to its antioxidant and immunostimulatory properties **(Son et al., 2018; Lee et al., 2019)**. While several *in vitro* studies have provided valuable information regarding the potential health advantages of plant-based probiotic products, additional *in vivo* studies are required to validate their effectiveness. It has been empirically observed that plant-based foods containing probiotics possess the capacity to enhance lipid profiles. Wistar rats subjected to a dietary intervention involving the consumption of pineapple and jussara juices supplemented with *Lacticaseibacillus rhamnosus* GG exhibited a reduction in levels of low-density lipoprotein cholesterol, potentially contributing to the prevention of coronary heart disease. The food products did not exhibit any signs of hepatotoxicity or nephrotoxicity **(de Almeida Bianchini Campos et al., 2019)**.

Phytophagous probiotic foods, which integrate plant-derived components with live beneficial microorganisms, present a significant array of nutritional benefits that enhance overall health (**Sakkas et al., 2020; Montazersaheb et al., 2021; Pimentel et al., 2021**). These foods possess a high concentration of dietary fiber, essential vitamins, minerals, antioxidants, and bioactive compounds, which are further augmented through the process of probiotic fermentation (**Montazersaheb et al., 2021; Pimentel et al., 2021**). The fermentation process enhances the bioavailability of essential nutrients, including B vitamins, calcium, iron, and polyphenols, while also generating supplementary bioactive compounds such as γ-aminobutyric acid (GABA) and urolithins, which exhibit calming, anti-aging, and anti-inflammatory effects. The probiotics found in these foods contribute to GI health by regulating the microbiome, optimizing digestive processes, and facilitating nutrient absorption (**de Almeida Bianchini Campos et al., 2019; Plaza-Diaz et al., 2019; de Oliveira Ribeiro et al., 2020; Sakkas et al., 2020; Soundharrajan et al., 2021**). Furthermore, phytophagous probiotic foods contribute positively to metabolic health, weight regulation, and cardiovascular performance, attributed to their fiber composition and the cholesterol-reducing and anti-inflammatory properties of probiotics (**Plaza-Diaz et al., 2019; Sakkas et al., 2020; Pimentel et al., 2021**). These foods, characterized by their lactose-free composition and low allergenic potential, represent an optimal nutritional selection suitable for diverse dietary preferences and various health conditions (**Lillo-Pérez et al., 2021**). Phytophagous probiotic foods serve as a nutritionally advantageous choice for improving health by integrating plant-derived nutrition with probiotic properties (**Lillo-Pérez et al., 2021; Pimentel et al., 2021**).

In addition to their nutritional advantages, various strains of probiotics found in fermented fruit and vegetable beverages have demonstrated enhancements in multiple physiological functions and health conditions. For example, **Koh et al. (2018)** conducted an *in vitro* assay and reported the presence of consistent α-glucosidase inhibitory activity in a fermented pumpkin beverage that contained *Lactobacillus mali* K8. This inhibitory activity demonstrated an anti-hyperglycemic effect. In a separate investigation, the administration of fermented beverages derived from *Quercus convallata*, *Q. arizonica*, and oak leaves demonstrated an anti-hyperglycemic impact in both *in vitro* and *in vivo* experiments involving female mice **(Gamboa-Gómez et al., 2017)**. In a double-blind, placebo-controlled trial **(Harima-Mizusawa et al., 2016)**, the administration of a fermented citrus beverage containing *L. plantarum* YIT0132 demonstrated a favorable impact on alleviating symptoms associated with perennial allergic rhinitis in the subjects. In a laboratory-based experiment, a mixture of fermented blueberry pomace by the bacteria strains *L.*

*rhamnosus* GG, *L. plantarum*-1, and *L. plantarum*-2 exhibited a hypocholesterolemic effect, as observed *in vitro* **(Mantzourani et al., 2018)**. In addition, these fermented beverages have been demonstrated remarkable anti-fatigue properties in a swimming test using a mouse weight as the subject. In a study conducted by **Thakkar et al. (2020)**, it was shown that the addition of probiotic strains *L. fermentum* strain PD2 (derived from dosa batter) and PH5 (derived from handvo batter) effectively decreased levels of serum cholesterol, LDL cholesterol, and total cholesterol in hyperlipemic, healthy adult Wistar rats. This reduction was observed when comparing the rats that were supplemented with LAB to those that were not, despite both groups being fed the same high cholesterol diet. The results of these studies suggest the potential use of probiotics in biotherapeutics for the treatment of hypercholesterolemia in humans.

In a study conducted using *in vitro* methods, a team of researchers observed a positive alteration in the composition of the fecal microbiota community. This alteration was accompanied by the production of short chain fatty acids (SCFAs) through the fermentation of blueberry pomace by a specific strain of *L. casei* known as CICC20280 **(Cheng et al., 2020)**. In a murine model experiment, **Wang et al. (2019)** demonstrated that the ingestion of fermented beverages enriched with fruits and vegetables from Changbai Mountain can modulate the Firmicutes/Bacteroidetes ratio and enhance the abundance of the Bacteroidales S24–7 group. Recent studies have indicated that anthocyanins derived from *Opuntia ficus-indica* can alter microbial diversity and enhance the synthesis of short-chain fatty acids in animal models (**Zhang et al., 2022**). Following the administration of anthocyanins derived from *O. ficus-indica*, a significant increase in the diversity of intestinal microorganisms was observed in mice ($p < 0.05$). The Firmicutes/Bacteroidetes ratio (F/B value) exhibited a significant reduction ($p < 0.05$), which correlates strongly with the relative abundances of beneficial bacterial strains such as *Lactobacillus*, *Bifidobacterium*, *Prevotella*, and *Akkermansia* within the intestinal microbiota of mice, alongside the relative abundance of pathogenic bacterial strains including *Escherichia, Shigella* and *Desulfovibrio*. Furthermore, anthocyanins markedly elevated the concentration of short-chain fatty acids in the cecum of mice. Comparable findings were documented by **Estrada-Sierra et al. (2024)**, who utilized mucilage pectin derived from *O. ficus* and *Citrus aurantium* extract, incorporating it into a food matrix to assess its impact on the gut microbiota of individuals with normal weight and those with obesity.

The strain *L. brevis* has been assessed for its effective synthesis of γ-aminobutyric acid and angiotensin-converting enzyme I (ACE), both of which are associated with blood pressure regulation (**Peñas et al., 2015**). Subsequently, sourdough bread exhibiting anti-hypertensive properties was developed utilizing the strain. The *in vitro* fermentation of barley, involving a sequential treatment of enzymatic hydrolysis followed by fermentation using the yeast *S. cerevisiae* and subsequent bacterial fermentation with *Weissella cibaria*, resulted in the synthesis of a polysaccharide exhibiting anti-tumor activity (**Gibson et al., 2017**). The polysaccharide demonstrated antimetastatic properties by enhancing the cytolytic activity of NK cells and activating macrophages in *in vivo* studies.

Additional probiotic fermented beverages, such as those derived from tomato, blueberry-blackberry, feijoa, prickly pear, and cactus pear fruits, demonstrated a favorable anti-inflammatory capacity *in vitro* and were observed to sustain the integrity of the intestinal barrier **(Di Cagno et al., 2016; Valero-Cases et al., 2017)**. In a study conducted by **Valero-Cases et al. (2017)**, it was observed that fermented tomato juices exhibited superior enhancement of the intestinal barrier as compared to fermented feijoa juices. Fermented jabuticaba berry beverages demonstrated vasorelaxant capacity in an *in vivo* investigation conducted on male Wistar rats **(Martins de Sá et al., 2014)**. This finding points to an interesting cardiovascular preventive potential of beverages containing this ingredient.

Studies have demonstrated that plant-derived food sources harboring probiotic microorganisms exhibit immunomodulatory characteristics. A scientific investigation was undertaken to examine the impact of fermented litchi juice containing *Lacticaseibacillus casei* FL on the immune system and gut microbiota of mice. The findings demonstrated that the administration of the probiotic supplement exhibited the potential to augment the immunomodulatory function of the mouse by elevating the indices of immune organs, namely the spleen and thymus. Additionally, it stimulated the secretion of cytokines, specifically IL-2 and IL-6, as well as immunoglobulins, including IgA, IgG, and SIgA. Furthermore, it displayed a protective effect on the integrity of the intestinal tract. Moreover, it exhibits the capacity to modulate the composition of the GI microbiota and significantly augment the abundance of advantageous bacterial species, namely *Faecalibaculum*, *Lactobacillus,* and *Akkermansia* **(Wen et al., 2020)**. The results of this study indicate that the inclusion of probiotics in litchi juice could potentially enhance immune system functionality and alter the gut microbiota composition in mice.A total of 61 isolates of LAB were obtained from naturally fermented rose jams and subjected to various *in vitro* probiotic assessments, including tests for low pH tolerance, bile salt resistance, simulated gastric and pancreatic digestion, and antibiotic susceptibility. Among the analyzed isolates, *Pediococcus pentosaceus* was determined to be one of the five isolates demonstrating the most notable probiotic activity. These isolates were specifically identified as MP3, MP11, MP13, MP16, and MY8. Remarkably, the MP13 isolate exhibited probiotic properties that were on par with or even superior to the standard *Lactiplantibacillus plantarum* ATCC 8014 probiotic strain. Additionally, it demonstrated enhanced technical performance, as determined through the quantification of total phenolic compounds, flavonoid contents, and anthocyanin content. In addition, the MP13 isolate exhibited an augmentation in the sensory perception of rose jam's taste and demonstrated significant antioxidant properties, quantified using the α, α-diphenyl-β-picrylhydrazyl (DPPH) assay **(Xia et al., 2021)**. Another investigation was conducted with the objective of identifying LAB strains that possess a hypoglycemic impact and could be employed for the fermentation of apple juice **(Wang et al., 2021)**. Principal component analysis (PCA) was employed to determine the optimal strain among a set of eight LAB strains. The analysis revealed that *Limosilactobacillus fermentum* 21828 exhibited the greatest resistance to acid and bile salts, superior adhesion capabilities, notable β-glucosidase inhibitory activity, and exceptional fermentation performance. The strain's adaptability to various apple juice types was also assessed. The Aksu apple juice exhibited the highest attainable count of viable microorganisms, specifically $3.40 \times 10^8$ CFU/mL, after undergoing fermentation by the strain *Limosilactobacillus fermentum* 21828. This fermentation process resulted in a sensory score of 84.33%, as reported in reference **(Wang et al., 2021)**.

