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Review

An Overview of the Microbiological, Nutritional, Sensory and Potential Health Aspects of Tree Nut-Based Beverages

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Abstract

In recent years, the rise in food allergies and intolerances, combined with the increasing consumer preference for healthier, plant-based alternatives to traditional dairy products, has driven the development of a diverse range of plant-based beverages. Among these, tree nut-based beverages, "ready-to-drink" products made from nuts such as almonds, hazelnuts, pistachios, walnuts, brazil nut, macadamia, cashew nut, coconut, pine nut, have gained significant popularity. This review offers a comprehensive analysis of the microbiological, nutritional, and sensory properties of tree nut-based beverages, highlighting their ability to deliver essential nutrients such as healthy fats, proteins, fiber, vitamins, and minerals. Additionally, these beverages provide a rich source of bioactive compounds (e.g., antioxidants, polyphenols) that can contribute to health benefits such as reducing oxidative stress, supporting cardiovascular health, and promoting overall well-being. The review also highlights the ability of different species of lactic acid bacteria to enhance flavour profiles and increase the bioavailability of certain bioactive compounds. Nevertheless, further research is essential to optimize the production methods, improve sensory characteristics, and address challenges related to cost, scalability, and consumer acceptance. Continued innovation in this area may position tree nut beverages as a key component of plant-based food models, contributing to the promotion of healthier eating patterns.

Keywords: almond; fermentation; pistachio; walnut; hazelnut; brazil nut; macadamia; cashew nut; lactic acid bacteria; plant-based milk alternatives

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Academic Editor: Nenad Naumovski

Received: 18 July 2025
Revised: 5 September 2025
Accepted: 22 September 2025
Published: 1 October 2025

Citation: Di Renzo, T.; Garzón, A.G.; Nazzaro, S.; Marena, P.; Carboni, A.D.; Puppo, M.C.; Drago, S.R.; Reale, A. An Overview of the Microbiological, Nutritional, Sensory and Potential Health Aspects of Tree Nut-Based Beverages. *Beverages* **2025**, *11*, 144. https://doi.org/10.3390/beverages11050144

1. Introduction

In recent years, the trend towards plant-based foods has gained substantial momentum, with the emergence of plant-based beverages (PBBs) as a key product category.

These beverages, derived from a wide range of raw plant sources, including cereals, pseudocereals, tree nuts, seeds, legumes and tubers, are increasingly consumed as an alternative to milk [1].

The rising demand in PBBs is closely linked to several key trends, including growing concerns about the environmental impact of livestock and the increasing prevalence of food allergies and intolerances, particularly to lactose and cow's milk proteins [2].

Selecting hypoallergenic ingredients such as oat, rice, or coconut in place of more common allergens like soy or nuts expands accessibility. Implementing strict allergen controls during production is also essential.

In addition, the global rise in vegetarianism, veganism, and health-conscious dietary patterns has contributed to the strong market expansion of these products [3,4].

According to market reports, the plant-based milk industry alone is set to grow by 12.7% annually between 2022 and 2030 [5].

Among the various PBBs, tree nut beverages, such as almond, coconut, macadamia, cashew, Brazil nut, pistachio, hazelnut, pecan, pine nut, and walnut milks, have emerged as popular choices due to their appealing sensory properties and perceived health benefits, as shown in Figure 1 [6–10].