Autochthonous strains of L. plantarum S-811 and S-TF2, along with *Fructobacillus fructosus* S-TF7, isolated from fermented cactus pear juice, exhibited antimicrobial activities against various pathogenic bacteria, including *Staphylococcus aureus* ATCC 29213, *Escherichia coli* ATCC 25922, *Pseudomonas aeruginosa* ATCC 27853, *Salmonella typhimurium* ATCC 14028, and *Listeria monocytogenes* CLIP 74910, as reported in a study conducted by **Verón et al. (2023)**. The findings indicated a safety profile characteristic of LAB in *in vitro* studies, and the juice fermented with these strains maintained the content of phenolic compounds and the antioxidant activity found in unfermented juice. **Hernández-Carranza et al. (2019**) demonstrated that cactus pear peel and its mucilage impart a vibrant magenta color to yogurts. Furthermore, yogurt containing 5.5% cactus pear peel and 7.5% mucilage exhibits the highest levels of bioactive compounds and antioxidant capacity. Additionally, these activities were significantly enhanced ($p < 0.05$) following the simulated GI process. The correlation may exist with the activity of GI enzymes such as pepsin and pancreatin, as well as the acidic conditions present during the gastric phase.

Ting, a traditional African food produced through the natural fermentation of sorghum, underwent fermentation with the incorporation of *L. fermentum* strains. It is significant to highlight that, in addition to its nutritional advantages, the levels of mycotoxins were reduced by as much as 98% across all fermented samples (**Adebo et al., 2019**). In a manner akin to this, conventional fermentation methods decreased the concentration of mycotoxin in two widely consumed traditional cereal-based African beverages—kunu-zaki and pito—by 59% and 99%, respectively (**Ezekiel et al., 2015**).

The process of fermentation utilizing probiotic microorganisms enhances the nutritional value of germinated rice by enriching it with natural dietary fibers, inositol hexaphosphate, and γ-aminobutyric acid **(Hung et al., 2005)**. The fermentation process conducted by *L. plantarum* dy-1 resulted in a transformation of β-glucan, changing its configuration from a compact rod-shaped form in raw barley to a smooth sheet-like structure in the fermented barley (**Struyf et al., 2017**). As per the findings of **Ray et al. (2016)**, various pyranose derivatives, such as 1,2,3,6-tetra-*O*-acetyl-4-*O*-formyl-D-glucopyranose, β-D-mannopyranose pentaacetate, 2,3,4,5-tetra-O-acetyl-1-deoxy-β-D-glucopyranose, and β-D-galactopyranose pentaacetate, undergo accumulation during the process of fermentation in haria (a locally produced rice beer). These derivatives exhibit notable immune-stimulatory, antioxidant, and antimutagenic properties. Furthermore, the rice beer contains various oligosaccharides, phenolics, and flavonoids that exhibit noteworthy capabilities in scavenging free radicals. These properties have the potential to mitigate the likelihood of developing cardiovascular ailments and other degenerative diseases **(Ghosh et al., 2015)**. The fermentation process of plant substrates by LAB is contingent upon their inherent ability to rapidly adjust and utilize the available nutritional components, including phenolic compounds (**Filannino et al., 2018**). This adaptation is tailored to each species and bacterial strain, exhibiting significant variability depending on the plant matrix. Additionally, a category of bacteria referred to as plant probiotics, specifically 'Plant Growth Promoting Rhizobacteria,' possesses the capability to colonize the roots of plants. These bacteria facilitate plant growth through various direct and indirect mechanisms, enhance the nutritional content of plants, and elevate the quality of crops (**Jiménez Gómez et al., 2017**).The fermented plant-based foods and beverages market has witnessed a surge in growth attributed to heightened recognition of their health-promoting properties and the enduring impact of the COVID-19 pandemic.

## 5. Veganism and Market Dynamic in Phytophagous Foods

Both vegetarianism and veganism can be traced back to the etymology of the Latin term "vegetus," denoting a state of well-being and vitality. The International Vegetarian Union has established a comprehensive definition of vegetarianism as a dietary preference characterized by the deliberate exclusion of meat, fish, and their byproducts from one's regular food consumption. This choice is primarily motivated by ethical, religious, or environmental considerations. However, it is important to note that vegetarianism does allow for the consumption of milk, dairy products, and eggs. The Vegetarian Society holds the distinction of being the inaugural society globally that is exclusively committed to the promotion and advocacy of the vegetarian lifestyle **(Hoek et al., 2004)**.

Preferences of consumers shift throughout time, and there is a current movement toward a higher level of health consciousness as well as concern for the nutritional value of food and the long-term sustainability of the food supply chain. Because of this, manufacturers have been placing a larger emphasis on promoting products that contain healthful ingredients. Therefore, the quality of the food and the concept of added value based on the utility of the food are essential components for successful marketing and the widespread adoption of novel foods **(Shafie et al., 2012)**. The food industry sees vegetarian and vegan consumers as a potentially lucrative market and has begun devoting greater resources to the promotion of smaller organic and vegan food producers as a result. In addition to this, they are formulating plans to market meat substitutes to customers who do not follow a vegetarian diet. However, it is essential to emphasize that the marketing of food products shouldn't solely center on the positive effects they have on consumers' health and the environment **(Hoek et al., 2004)**. The European Food Safety Authority (EFSA) in Europe issued a call to action to the European Commission, urging them to comply with Article 36.3 of Regulation (EU) 1169/2011 on Information to Food Consumers. This article has stated that the Commission requires the establishment of operational procedures for voluntary nutritional information related to the appropriateness of food for vegetarians or vegans. The objective of this initiative was to develop a comprehensive checklist delineating the fundamental constituents that must be included in vegan or vegetarian food, with the purpose of ascertaining the criteria for determining the suitability of the food for these dietary preferences. In essence, what are the essential criteria that must be satisfied in order to categorize a food preparation as appropriate for individuals adhering to vegetarian dietary practices or the philosophy of vegetarianism?

Upon conducting a comprehensive analysis of the existing legal framework, it becomes apparent that there is presently an absence of an official delineation as well as established regulations pertaining to the production and labeling criteria for the category of plant-based food products. Hence, individuals adhering to plant-based dietary preferences face challenges in discerning between probiotic products that are authentically derived from plants and those that incorporate animal-derived constituents **(Sakkas et al., 2020)**. The absence of a precise delineation and established criteria for the phytophagous food category engenders perplexity within the industry and among consumers, thereby exerting an adverse influence on the expansion of phytophagous probiotic commodities and impeding the seamless movement of products. The implementation of a formal regulatory framework would confer advantages to the industry by facilitating the dissemination of information regarding the lack of animal-derived constituents in their merchandise to their intended consumer base. Furthermore, the potential for consumers to be misinformed could be mitigated **(Lillo-Pérez et al., 2021)**. Given the scarcity of research pertaining to the proliferation of products targeting the phytophagous market, the data gathered in this study may hold significant value in formulating efficacious approaches for the development of functional phytophagous products. This information could be of particular significance to retailers specializing in phytophagous food products.

## 6. Future Directions, Research Opportunities and Concluding Insights in Phytophagous Probiotic Foods

Probiotic microorganisms, such as LAB, *Bifidobacterium*, and *Saccharomyces boulardii*, are experiencing an increase in demand within the dairy and non-dairy food industries owing to their advantageous health-related effects **(Shahein et al., 2022)**. As a result, there has been a notable surge in the worldwide market demand for probiotics incorporated in food products, positioning them as the foremost category within the realm of functional foods. Soy milk and almond milk are two widely consumed exemplars of these non-dairy plant-based beverages. These products exhibit a visually appealing, smooth, and opaque texture and can be employed in the formulation of diverse plant-based culinary products, such as soy-based cheese, soy-based yogurt, and tofu, through the utilization of probiotic microorganisms. The perception of sensory qualities by consumers plays a vital role in the context of large-scale industrial production. It is important to preserve the sensory attributes of these products, as consumers have a tendency to reject functional foods that exhibit peculiar tastes or odors, despite their primary motivation being the health advantages of consuming probiotics **(Elkot et al., 2022)**. Almonds are a highly concentrated reservoir of essential nutrients, such as α-tocopherol, which plays a crucial role in mitigating oxidative stress. Additionally, almonds exhibit a notable abundance of monounsaturated fatty acids, which have the potential to confer cardiovascular benefits **(Lipan et al., 2021)**. Therefore, the integration of probiotics in fermented products based on almond milk also demonstrates a favorable outlook.

Fermented vegetables such as kimchi, sauerkraut, and other fruit and vegetable-based fermented beverages show potential for utilizing beneficial probiotic microorganisms. However, it is necessary to alter their sensory characteristics based on consumer feedback, which can be obtained through a comprehensive survey conducted on a large scale. This will facilitate the expansion of the global market for functional plant-based probiotic products, as the sensory attributes may exhibit regional variations. The identical methodology should be employed for probiotic functional foods derived from cereals. Furthermore, it is imperative to employ innovative methodologies such as microencapsulation in order to augment the survivability of probiotics in various plant-derived products. This will consequently facilitate the implementation of controlled drug release mechanisms and enable sustained therapeutic outcomes for the treatment of targeted diseases or the enhancement of overall well-being. Furthermore, the predominant body of research investigating the health-enhancing or therapeutic properties of non-dairy probiotics primarily consists of *in vitro* and in vivo studies utilizing animal models. Consequently, it is imperative to conduct intervention studies in humans to assess the physiological impact on health improvement in the future. Moreover, the results of various studies can be influenced by the diverse plant matrices, such as vegetables, fruits, or cereal beverages. Hence, to augment the abundance of phytophagous probiotic products, it is imperative to undertake the development and exploration of novel matrices. Thus, there are a lot of promising opportunities for further study in the area of phytophagous probiotic foods (**Table-5**). New probiotic strains that thrive in plant-based environments, as well as ways to make them more stable and effective, are important research priorities. Studying how different plant-based food components interact with probiotics, finding the best way to ferment foods, and increasing their bioavailability and health benefits are all areas that may need more investigation. Further opportunities exist to learn about consumer preferences, improve sensory qualities, and evaluate production processes in terms of their sustainability and environmental effects. Future research should also focus on establishing regulatory criteria and assessing long-term health consequences. In sum, there are many chances for research to improve the development of phytophagous probiotic foods, which in turn may improve public health outcomes, contribute to a more sustainable food sector, and raise awareness about the need to eat healthily.

Phytophagous probiotic supplements have been found to potentially offer various advantages, such as enhancing lipid profiles and immune systems, regulating diabetes, mitigating bacterial infections, demonstrating anticarcinogenic properties, and promoting overall health. The production of premium plant-based food products incorporating these supplements necessitates careful consideration of various factors, including the genetic lineage of the strain, the techniques employed during processing, the composition of the food matrix, the specific probiotic strain employed, the strain's unique effects, optimal environmental conditions, and the inclusion of prebiotic nutrients. Nevertheless, the current progress in the industrial advancement of phytophagous food products enhanced with probiotics is constrained by the predominant utilization of animal milk in research studies and the prevalent reliance on probiotic strains derived from human, animal, or associated sources. In order to effectively cater to the growing and promising market segment, it is imperative to establish standardized protocols for phytophagous products. Additionally, marketing strategies should be tailored towards consumers who are actively seeking to reduce their consumption of animal products. Furthermore, it is crucial to develop practical and easily accessible regulations that can be implemented by the industry.

## References

1. Abaci, N., Deniz, F. S. S., & Orhan, I. E. (2022). Kombucha–An ancient fermented beverage with desired bioactivities: A narrowed review. *Food chemistry: X*, *14*, 100302.

2. Adebo O.A., Kayitesi E., Njobeh P.B. Reduction of mycotoxins during fermentation of whole Grain sorghum to whole grain Ting (a southern African Food) *Toxins* 2019,11:180. doi: 10.3390/toxins11030180.
3. Ashaolu, T.J.; Reale, A. A Holistic Review on Euro-Asian Lactic Acid Bacteria Fermented Cereals and Vegetables. *Microorganisms* 2020, *8*, 1–24.
4. Atwaa, E.; Elmaadawy, A.; Awaad, E. Production of Fruit Flavored Probiotic Rice Milk Beverage. *Journal of Food and Dairy Sciences* 2019, *10*, 453–458, doi:10.21608/jfds.2019.71360.
5. Aydar, A. Y. (2023). An Overview of Plant-Based Food Alternatives (PBFAs): Classification, Textural and Sensory Characteristics. *Plant-Based Foods: Ingredients, Technology and Health Aspects*, 1-17.
6. Barbosa, M.L.S.; de Alencar, E.R.; Leandro, E. dos S.; Borges, R.M.; Mendonça, M.A.; Ferreira, W.F. de S. Characterization of Fermented Beverages Made with Soybean and Brazil Nut Hydrosoluble Extracts. *Int J Gastron Food Sci* 2020, *21*, doi:10.1016/j.ijgfs.2020.100228.
7. Borah, T.; Gogoi, B.; Khataniar, A.; Gogoi, M.; Das, A.; Borah, D. Probiotic characterization of indigenous *Bacillus velezensis* strain DU14 isolated from Apong, a traditionally fermented rice beer of Assam. *Biocatalysis and agricultural biotechnology*. 2019, 1(18), 101008.
8. Canaviri Paz, P.; Janny, R.J.; Håkansson, Å. Safeguarding of Quinoa Beverage Production by Fermentation with Lactobacillus Plantarum DSM 9843. *Int J Food Microbiol* 2020, *324*, doi:10.1016/j.ijfoodmicro.2020.108630.
9. Chen, P., Xu, T., Zhang, C., Tong, X., Shaukat, A., He, Y., ... & Huang, S. (2022). Effects of probiotics and gut microbiota on bone metabolism in chickens: a review. *Metabolites*, *12*(10), 1000.
10. Cosme, F.; Inês, A.; Vilela, A. Consumer's Acceptability and Health Consciousness of Probiotic and Prebiotic of Non-Dairy Products. *Food Research International* 2022, *151*, 110842, doi:10.1016/j.foodres.2021.110842.
11. Das, S.; Deb, D.; Adak, A.;  Khan, M. R. Exploring the microbiota and metabolites of traditional rice beer varieties of Assam and their functionalities. *3 Biotech*, 2019, *9*(5), 174. https://doi.org/10.1007/s13205-019-1702-z
12. de Almeida Bianchini Campos, R.C.; Martins, E.M.F.; de Andrade Pires, B.; do Carmo Gouveia Peluzio, M.; da Rocha Campos, A.N.; Ramos, A.M.; de Castro Leite Júnior,

B.R.; de Oliveira Martins, A.D.; da Silva, R.R.; Martins, M.L. In Vitro and in Vivo Resistance of *Lactobacillus rhamnosus* GG Carried by a Mixed Pineapple (*Ananas comosus* L. Merril) and Jussara (*Euterpe edulis* Martius) Juice to the Gastrointestinal Tract. *Food Research International* 2019, *116*, 1247–1257, doi:10.1016/j.foodres.2018.10.012.

13. de Godoy Alves Filho, E.; Rodrigues, T.H.S.; Fernandes, F.A.N.; Pereira, A.L.F.; Narain, N.; de Brito, E.S.; Rodrigues, S. Chemometric Evaluation of the Volatile Profile of Probiotic Melon and Probiotic Cashew Juice. *Food Research International* 2017, *99*, 461–468, doi:10.1016/j.foodres.2017.05.030.
14. de Oliveira Ribeiro, A.P.; Gomes, F. dos S.; Maria Olbrich dos Santos, K.; da Matta, V.M.; Freitas de Sá, D. de G.C.; Santiago, M.C.P. de A.; Conte, C.; de Oliveira Costa, S.D.; Oliveira Ribeiro, L. de; de Oliveira Godoy, R.L.; et al. Development of a Probiotic Non-Fermented Blend Beverage with Juçara Fruit: Effect of the Matrix on Probiotic Viability and Survival to the Gastrointestinal Tract. *LWT* 2020, *118*, doi:10.1016/j.lwt.2019.108756.
15. Di Cagno, R.; Filannino, P.; Vincentini, O.; Lanera, A.; Cavoski, I.; Gobbetti, M. Exploitation of *Leuconostoc mesenteroides* strains to improve shelf life, rheological, sensory and functional features of prickly pear (*Opuntia ficus-indica* L.) fruit puree. *Food Microbiol.* 2016, 59, 176–189. doi: 10.1016/j.fm.2016.06.009.
16. do Nascimento, L. C. P., Neto, J. P. R. C., de Almeida Callou, K. R., Dejani, N. N., & de Brito Alves, J. L. (2022). Probiotics for liver disease prevention and treatment. In *Probiotics for Human Nutrition in Health and Disease* (pp. 579-588). Academic Press.
17. Elkot, W. F.; Khalil, O. S. Physicochemical, textural, microbiological and sensory properties of low-fat bio-Labneh using sweet lupine powder and *Bifidobacterium longum* ATCC 15707. *Journal of Food Processing and Preservation*, 2022, *46*(3), e16311.
18. Elvan, M.; Baysal, A.H.; Harsa, Ş. Microencapsulation of a Potential Probiotic LactiplantibacillusPentosus and Its Impregnation onto Table Olives. *LWT* 2021, 112975, doi:10.1016/j.lwt.2021.112975.
19. Estrada-Sierra, N.A.; Gonzalez-Avila, M.; Urias-Silvas, J.-E.; Rincon-Enriquez, G.; Garcia-Parra, M.D.; Villanueva-Rodriguez, S.J. The Effect of *Opuntia ficus* Mucilage Pectin and *Citrus aurantium* Extract Added to a Food Matrix on the Gut Microbiota of

Lean Humans and Humans with Obesity. *Foods* **2024**, *13*, 587. https://doi.org/10.3390/foods13040587

20. Ezekiel C.N.; Abia W.A.; Ogara I.M.; Sulyok M.; Warth B.; Krska R. Fate of mycotoxins in two popular traditional cereal-based beverages (kunu-zaki and pito) from rural Nigeria. LWT Food Science & Technology 2015, 60:137–141. doi: 10.1016/j.lwt.2014.08.018.
21. Fijan, S., Fijan, P., Wei, L., & Marco, M. L. (2024). Health Benefits of Kimchi, Sauerkraut, and Other Fermented Foods of the Genus Brassica. *Applied Microbiology*, *4*(3), 1165-1176.
22. Filannino, P.; Di Cagno, R.; Gobbetti, M. Metabolic and functional paths of lactic acid bacteria in plant foods: Get out of the labyrinth. *Current Opinion in Biotechnology* 2018. *49*, pp.64-72. https://doi.org/10.1016/j.copbio.2017.07.016
23. FMI (Future Market Insights) (2023). Plant-Based Food Market Outlook (2023 to 2033). Accessed on 30th July 2023. URL https://www.futuremarketinsights.com/reports/plant-based-food-market
24. Gamboa-Gómez, C.I.; Simental-Mendía, L.E.; González-Laredo, R.F.; Alcantar-Orozco E.J.; Monserrat-Juarez V.H.; Ramírez-Espana, J.C.; Gallegos-Infante, J.A.; Moreno-Jiménez, M.R.; Rocha-Guzmán, N.E. In vitro and in vivo assessment of anti-hyperglycemic and antioxidant effects of Oak leaves (*Quercus convallata* and *Quercus arizonica*) infusions and fermented beverages. *Food Res. Int.* 2017, 102, 690–699. doi: 10.1016/j.foodres.2017.09.040.
25. Gibson, G.R.; Hutkins, R.; Sanders, M.E.; Prescott, S.L.; Reimer, R.A.; Salminen, S.J.;et al. Expert consensus document: The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of prebiotics. *Nature reviews Gastroenterology & hepatology* 2017 *14*(8), pp.491-502. doi: 10.1038/nrgastro.2017.75.
26. Hashemi, S.M.B.; Jafarpour, D. Fermentation of Bergamot Juice with *Lactobacillus plantarum* Strains in Pure and Mixed Fermentations: Chemical Composition, Antioxidant Activity and Sensorial Properties. *LWT* 2020, *131*, doi:10.1016/j.lwt.2020.109803.
27. Hernández-Carranza, P.; Jattar-Santiago, K.Y.; Avila-Sosa, R.; Pérez-Xochipa, I.; Guerrero-Beltrán, J.A.; Ochoa-Velasco, C.E.; Ruiz-López, I.I., Antioxidant fortification

of yogurt with red cactus pear peel and its mucilage. *Cyta-journal of Food* 2019. *17*(1), pp.824-833. https://doi.org/10.1080/19476337.2019.1654548

28. Hung, C.-L. (2005). Health food processing process using germinated rice to make health food containing natural eatable fibers, GABA, IP6, and Probiotic. U.S. Patent 6,977,093, issued December 20, 2005.
29. Ilango, S.; Pandey, R.; Antony, U. Functional characterization and microencapsulation of probiotic bacteria from koozh. *Journal of food science and technology*, 2016, *53*, 977-989.
30. Jackson, S.A.; Schoeni, J.L.; Vegge, C.; Pane, M.; Stahl, B.; Bradley, M.; Goldman, V.S.; Burguière, P.; Atwater, J.B.; Sanders, M.E. Improving End-User Trust in the Quality of Commercial Probiotic Products. *Front Microbiol* 2019, *10*, doi:10.3389/fmicb.2019.00739.
31. Jayarathna, S.; Priyashantha, H.; Johansson, M.; Vidanarachchi, J.K.; Jayawardana, B.C.; Liyanage, R. Probiotic Enriched Fermented Soy-Gel as a Vegan Substitute for Dairy Yoghurt. *J Food Process Preserv* 2021, *45*, doi:10.1111/jfpp.15092.
32. Jiménez Gómez, A.; Celador Lera, L.; Fradejas Bayón, M.; Rivas, R. Plant probiotic bacteria enhance the quality of fruit and horticultural crops. *AIMS Microbiology* 2017 Jun 19;3(3):483-501. doi: 10.3934/microbiol.2017.3.483.
33. Jung, S.; Hwang, H.; Lee, J.H. Effect of Lactic Acid Bacteria on Phenyllactic Acid Production in Kimchi. *Food Control* 2019, *106*, doi:10.1016/j.foodcont.2019.06.027.
34. Kasapoglu, M. Z., Sagdic, O., Avci, E., Tekin-Cakmak, Z. H., Karasu, S., & Turker, R. S. (2023). The potential use of cold-pressed coconut oil by-product as an alternative source in the production of plant-based drink and plant-based low-fat ice cream: The rheological, thermal, and sensory properties of plant-based ice cream. *Foods*, *12*(3), 650.
35. Khalil, O.S.F.; Ismail, H.A.; Elkot, W.F. Physicochemical, Functional and Sensory Properties of Probiotic Yoghurt Flavored with White Sapote Fruit (*Casimiroa Edulis*). *J Food Sci Technol* 2022, doi:10.1007/s13197-022-05393-5.
36. Koh, J. H., Kim, Y., & Oh, J. H. (2010). Chemical characterization of tomato juice fermented with bifidobacteria. *Journal of Food Science*, *75*(5), C428-C432.
37. Koh, W.Y.; Uthumporn, U.; Rosma, A.; Irfan, A.R.; Park, Y.H. Optimization of a fermented pumpkin-based beverage to improve *Lactobacillus mali* survival and α-

glucosidase inhibitory activity: A response surface methodology approach. *Food Sci. Hum. Wellness.* 2018, 7, 57–70. doi: 10.1016/j.fshw.2017.11.001.