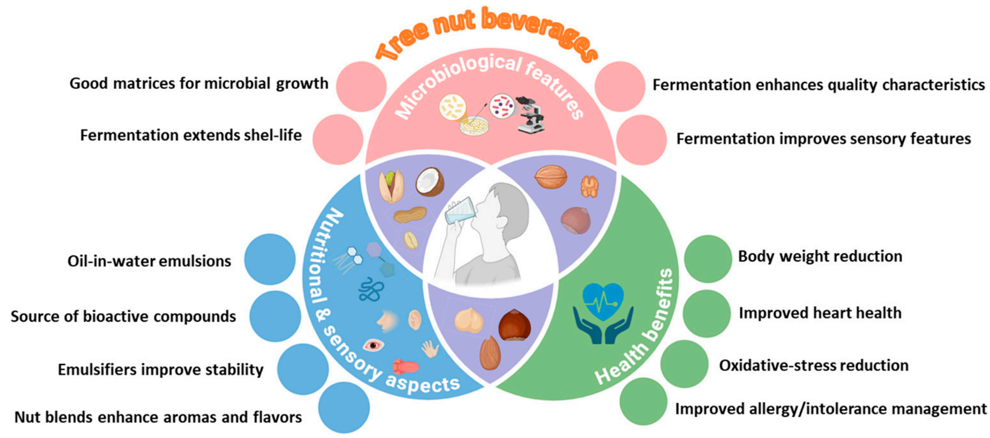

Figure 1. Role of tree nut beverages: microbial, nutritional, sensory and health perspectives. The figure was created with Biorender.com.

However, despite their growing appeal, these beverages present several limitations from nutritional, technological, environmental, and economic perspectives.

One of the main drawbacks of nut-based beverages is their relatively low protein content. Furthermore, these beverages may also lack essential micronutrients such as calcium, vitamin D, and vitamin B12, which are crucial for bone health and overall health. In this sense, fortification with specific vitamins and minerals may be an interesting strategy to ensure sufficient quantities of micronutrients in populations that consume these beverages as a replacement for dairy products. Additional approaches, such as the fermentation of PBBs, have the potential to enhance the bioavailability of vitamins and minerals.

These beverages are typically produced by soaking, grinding, and filtering nuts, resulting in a milk-like emulsion composed of suspended nut particles, water, and natural oils [11]. However, tree nut-based beverages are prone to phase separation, where the fat and aqueous components stratify over time during storage.

To address this instability and maintain a homogeneous appearance and texture, manufacturers commonly incorporate emulsifiers and stabilizers into the formulation. Additionally, the sensory profile of some tree nut-based beverages may be less appealing to certain consumers, who report bitterness, graininess, or other off-notes in taste and mouthfeel. At the same time, careful optimization of formulation and processing is necessary to ensure nutrient stability while preserving desirable sensory properties and emulsion stability.

To address these issues, various research initiatives are currently being developed to improve the nutritional composition, sensory attributes, and health-promoting potential of tree nut-based beverages. Explored strategies include fortification with vitamins and minerals to fill nutritional gaps [12,13].

Technological and sensory improvements have also been explored, employing natural flavour enhancers, emulsifiers, and advanced processing methods such as colloidal milling or ultrasonic treatment to achieve a smoother texture and improved stability [8,10,14,15]. Reducing the use of artificial additives and stabilizers aligns with consumer preferences for natural, transparent products and can enhance digestibility. Moreover, fermentation with selected microbial strains has been identified as a promising strategy to enhance the flavour, texture, and nutritional value of tree nut-based beverages [6,16,17]. Furthermore, the incorporation of probiotic cultures and prebiotic fibers has positioned these beverages as functional foods with potential benefits for gut health, immune modulation, and metabolic function [18,19]. These functional enhancements make fermented tree nut-based beverages a promising category in the expanding field of health-oriented functional foods.

This review is a comprehensive overview of the available literature on nut-based beverages. Relevant articles were identified by searching the databases ISI "Web of Science", "Scopus", "Ebsco," "Scielo" and "Pub Med" where the descriptors used were: "nuts", or "almonds" or "hazelnuts" or "pistachios", or "walnuts" AND "(beverages OR drink OR extract OR plant-based)". The search covered publications from 2010 to 2025. Only articles published in English and focused on the nutritional, technological, microbiological and functional aspects of nut-based beverages were included. After applying the filters, the articles were previously read (abstract and title), and duplicates were excluded. Additional references were identified from the bibliographies of the retrieved papers. A total of 104 articles were considered relevant to this review, highlighting the challenges and opportunities associated with the production and consumption of tree nut-based beverages, thereby contributing to a deeper understanding of their potential role in sustainable and health-conscious dietary patterns.

2. Microbiological Aspects

Tree nut-based beverages possess a high moisture content and are rich in nutrients, including carbohydrates, proteins, and lipids, which create an ideal environment for microbial growth. This composition makes them particularly susceptible to microbial contamination and spoilage, especially in the absence of proper hygienic practices and preservation methods.