38. Küçükgöz, K.; Trząskowska, M. Nondairy Probiotic Products: Functional Foods That Require More Attention. *Nutrients*, 2022, *14*(4), 753. https://doi.org/10.3390/nu14040753
39. Kumar, M.; Tomar, M.; Potkule, J.; Reetu; Punia, S.; Dhakane-Lad, J.; Singh, S.; Dhumal, S.; Chandra Pradhan, P.; Bhushan, B.; et al. Functional Characterization of Plant-Based Protein to Determine Its Quality for Food Applications. *Food Hydrocoll* 2022, *123*.
40. Lan, G.; Li, C.; He, L.; Zeng, X.; Zhu, Q. Effects of Different Strains and Fermentation Method on Nattokinase Activity, Biogenic Amines, and Sensory Characteristics of Natto. *J Food Sci Technol*, 2020, *57*, 4414–4423, doi:10.1007/s13197-020-04478-3.
41. Lanza, B.; Zago, M.; Di Marco, S.; Di Loreto, G.; Cellini, M.; Tidona, F.; Bonvini, B.; Bacceli, M.; Simone, N. Single and Multiple Inoculum of Lactiplantibacillus Plantarum Strains in Table Olive Lab-Scale Fermentations. *Fermentation* 2020, *6*, doi:10.3390/fermentation6040126.
42. Lee, J.J.; Choi, Y.J.; Lee, M.J.; Park, S.J.; Oh, S.J.; Yun, Y.R.; Min, S.G.; Seo, H.Y.; Park, S.H.; Lee, M.A. Effects of Combining Two Lactic Acid Bacteria as a Starter Culture on Model Kimchi Fermentation. *Food Research International* 2020, *136*, doi:10.1016/j.foodres.2020.109591.
43. Li, Q.; Xia, Y.; Zhou, L.; Xie, J. Evaluation of the Rheological, Textural, Microstructural and Sensory Properties of Soy Cheese Spreads. *Food and Bioproducts Processing*2013, *91*, 429–439, doi:10.1016/j.fbp.2013.03.001.
44. Lillo-Pérez, S.; Guerra-Valle, M.; Orellana-Palma, P.; Petzold, G. Probiotics in Fruit and Vegetable Matrices: Opportunities for Nondairy Consumers. *LWT* 2021, *151*.
45. Lipan, L.; Rusu, B.; Simon, E.L.; Sendra, E.; Hernández, F.; Vodnar, D.C.; Corell, M.; Carbonell-Barrachina, Á. Chemical and Sensorial Characterization of Spray Dried HydroSOStainable Almond Milk. *J Sci Food Agric* 2021, *101*, 1372–1381, doi:10.1002/jsfa.10748.
46. Majid, A.A.; Suroto, D.A.; Utami, T.; Rahayu, E.S. Probiotic Potential of Kombucha Drink from Butterfly Pea (ClitoriaTernatea L.) Flower with the Addition of *Lactiplantibacillus plantarum* Subsp. *plantarum* Dad-13. *Biocatal Agric Biotechnol*2023, *51*, 102776, doi:10.1016/j.bcab.2023.102776.

47. Masenga, S. K., Hamooya, B., Hangoma, J., Hayumbu, V., Ertuglu, L. A., Ishimwe, J., ... & Kirabo, A. (2022). Recent advances in modulation of cardiovascular diseases by the gut microbiota. *Journal of Human Hypertension*, *36*(11), 952-959.
48. Masiá, C., Geppel, A., Jensen, P. E., & Buldo, P. (2021). Effect of Lactobacillus rhamnosus on physicochemical properties of fermented plant-based raw materials. *Foods*, *10*(3), 573.
49. Mazziotta, C., Tognon, M., Martini, F., Torreggiani, E., & Rotondo, J. C. (2023). Probiotics mechanism of action on immune cells and beneficial effects on human health. *Cells*, *12*(1), 184.
50. Miguel, I.; Coelho, A.; Bairrada, C.M. Modelling Attitude towards Consumption of Vegan Products. *Sustainability (Switzerland)* 2021, *13*, 1–17, doi:10.3390/su13010009.
51. Min, M.; Bunt, C.R.; Mason, S.L.; Hussain, M.A. Non-Dairy Probiotic Food Products: An Emerging Group of Functional Foods. *Crit Rev Food Sci Nutr* 2019, *59*, 2626–2641.
52. Miranda, J.S.; Costa, B.V.; de Oliveira, I.V.; de Lima, D.C.N.; Martins, E.M.F.; de Castro Leite Júnior, B.R.; Almeida do Nascimento Benevenuto, W.C.; Campelo de Queiroz, I.; Ribeiro da Silva, R.; Martins, M.L. Probiotic Jelly Candies Enriched with Native Atlantic Forest Fruits and Bacillus Coagulans GBI-30 6086. *LWT* 2020, *126*, doi:10.1016/j.lwt.2020.109275.
53. Montazersaheb, H., Zamani, A. A., Sharifi, R., & Darbemamieh, M. (2021). Effects of plant probiotic bacteria and herbivore-induced plant volatiles on life table parameters of Tetranychus urticae (Acari: Tetranychidae) on kidney bean's attached leaves. *International Journal of Acarology*, *47*(6), 520-527.
54. Montero, M. L., & Ross, C. F. (2023). Physiology of Sensory Perception. In *The Sensory Evaluation of Dairy Products* (pp. 19-52). Cham: Springer International Publishing.
55. Mouritsen, O. G., & Styrbæk, K. (2020). Design and 'umamification'of vegetable dishes for sustainable eating. *International Journal of Food Design*, *5*(1-2), 9-42.
56. Nguyen, B.T.; Bujna, E.; Fekete, N.; Tran, A.T.M.; Rezessy-Szabo, J.M.; Prasad, R.; Nguyen, Q.D. Probiotic Beverage from Pineapple Juice Fermented with Lactobacillus and Bifidobacterium Strains. *Front Nutr* 2019, *6*, doi:10.3389/fnut.2019.00054.
57. Niamah, A.K. Physicochemical and Microbial Characteristics of Yogurt with Added Saccharomyces Boulardii. *Current Research in Nutrition and Food Science* 2017, *5*, 300–307, doi:10.12944/CRNFSJ.5.3.15.

58. Niamah, A.K. Ultrasound Treatment (Low Frequency) Effects on Probiotic Bacteria Growth in Fermented Milk. *Future of Food: Journal on Food, Agriculture and Society* 2019, *7*, 1–8, doi:10.17170/kobra-20190709592.
59. Niamah, A.K.; Gddoa Al-Sahlany, S.T.; Ibrahim, S.A.; Verma, D.K.; Thakur, M.; Singh, S.; Patel, A.R.; Aguilar, C.N.; Utama, G.L. Electro-Hydrodynamic Processing for Encapsulation of Probiotics: A Review on Recent Trends, Technological Development, Challenges and Future Prospect. *Food Biosci* 2021, *44*.
60. Niamah, A.K.; Sahi, A.A.; Al-Sharifi, A.S.N. Effect of Feeding Soy Milk Fermented by Probiotic Bacteria on Some Blood Criteria and Weight of Experimental Animals. *Probiotics Antimicrob Proteins* 2017, doi:10.1007/s12602-017-9265-y.
61. Peñas E.; Diana M.; Frias J.; Quílez J.; Martínez-Villaluenga C. A Multistrategic Approach in the Development of Sourdough Bread Targeted Towards Blood Pressure Reduction. Plant Foods in Human Nutrition 2015, 70:97–103. doi: 10.1007/s11130-015-0469-6.
62. Pereira, A.L.F.; Feitosa, W.S.C.; Abreu, V.K.G.; Lemos, T. de O.; Gomes, W.F.; Narain, N.; Rodrigues, S. Impact of Fermentation Conditions on the Quality and Sensory Properties of a Probiotic Cupuassu (Theobroma Grandiflorum) Beverage. *Food Research International* 2017, *100*, 603–611, doi:10.1016/j.foodres.2017.07.055.
63. Pimentel, T. C., Da Costa, W. K. A., Barão, C. E., Rosset, M., & Magnani, M. (2021). Vegan probiotic products: A modern tendency or the newest challenge in functional foods. *Food Research International*, *140*, 110033. doi:10.1016/j.foodres.2020.110033.
64. Plaza-Diaz, J.; Ruiz-Ojeda, F.J.; Gil-Campos, M.; Gil, A. Mechanisms of Action of Probiotics. *In*: Proceedings of the Advances in Nutrition; Oxford University Press, January 1 2019; Vol. 10, pp. S49–S66.
65. Pua, A., Tang, V. C. Y., Goh, R. M. V., Sun, J., Lassabliere, B., & Liu, S. Q. (2022). Ingredients, processing, and fermentation: addressing the organoleptic boundaries of plant-based dairy analogues. *Foods*, *11*(6), 875.
66. Qamaruz-Zaman, N., Yaacof, N., & Kamarzaman, F. F. (2020). Control of odors in the food industry. In *The Interaction of Food Industry and Environment* (pp. 281-313). Academic Press.
67. Rasika, D. M. D., Vidanarachchi, J. K., Luiz, S. F., Azeredo, D. R. P., Cruz, A. G., & Ranadheera, C. S. (2021). Probiotic delivery through non-dairy plant-based food matrices. *Agriculture, 11*(7), 599.