To ensure microbiological safety, extend shelf-life, and preserve quality, various technological strategies have been developed. These methods primarily aim to inactivate pathogenic and spoilage microorganisms, such as *Salmonella* spp., *Listeria monocytogenes*, *Bacillus cereus*, and *Escherichia coli*, as well as enzymes like lipases and proteases, which contribute to chemical degradation and impact flavor, texture, and nutritional quality.

Tree nut-based beverages are typically produced using different steps, such as soaking, blanching, roasting, filtration, ingredient addition, sterilization, homogenization, aseptic packaging, and cold storage. Additionally, advanced technologies such as ultrasound, pulsed electric fields, ohmic heating, and high or ultra-high-pressure homogenization are increasingly employed to improve product stability while minimizing or eliminating the need for chemical additives [20–22].

Table 1 shows the main technological treatments applied to tree nut-based beverages and their effects on microbiological and nutritional quality. As shown in Table 1, thermal processing is one of the most widely used preservation methods in the production of this type of beverage [7,21–25].

Table 1. Effects of different technological treatments on the quality characteristics of tree nut-based beverages.

Raw Nut	Technological Treatment	Main Results	References
Almond (*Prunus amygdalus*)	Heat treatment (HT) at 90 °C for 90 s	↓ bacterial growth and stability, ↑ sedimentation	[21,22]
	UHT at 142 °C for 6 s	no bacterial growth	[21,22]
	UHPH (200 and 300 MPa at 55, 65, and 75 °C) with lecithin	no bacterial growth, ↓ particle size and sedimentation, ↑ colloidal stability and hydroperoxide index	[21,22]
	Hydrodynamic Cavitation (HC)	extremely low microbial loads	[26]
Brazil nut (*Bertholletia excelsa*)	HT at 63 °C for 20 min	↓ microbial loads, total phenolic content and squalene and γ-tocopherol	[7,23]
	HPH (50, 100, 150, 180 MPa at 55, 65, and 75 °C)	Inactivation of *Escherichia coli* and controlled microbial loads, good oxidative stability, no significant lipolysis processes, unaltered levels of essential minerals, proteins, and phytochemicals; stable pH, acidity, and °Brix. ↓ in particle size, ↓ total phenolic content, squalene and γ-tocopherol	[7,23]
	Use of nanoadditives (Annatto-nanodispersion)	Good physical stability, no significant phase separation or creaming, significant antioxidant activity, ↑ content in lipids, protein, and essential minerals	[2]
Macadamia (*Macadamia integrifolia*)	Use of Xanthan gum, soy lecithin + HT at 85 °C for 15 min	↓ particle size, ↑ stability of the emulsion, ↓ saturated fatty acids (SFA) and polyunsaturated fatty acids (PUFA), ↑ monounsaturated fatty acids (MUFA), ↓ antioxidant capacity and texture	[10]
	Gellan gum and soy + lecithin + HT at 70 °C for 6 min	↓ particle size, ↑ homogeneity of the mixture and physical stability	[27]
Cashew nut (*Anacardium occidentale*)	UHT at 140 °C for 4 s	no *Salmonella* spp. detection, ↓ counts of coliforms, yeasts, molds, and *Staphylococcus aureus*	[25]
	Carbonated water + fructooligosaccharide (FOS) + preservatives with or without HT at 90° for 1 min	non-significant changes in pH, acidity, soluble solids (°Brix) and reducing sugars, ↓ vitamin C content, stable fructooligosaccharides (FOS) with no hydrolysis, ↓ coliforms and yeasts/molds, no significant sensory difference. ↓↓ vitamin C with heat treatment	[28]
Pistachio (*Pistacia vera* L.)	Colloidal milling + blending in hot water (80 ± 2 °C) for 30 min. + pH 8.5. HT at 70 °C for 30 s	↑ protein, fat, dry matter, total soluble solid content	[29]
	Mixing with hot water (80 °C) + grinding + filtration + HT at 70 °C for 30 min	↓ below 1 log CFU/mL *Enterobacteriaceae*, fecal and total coliforms, enterococci, total mesophilic bacteria, yeasts, molds, *Pseudomonadaceae* and LAB. Production of waste in the filtration phase of the beverage (e.g., fibrous outer skin)	[6]
	Colloidal mill (3000 rpm with recirculation for 5/10 min) + HT at 70 °C for 30 min	Physically stable beverage with minimal sedimentation, ↓ microbial counts, no processing waste, richness in essential amino acids and bioactive peptides (Angiotensin-Converting Enzyme (ACE) inhibition, and dipeptidyl peptidase IV (DPP-IV) inhibition)	[8,30]