68. Ray, M.; Ghosh, K.; Singh, S.; Mondal, K. C. Folk to functional: an explorative overview of rice-based fermented foods and beverages in India. *Journal of Ethnic Foods*, 2016, *3*(1), 5-18.
69. Ren, W., Liang, H., Liu, S., Li, Y., Chen, Y., Li, B., & Li, J. (2024). Formulations and assessments of structure, physical properties, and sensory attributes of soy yogurts: Effect of carboxymethyl cellulose content and degree of substitution. *International Journal of Biological Macromolecules*, *257*, 128661.
70. Ryan, J.; Hutchings, S.C.; Fang, Z.; Bandara, N.; Gamlath, S.; Ajlouni, S.; Ranadheera, C.S. Microbial, Physico-Chemical and Sensory Characteristics of Mango Juice-Enriched Probiotic Dairy Drinks. *Int J Dairy Technol* 2020, *73*, 182–190, doi:10.1111/1471-0307.12630.
71. Sajankila, N., Wala, S. J., Ragan, M. V., Volpe, S. G., Dumbauld, Z., Purayil, N., ... & Besner, G. E. (2023). Current and future methods of probiotic therapy for necrotizing enterocolitis. *Frontiers in pediatrics*, *11*, 1120459.
72. Sakkas, H.; Bozidis, P.; Touzios, C.; Kolios, D.; Athanasiou, G.; Athanasopoulou, E.; Gerou, I.; Gartzonika, C. Nutritional Status and the Influence of the Vegan Diet on the Gut Microbiota and Human Health. *Medicina (Lithuania)* 2020, *56*.
73. Samedi, L.; Charles, A.L. Isolation and Characterization of Potential Probiotic Lactobacilli from Leaves of Food Plants for Possible Additives in Pellet Feeding. *Annals of Agricultural Sciences* 2019, *64*, 55–62, doi:10.1016/j.aoas.2019.05.004.
74. Sasaki, H.; Pham Thi Ngoc, D.; Nishikawa, M.; Kanauchi, M. Lipopolysaccharide Neutralizing Protein in Miso, Japanese Fermented Soybean Paste. *J Food Sci*2020, *85*, 2498–2505, doi:10.1111/1750-3841.15315.
75. Shahein, M. R.; Atwaa, E. S. H.; Elkot, W. F.; Hijazy, H. H. A.; Kassab, R. B.; Alblihed, M. A.; Elmahallawy, E. K. The impact of date syrup on the physicochemical, microbiological, and sensory properties, and antioxidant activity of bio-fermented camel milk. *Fermentation*, 2022, *8*(5), 192.
76. Sharma, K.; Attri, S.; Goel, G. Selection and Evaluation of Probiotic and Functional Characteristics of Autochthonous Lactic Acid Bacteria Isolated from Fermented Wheat Flour Dough Babroo. *Probiotics Antimicrob Proteins* 2019, *11*, 774–784, doi:10.1007/s12602-018-9466-z.

77. Shivangi, S.; Devi, P.B.; Ragul, K.; Shetty, P.H. Probiotic Potential of Bacillus Strains Isolated from an Acidic Fermented Food Idli. *Probiotics Antimicrob Proteins* 2020, *12*, 1502–1513, doi:10.1007/s12602-020-09650-x.
78. Sobal, J.; Bisogni, C.A.; Jastran, M. Food Choice Is Multifaceted, Contextual, Dynamic, Multilevel, Integrated, and Diverse. *Mind, Brain, and Education*, 2014, *8*(1), 6-12.
79. Son, S.H.; Yang, S.J.; Jeon, H.L.; Yu, H.S.; Lee, N.K.; Park, Y.S.; Paik, H.D. Antioxidant and Immunostimulatory Effect of Potential Probiotic Lactobacillus Paraplantarum SC61 Isolated from Korean Traditional Fermented Food, Jangajji. *MicrobPathog* 2018, *125*, 486–492, doi:10.1016/j.micpath.2018.10.018.
80. Soundharrajan, I.; Yoon, Y.H.; Muthusamy, K.; Jung, J.-S.; Lee, H.J.; Han, O.-K.; Choi, K.C. Isolation of Lactococcus Lactis from Whole Crop Rice and Determining Its Probiotic and Antimicrobial Properties towards Gastrointestinal Associated Bacteria. *Microorganisms* 2021, *9*, 2513, doi:10.3390/microorganisms9122513.
81. Springmann, M.: Clark, M.; Mason-D’Croz, D.; Wiebe, K.; Bodirsky, B. L.; Lassaletta, L.; et al. Options for keeping the food system within environmental limits. *Nature*. 2018, 562(7728), 519–25. doi:10.1038/ s41586-018-0594-0
82. Struyf, N.; Laurent, J.; Verspreet, J.; Verstrepen, K.J.; Courtin, C.M. *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* cocultures allow reduction of fermentable oligo-, di-, and monosaccharides and polyols levels in whole wheat bread. *Journal of Agricultural and Food Chemistry* 2017.*65*(39), pp.8704-8713. doi: 10.1021/acs.jafc.7b02793.
83. Subhashree, S.; Kavita, M.S. A Study on Suitable Non Dairy Food Matrix for Probiotic Bacteria - A Systematic Review. *Current Research in Nutrition and Food Science* 2019, *7*, 5–16.
84. Suharyono S.; Rizal S.; Astuti S.; Amalia R, Effect of Wheat Flour and oow Temperature Storage to Shelf Life and Sensory Properties of Probiotic Soy Tempeh. *Jurnal Agroindustri*. 2019 Jun 27;9(1):37-48. doi:10.31186/j.agroind.
85. Tamminen, M.; Salminen, S.; Ouwehand, A.C. *Fermentation of Carrot Juice by Probiotics: Viability and Preservation of Adhesion*, *International Journal of Biotechnology for Wellness Industries*, 2013,2 (1), 10.
86. Tayo, B.A.; Akpeji, S. Probiotic Viability, Physicochemical and Sensory Properties of Probiotic Pineapple Juice. *Fermentation*2016, *2*, doi:10.3390/fermentation2040020.

87. Thakkar, P. N.; Patel, A.; Modi, H. A.; Prajapati, J. B. Hypocholesterolemic effect of potential probiotic Lactobacillus fermentum strains isolated from traditional fermented foods in Wistar rats. *Probiotics and antimicrobial proteins*, 2020, *12*(3), 1002-1011.
88. Tomar, O. The Effects of Probiotic Cultures on the Organic Acid Content, Texture Profile and Sensory Attributes of Tulum Cheese. *Int J Dairy Technol* 2019, *72*, 218–228, doi:10.1111/1471-0307.12574.
89. Tosya, F.; Bölek, S. Encapsulation of Bioactive Compounds in Shalgam and Investigation of the Possibilities of Their Use in Probiotic Food Production. *Food Biosci*2022, *50*, doi:10.1016/j.fbio.2022.102166.
90. Ucak, S.; Yurt, M.N.Z.; Tasbasi, B.B.; Acar, E.E.; Altunbas, O.; Soyucok, A.; Aydin, A.; Ozalp, V.C.; Sudagidan, M. Identification of Bacterial Communities of Fermented Cereal Beverage Boza by Metagenomic Analysis. *LWT* 2022, *153*, doi:10.1016/j.lwt.2021.112465.
91. Uruc, K., Tekin, A., Sahingil, D. İ. D. E. M., & Hayaloglu, A. A. (2022). An alternative plant-based fermented milk with kefir culture using apricot (Prunus armeniaca L.) seed extract: Changes in texture, volatiles and bioactivity during storage. *Innovative Food Science & Emerging Technologies*, *82*, 103189.
92. Valero-Cases, E.; Roy, N.C.; Frutos, M.J.; Anderson, R.C. Influence of the fruit juice carriers on the ability of *Lactobacillus plantarum* DSM20205 to improve in vitro intestinal barrier integrity and its probiotic properties. *J. Agric. Food Chem.* 2017, 65, 5632–5638. doi: 10.1021/acs.jafc.7b01551.
93. Verón, H.E.; Contreras, L.; Isla, M.I.; Torres, S. Assessment of technological and functional features of *Lactiplantibacillus* and *Fructobacillus* strains isolated from Opuntia ficus-indica fruits. *NFS Journal* 2023. *31*, pp.110-122. https://doi.org/10.1016/j.nfs.2023.04.003
94. Wang, P.; Wu, J.; Wang, T.; Zhang, Y.; Yao, X.; Li, J.; Wong, X.; Lü, X. Fermentation process optimization, chemical analysis, and storage stability evaluation of a probiotic barley malt kvass. *Bioprocess Biosyst Eng*. 2022, 45, 1175–1188,https://doi.org/10.1007/s00449-022-02734-8
95. Wang, X.; Han, M.; Zhang, M.; Wang, Y.; Ren, Y.; Yue, T.; Gao, Z. In Vitro Evaluation of the Hypoglycemic Properties of Lactic Acid Bacteria and Its Fermentation Adaptability in Apple Juice. *LWT* 2021, *136*, doi:10.1016/j.lwt.2020.110363.

96. Xia, A.N.; Meng, X.S.; Tang, X.J.; Zhang, Y.Z.; Lei, S.M.; Liu, Y.G. Probiotic and Related Properties of a Novel Lactic Acid Bacteria Strain Isolated from Fermented Rose Jam. *LWT* 2021, *136*, doi:10.1016/j.lwt.2020.110327.
97. Yilmaz-Ersan, L.; Topcuoglu, E. Evaluation of Instrumental and Sensory Measurements Using Multivariate Analysis in Probiotic Yogurt Enriched with Almond Milk. *J Food Sci Technol*2022, *59*, 133–143, doi:10.1007/s13197-021-04994-w.
98. Zhang, Y., Chang, H., Shao, S., Zhao, L., Zhang, R. and Zhang, S., (2022). Anthocyanins from opuntia ficus-indica modulate gut microbiota composition and improve short-chain fatty acid production. *Biology*, *11*(10), p.1505.
99. Zheng, X.; Yu, Y.; Xiao, G.; Xu, Y.; Wu, J.; Tang, D.; Zhang, Y. Comparing Product Stability of Probiotic Beverages Using Litchi Juice Treated by High Hydrostatic Pressure and Heat as Substrates. *Innovative Food Science and Emerging Technologies* 2014, *23*, 61–67, doi:10.1016/j.ifset.2014.01.013.
100. Zielinska, D.; Kaminska, A.; Kolozyn-Krajewska, D. Development of Tofu Production Method with Probiotic Bacteria Addition. *Journal of Microbiology, Biotechnology and Food Sciences* 2015, *04*, 485–490, doi:10.15414/jmbfs.2015.4.6.485-490.

**List of Tables**

**Table-1:** Some examples of foods and beverages that include phytophagous probiotics.

| **Food type** | **Probiotic cultures** | **References** |
|---|---|---|
| Probiotic soy yoghurt | *Lactobacillus acidophilus* LA-5, *Bifidobacterium bifidum* Bb-12, *Streptococcus thermophilus* | **(Niamah et al., 2017)** |
| Kimchi | *Lactobacillus brevis, Pediococcus pentosaceus, Lactiplantibacillus plantarum, Leuconostoc lactis, Latilactobacillus sakei, Leuconostoc mesenteroide.* | **(Jung et al., 2021)** |
| Sauerkraut | *Lactiplantibacillus plantarum* L4, *Leuconostoc mesenteroides* LMG 7954 | **(Beganović et al., 2011)** |
| Pumpkin and sesame seed milk | *Lactobacillus acidophilus* LA-5, *Bifidobacterium bifidum* Bb-12, *Streptococcus thermophilus* | **(Hassan et al., 2012)** |
| Boza | *Lacticaseibacillus casei, Lactobacillus acidophilus, Weisella paramesenteroides* | **(Tornuk et al., 2014)** |
| Cornelian cherry juice | *Lactiplantibacillus plantarum* | **(Mantzourani et al., 2018)** |
| Litchi | *Lacticaseibacillus casei* | **(Zheng et al., 2014)** |
| Babroo | *Limosilactobacillus fermentum, Lactiplantibacillus plantarum, acidilactici* | **(Sharma et al., 2019)** |
| Idli | *Bacillus* spp. | **(Shivangi et al., 2020)** |
| Bergamot juice | *Lactiplantibacillus plantarum* subsp. *plantarum* | **(Hashemi et al., 2020)** |
| Tomato juice | *Bifidobacterium breve*, *B. longum*, and *B. infants* | **(Koh et al., 2010)** |

**Table-2:** Viability of probiotic starters in phytophagous probiotic products as functional foods.

| **Food type** | **Phytophagous probiotic products** | **Probiotic staters** | **Probiotics viability in the products (CFU/ mL or gm)** | **Fermentation conditions** | **References** |
|---|---|---|---|---|---|
| **Juices and beverages** | Beet juice | *Lb. acidophilus*, *Lb. casei*, *Lb. delbrueckii* and *Lb. plantarum* | $10^6$-$10^8$ | - | **(Kyung et al., 2015)** |
| | Pomegranate juice | *Lb. plantarum*, *Lb. delbruekii*, *Lb. paracasei*, and *Lb. acidophilus* | $10^7$-$10^8$ | 30°C for 72 h under microaerophilic conditions | **(Mousavi et al., 2011)** |
| | Malt beverage | *Lb. plantarum* and *Lb. acidophilus* | $10^8$ | - | **(Rathore et al., 2012)** |
| | Carrot juice | *Lb. plantarum* Lp-115, *B. lactis* 420, *B. lactis* Bb-12, *B. bifidum* B7.1 and *B. bifidum B3.2* | $10^8$-$10^9$ | Anaerobically for 18 h at 37°C. | **(Tamminen et al., 2013)** |
| | Litchi juice | *Lb. casei* | $10^8$ | 30°C for 18 h | **(Zheng et al., 2014)** |
| | Cshew juice | *Lb. casei* NRRL B-442 | $10^9$ | - | **(de Godoy Alves Filho et al., 2017)** |
| | Cupuassu beverage | *Lb. casei* | $10^9$ | - | **(Pereir et al., 2017)** |
| | Pineapple Juice | *B.lactis* Bb12, *Lb. plantarum* 299V, and *Lb. acidophilus* La5 | $10^8$-$10^9$ | - | **(Nguyen et al., 2019)** |
| | Quinoa beverage | *Lb. plantarum* DSM 9843 | $10^{10}$-$10^{11}$ | - | **(Canaviri Paz et al., 2020)** |

| | | | | | |
|---|---|---|---|---|---|
| **Foods** | Soy yogurt | *St. thermophilus*, *Lb. acidophilus* LA-5, and *B. bifidum* Bb-12 | $10^{11}$ | 40 °C for 7 h and cooled at 4 °C. | **(Niamah et al., 2017)** |
| | Fruit salads | *Lb. rhamnosus* HN001 | $10^{4}$-$10^{5}$ | Non-fermentation | **(Martins et al., 2016)** |
| | Oat flour | *Lb. acidophilus* and *S. thermophilus* | $10^{9}$ | 37 °C, with constant shaking (150 rpm) until a pH of 4.9 ± 0.2 | **(Duru et al., 2016)** |
| | Tofu | *B. animalis* subsp. *lacti*s BB-12, *Lb. casei*, and *Lb. Paracasei* | $10^{9}$-$10^{10}$ | 37°C for 22 h and cooled at 4 °C. | **(Zielinska et al., 2015)** |

**Table-3:** Sensory characteristics of some probiotic plant foods.

| **Food Product** | **Sensory characteristics** | **Probiotics** | **Plant types** | **References** |
|---|---|---|---|---|
| Kimchi | Sour flavour and sour taste | *Leuconostoc mesenteroides*, *Leu. citreum*, *Lb. plantarum*, *Lb. sakei*, *Weissella cibaria* and *W. koreensis* | Cabbage | **(Springmann et al., 2018)** |
| Pineapple Juice | Sour taste, refreshing aroma, strong color and non-turbid appearance | *Lacticaseibacillus rhamnosus* and *Pediococcus pentosaceus* | Pineapple | **(Khalil et al., 2022)** |
| Kombucha | fresh sour-fruity taste | *Lactiplantibacillus plantarum* | Green tea or sweet black tea | **(Abaci et al., 2022)** |
| Tempeh | The odor and color were deemed to be within normal ranges. The attributes of odor, color, and taste were well-received. | *Lacticaseibacillus casei* | Soaked soybean or Jack Bean | **(Küçükgöz et al., 2022)** |
| Soy cheese | Sensory evaluation acceptance good for appearance, colour, flavour, creaminess, consistency, spreading ability and overall impression | *Lb. acidophilus* and *Bifidobacterium lactis* | Soybean | **(Niamah et al., 2017)** |
| Yogurt (plant-based) | Refreshing flavor, a smooth viscous gel, and a slight sour taste. | *St. thermophilus*, *Lb. bulgaricus*, *Lb. acidophilus* and *B. lactis* | Almond milk | **(Kumar et al., 2022)** |

| | | | | |
|---|---|---|---|---|
| Kvass | slightly cloudy appearance, light–dark brown color; sour taste | *Lb. paracasei*, *Acetobacter pasteurianus*, and *Saccharomyces cerevisiae* | malted barley | **(Wang et al., 2022)** |
| Boza | a thick liquid, pale yellow color; sweet or sour taste | *Lb. acidophilus* LA-5, *B. bifidum* BB-12 and *Saccharomyces boulardii* | Wheat, millet, maize, and other cereals | **(Miguel et al., 2021)** |
| Shalgam | red color; sour taste | Kefir starter culture | Shalgam | **(Sobal et al., 2014)** |
| Natto | white color; sweet, acidic, cereal taste; soft texture | *Bacillus subtilis* and *Bifidobacterium animalis subsp. lactis* | Soybeans | **(Jayarathna et al., 2021)** |

**Table-4:** Key sensory characteristics associated with foods derived from plants that contain probiotics.

| **Prevalent Sensory Attributes** | **Key Remarks** | **References** |
|---|---|---|
| *Flavor* | • The process of fermentation employed for the production of probiotic plant-based food can produce a wide range of unique and varied sensory experiences.<br>• Fermented plant-based milks, such as kefir or yogurt, exhibit varying levels of acidity, resulting in a tangy or sour flavor profile.<br>• Fermented vegetables such as kimchi and sauerkraut exhibit a range of taste profiles, characterized by the presence of saltiness, sourness, or spiciness. | **(Pua et al., 2022; Uruc et al., 2022; Fijan et al., 2024)** |
| *Texture* | • The fermentation process can exert an influence on the physical properties of probiotic plant-based food.<br>• Fermented plant-based milks, such as those derived from various botanical sources, exhibit a notable propensity for acquiring a luxuriously smooth and velvety consistency.<br>• Conversely, the fermentation of vegetables is known to impart a distinctively crisp or crunchy texture to the resultant product. | **(Rasika et al., 2021; Mouritsen & Styrbæk, 2020)** |
| *Aroma/Odor* | • The microbial fermentation process occurring in probiotic plant-based food can yield various aromatic compounds.<br>• Fermented plant-based milks, such as those derived from plant sources, may exhibit an olfactory profile characterized by a mildly acidic or tangy fragrance reminiscent of cheese.<br>• Conversely, fermented vegetables are known to emit a strong or intense aroma, often described as pungent or spicy in nature. | **(Ankomah, 2022; Montero & Ross, 2023; Qamaruz-Zaman et al., 2020)** |
| *Mouthfeel (Masticatory Sensation)* | • The physical properties of probiotic plant-based foods can likewise exert an impact on masticatory sensation, i.e., the tactile experience perceived within the oral cavity.<br>• Certain plant-based foods containing probiotics exhibit varying textures, such as a velvety and creamy consistency, while others may possess a chewy or crispy texture. | **(Masiá et al., 2021; Aydar, 2023)** |
| *Appearance (Visual Characteristics)* | • The fermentation process exerts an influence on the visual attributes of probiotic plant-based foods.<br>• Fermented plant-based milks exhibit a perceptible increase in viscosity and creaminess compared to their non-fermented counterparts. | **(Pimentel et al., 2021; Ren et al., 2024; Kasapoglu et al., 2023)** |

**Table-5:** Key areas of future exploration with potential research opportunities on phytophagous probiotic foods driven by the growing demand for plant-based products and the recognized health benefits of probiotics.

| Key areas | New frontiers with exciting possibilities for further research |
|---|---|
| Development of novel probiotic strains | New probiotic strains that thrive in plants are of great scientific interest. These strains must be tough enough to endure the food processing sector while preserving their benefits and growing potential during storage. This approach uses probiotics that can tolerate digestive system acidity and enzymes and are stable in non-dairy matrices. |
| Mechanisms of action in plant matrices | Another important area of research is how probiotics interact with plant-based dietary components such fibers, polyphenols, and bioactive compounds. These interactions can affect the probiotic's gut health, immune response, and other physiological effects. Another study topic is how these interactions impact gut microbiota metabolic activity and probiotic bioavailability. |
| Optimization of fermentation processes | Plant-based foods can benefit from probiotic fermentation's nutritional and taste benefits. Scientific research can determine the optimal fermentation environment for probiotic development, product flavor, texture, shelf life, and beneficial metabolite concentration. This approach includes exploring alternate fermenting methods like mixed cultures for synergy. |
| Bioavailability and efficacy studies | Studying probiotic bioavailability in plant-based meals is crucial to understanding health consequences. Future studies should examine how effectively these probiotics colonize the stomach, digest, and compare to dairy-derived probiotics. Clinical trials on phytophagous probiotic food consumption and immunological function, gastrointestinal health, and chronic disease risk are included. |
| Consumer preferences and sensory improvement | Consumers must like phytophagous probiotic foods to survive. Research can reveal consumer preferences and sensory factors that influence purchases. Formulations that improve flavor, texture, and appearance while being healthy are included. Sensory research can improve product development that meets customer expectations and offers effective probiotics. |
| Sustainability and environmental impact | Growing environmental concerns surround the plant-based food business. More study is needed on the environmental impacts of plant-based foods containing probiotics, including resource utilization, carbon footprint, and waste reduction. Sustainable food production and marketing strategies |

| | |
|---|---|
| | may be researched to develop a more sustainable food system. |
| Regulatory and safety evaluation | Safety and quality of phytophagous probiotic foods are crucial. Future studies may focus on food product safety standards. We may examine health concerns, test novel probiotic strains, and ensure our production processes meet food safety standards as part of this process. |
| Long-term health outcomes | Epidemiological and long-term clinical investigations are needed to assess the health impacts of phytophagous probiotic diets. These findings may lead to public health policies and dietary guidelines that promote illness prevention through particular foods. |
| Personalized nutrition and probiotics | Personalized nutrition investigates if phytophagous probiotic foods perform better for persons with different gut flora, genetics, and lifestyles. This research might lead to individualized probiotic treatments that meet individual health demands to optimize benefits and user satisfaction. |

## List of Figures

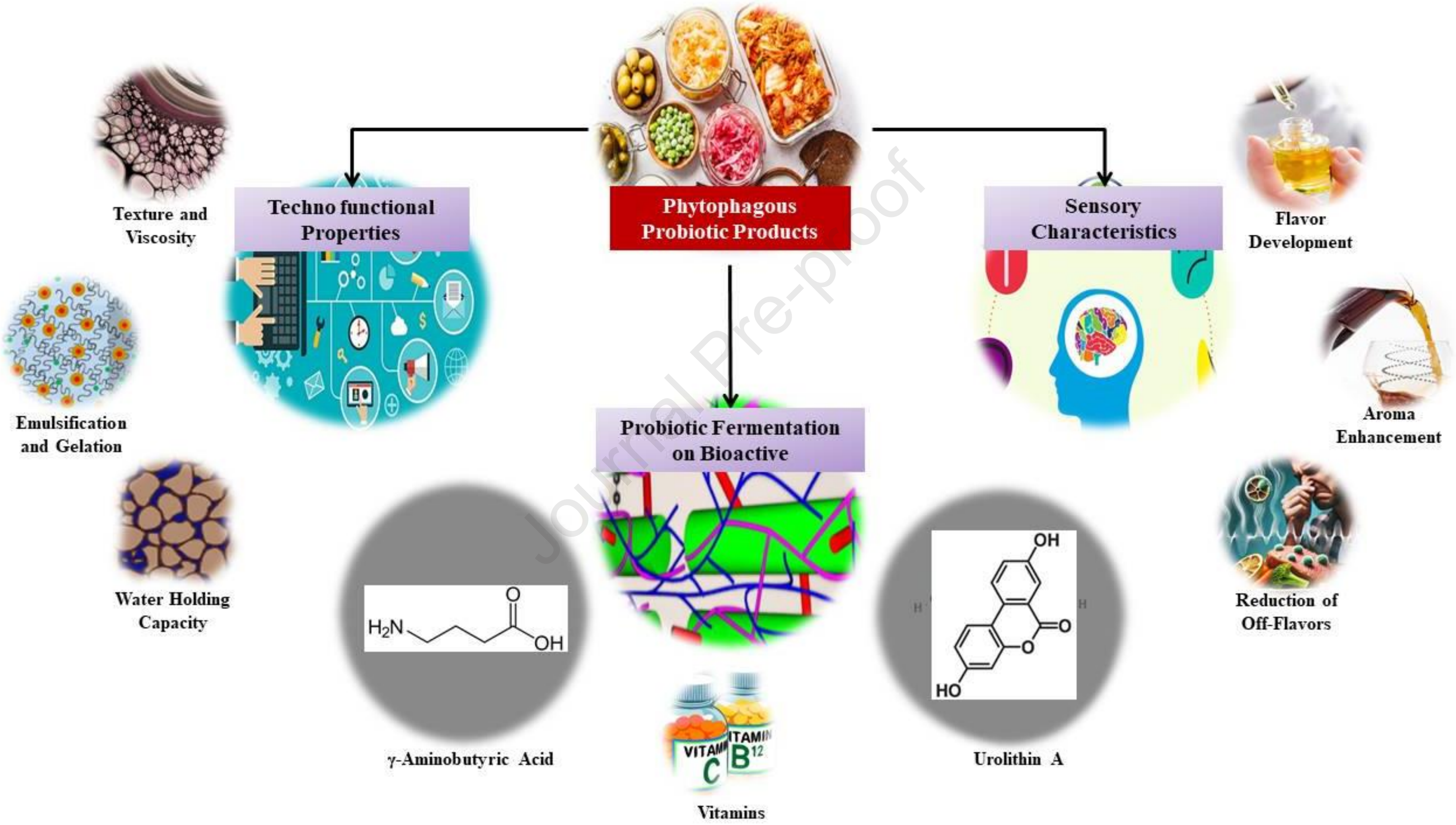
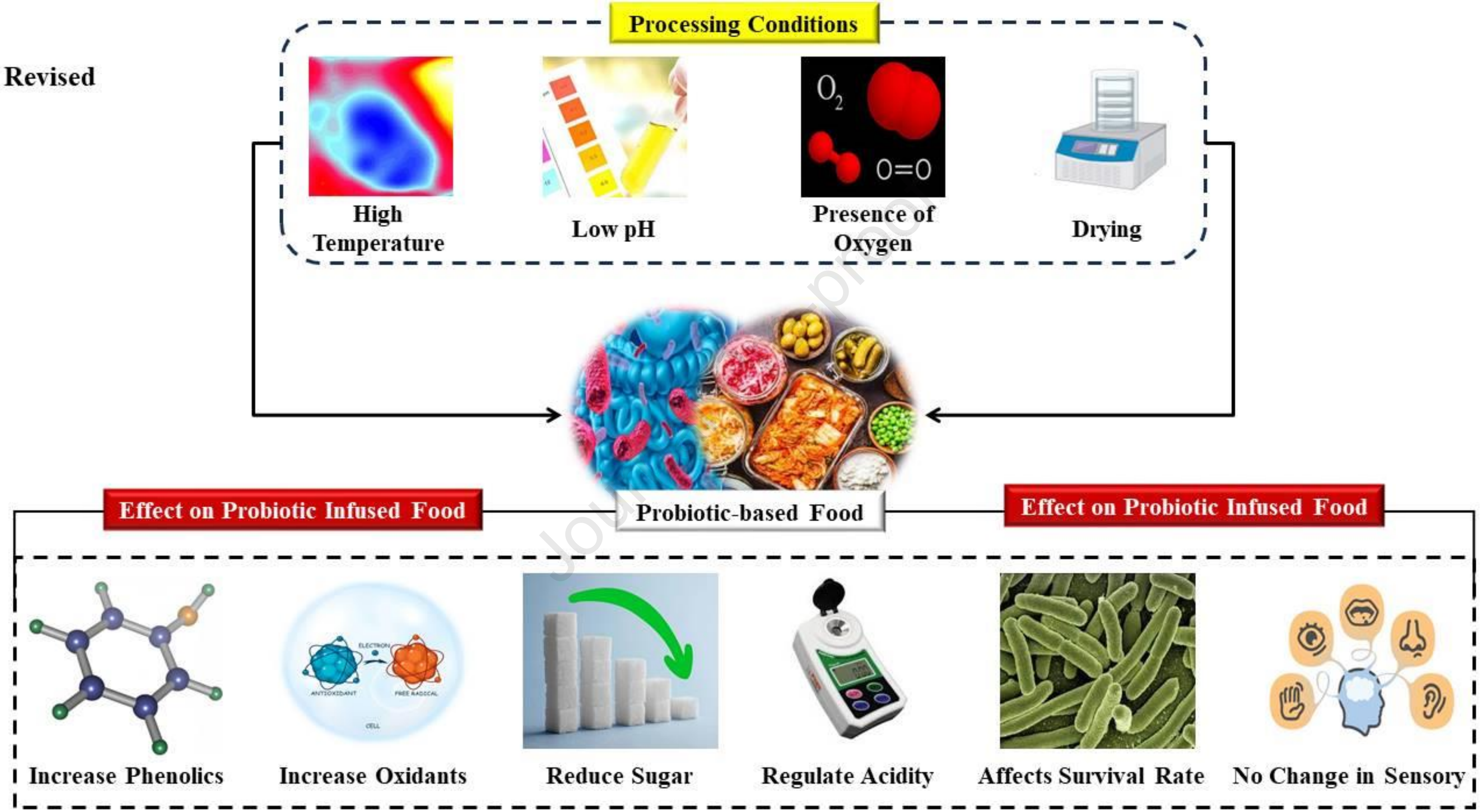
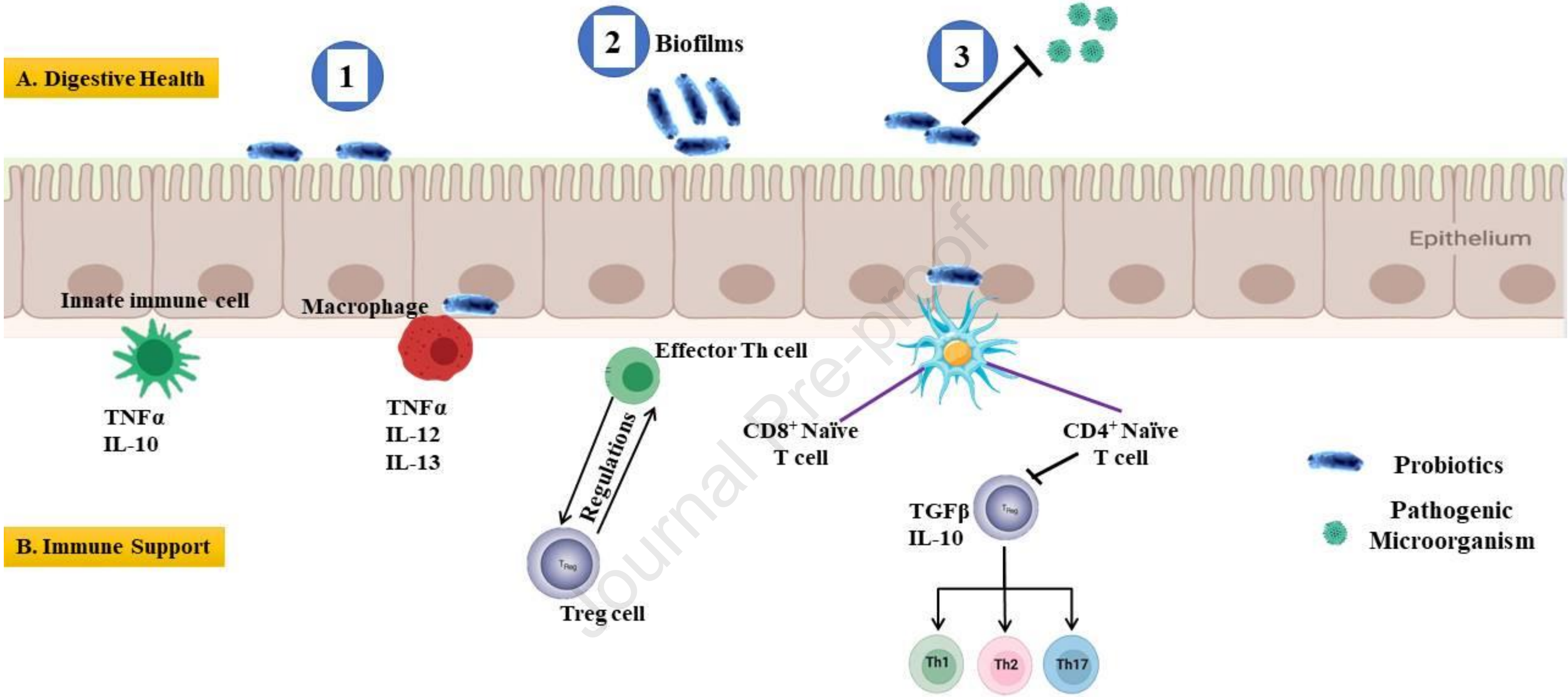


**Figure-1:** The major impact of probiotic strains on the techno-functional and sensory properties of diverse plant-based food products.

**Revised**




A. Digestive Health
1
2
Biofilms
3
Epithelium
Innate immune cell
Macrophage
TNFα
IL-10
TNFα
IL-12
IL-13
Effector Th cell
Regulations
Treg cell
$T_{Reg}$
CD8⁺ Naïve T cell
CD4⁺ Naïve T cell
TGFβ
IL-10
$T_{Reg}$
Th1
Th2
Th17
B. Immune Support
Probiotics
Pathogenic Microorganism

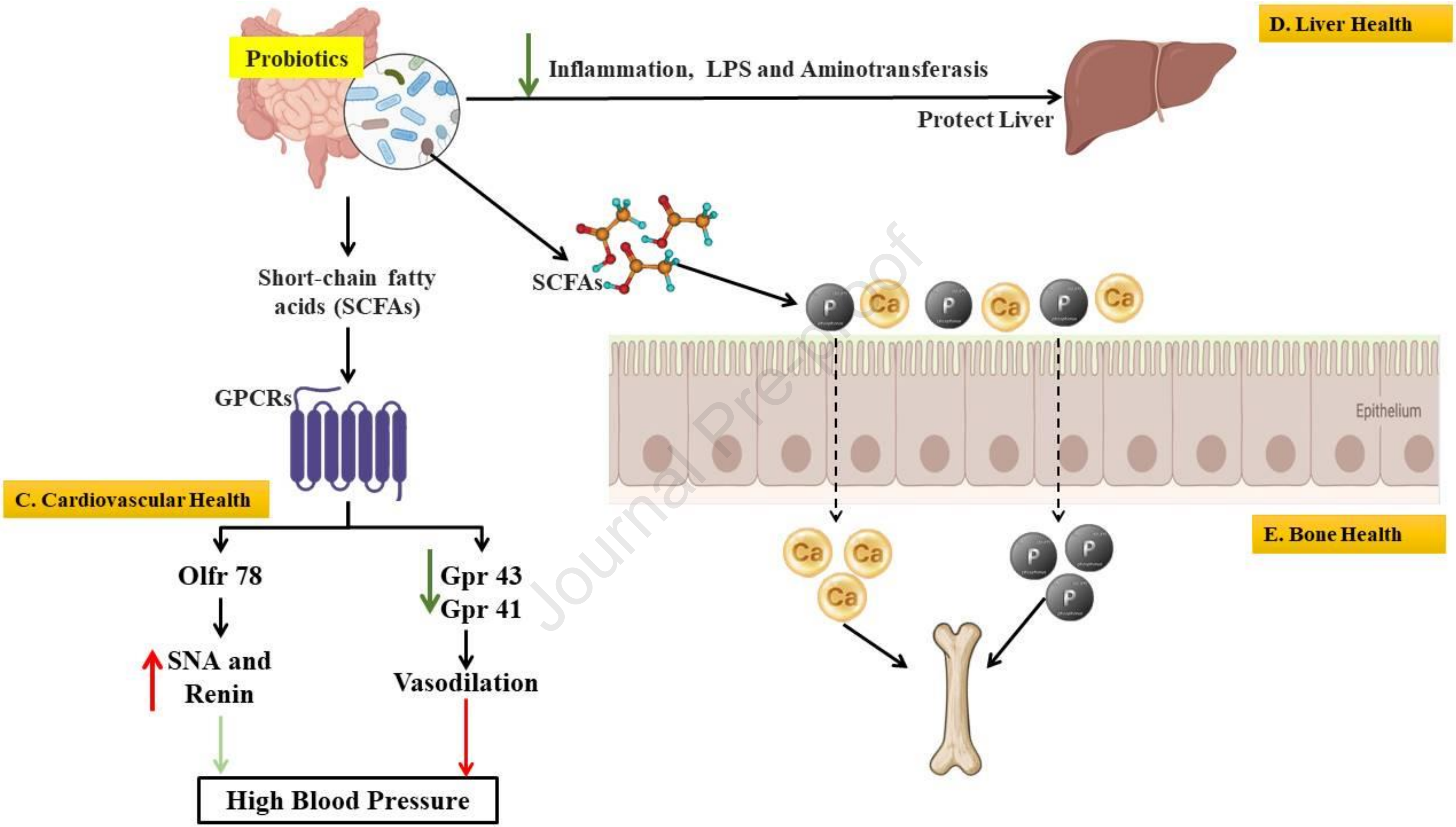

Probiotics
Inflammation, LPS and Aminotransferasis
D. Liver Health
Protect Liver
Short-chain fatty acids (SCFAs)
SCFAs
P
Ca
Epithelium
GPCRs
C. Cardiovascular Health
Olfr 78
Gpr 43
Gpr 41
SNA and Renin
Vasodilation
High Blood Pressure
E. Bone Health

**Figure-2:** Main health-promoting effects of diverse phytophagous products supplemented with probiotics, they are: (A) Human digestive health, (B) Immunity, (C) Cardiovascular health, (D) Liver health, and (E) Bone health.

**(A)** ***Human digestive health*****:** The health of the human digestive system pertains to its effective operation, which involves the breakdown of food, the absorption of nutrients, and the expulsion of waste from the organism. An optimally functioning digestive system effectively breaks down food to assimilate critical nutrients, such as vitamins, minerals, proteins, carbohydrates, and fats, which are essential for energy production, growth, and tissue repair (**Sajankila et al., 2023**). Probiotics enhance the functionality of the gut barrier by maintaining the integrity of tight junction proteins, including claudin 4 and occludin. Probiotics exhibit anti-apoptotic and cytoprotective properties in the neonatal intestine (1). Probiotics with high adhesive capabilities to the intestinal lining generate intricate biofilms that enhance attachment and, theoretically, the effectiveness of the probiotic (2). Probiotics can diminish the prevalence of pathobionts through mechanisms such as direct competition or the synthesis of anti-microbial compounds (3).

**(B)** ***Immunity*****:** Immunity denotes the robustness, equilibrium, and operational efficacy of the body'’s immune system, which serves as a defense mechanism against infections, diseases, and various detrimental agents including bacteria, viruses, and toxins. An optimal immune system is capable of accurately detecting and responding to various threats, thereby enhancing the prevention of diseases and the efficacy of combating infections (**Mazziotta et al., 2023**). Probiotics influence the host's innate and adaptive immune responses through the modulation of immune cells, including dendritic cells (DCs), macrophages, and B and T lymphocytes. Ingested probiotic bacteria attach to intestinal epithelial cells and stimulate them through pattern recognition receptors (PRRs). The stimulation of cytokines by probiotic bacteria results in the activation of T regulatory (Treg) cells, which are essential for maintaining immune homeostasis within the intestinal mucosa. Tregs function as potent modulators of the immune response, significantly contributing to the regulation and limitation of immune activity. Intestinal antigens are conveyed to dendritic cells through specialized enterocytes referred to as microfold cells (M cells), situated in the epithelium that overlays Peyer’s patches. Probiotics undergo direct processing by dendritic cells within the lamina propria of the intestinal lumen. Intestinal dendritic cells have the capacity to activate naïve CD8+ and CD4+ T cells, guiding helper T cell responses towards Th1, Th2, Th17, or regulatory profiles.

The Th1 immune response is primarily defined by the production of interferon (IFN)-γ and plays a crucial role in cell-mediated immunity. The Th2 immune response is characterized by the release of interleukin (IL)-4 and IL-5, which subsequently promotes humoral immunity. The Th17 immune response is defined by the production of IL-17. The induction of regulatory T cells (Tregs) results in the release of interleukin-10 (IL-10) or transforming growth factor-beta (TGF-β).

**(C)** ***Cardiovascular health*****:** The state of cardiovascular health pertains to the comprehensive condition and operational efficacy of the cardiovascular system, encompassing both the heart and the blood vessels. Preserving optimal cardiovascular health is crucial for facilitating effective blood circulation, transporting oxygen and nutrients to tissues and organs, and eliminating metabolic waste products from the body (**Masenga et al., 2022**). Microbiota metabolites, specifically short-chain fatty acids (SCFAs), influence various G protein-coupled receptors (GPCRs), subsequently impacting blood pressure regulation. The activation of Gpr43 and Gpr41 leads to vasodilation and a reduction in blood pressure. The activation of olfr78 leads to an increase in sympathetic nerve activity (SNA) and renin secretion, which subsequently results in an elevation of blood pressure.

**(D)** ***Liver health*****:** Liver health pertains to the comprehensive functioning and status of the liver, a critical organ that undertakes numerous essential physiological processes, such as detoxification, metabolism, digestion, and nutrient storage. Ensuring optimal liver health involves facilitating the liver's ability to execute its functions efficiently and without dysfunction (**do Nascimento et al., 2022**). Probiotics enhance the composition of intestinal microbiota (MI), leading to a reduction in liver inflammation, a decrease in LPS concentrations, and an improvement in aminotransferase levels, thereby providing protective effects for the liver.

**(E)** ***Bone health*****:** The term "bone health" encompasses the strength, density, and overall condition of bones, which play a critical role in maintaining the body's structural integrity, safeguarding internal organs, facilitating movement, and serving as a reservoir for minerals like calcium and phosphorus. Optimal bone health is defined by the presence of strong, resilient bones that exhibit a reduced susceptibility to fractures, breaks, or osteoporosis, a pathological condition characterized by weakened and brittle bone structure **(Chen et al., 2022).** Probiotics influence the growth and development of bone through the regulation of gut microbiota composition and function. Probiotics play a crucial role in sustaining bone homeostasis through their impact on the absorption of intestinal nutrients, specifically calcium and phosphorus, as well as the production of metabolites such as short-chain fatty acids. Probiotics influence nutrient absorption in the intestinal tract primarily through the modulation of the renewal rate of intestinal epithelial cells and the mechanisms of calcium and phosphorus transport.

**Highlights**

- Highlights the food products demand with enhanced bioactive and probiotic value
- States phytophagous probiotics (PP) as important in non-dairy, plant-based products
- Emphasizes numerous probiotic traits that promote food quality, safety, and health
- Provides deep analysis of PP products detailing with health-promoting properties
- 
- Valuable facts provide for scientists and industrialists, guiding future research on vegan food

## Declaration of competing interest

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