Table 1. *Cont.*

Raw Nut	Technological Treatment	Main Results	References
Hazelnut (*Corylus avellana*)	HPH at 100 MPa + HT at 72 °C for 20 min	No total aerobic bacteria, yeasts and molds, stable pH, ↑ protein solubility, better preservation of bioactive compounds, ↓ oxidation, no changes in hydroperoxide index, ↓ viscosity	[31,32]
	HPH at 100 MPa + HT at 105 °C for 1 min	No total aerobic bacteria, yeasts and molds, ↓ pH and protein solubility, lipolysis and proteolysis, ↑ total solid content, hydroperoxide index and viscosity, degradation of heat-sensitive compounds, starch gelatinization	[31,32]
	HPP at 200, 400, or 600 MPa for 5–10 min, at an initial temperature of 25 °C	Inhibition of total microorganisms, *Escherichia coli*, coliforms, and yeasts/molds, ↓ hazelnut allergenicity at 600 MPa; ↓ essential and non-essential amino acids; not affected fatty acid composition; stable pH, °Brix, and total sugar contents; ↑ total phenolics and flavonoids; optimum antioxidant activity	[33]
	Heat treatment at 80 °C for 3 min	↓ essential and non-essential amino acids, unaffected fatty acid composition, ↑ total sugar content, not good antioxidant activity, inhibited microbial growth	[33]
	HPH at 100 MPa + Thermosonication at 40% and 60% amplitudes for 5, 10, 15, 20, and 25 min; 80% amplitude for 3, 5, 10, and 15 min at 40–75 °C	↓ particle size, sedimentation, ↑ viscosity and consistency at 40–80% amplitude for 3–5 min, complete inactivation of total aerobic mesophilic bacteria and yeast-mould, ↓ pH, soluble protein content, syneresis and sedimentation, ↑ total phenolic compounds and antioxidant activity	[34]
	HPH at 100 MPa + HT at 85 °C for 2 min	Complete inactivation of total aerobic mesophilic bacteria and yeast-mould, ↓ pH, antioxidant capacity and soluble protein content, less desirable effects on colour, bioactive compounds and structural/rheological properties	[34]
	Cow milk + hazelnut milk in different proportions + HPH at 100 MPa	more stable pH, ↑ acidity, protein content, peroxide value, ↑ fat content, more fluctuation in pH, ↓ acidity, protein content and peroxide value	[35]
	Ingredients for probiotic yogurt fortification (0% to 50% hazelnut milk addition)	↑ pH at ↑ % hazelnut milk addition, ↑ dry matter, total phenolic content, DPPH radical scavenging activity, protein content, softer, less viscous yogurt with 50% hazelnut milk	[36]
Coconut (*Cocos nucifera* L.)	Pectin addition (0.2%, 0.3%, 0.4%) + SO_2 addition (0, 30, 50, 70 ppm) + Homogenization + HT at 100 °C for 5, 10, 15, or 20 min	↓ sedimentation level, best emulsion stability, absence of yeasts, molds, or bacterial growth, ↓ pH with at 13,000 rpm for 2 min + Pasteurization at 100 °C for 5 min + 0.3% pectin + 30 ppm SO_2	[37]
Walnut (*Juglans regia*)	HT at 120 °C for 10 min	↑ particle size, larger oil droplet aggregates formed	[24]
	Homogenization-2-stage 40 MPa	↑ particle size, large droplets broke down but tended to flocculate	[24]
	Homogenization (2-stage) at 40 MPa + HT at 120 °C for 10 min	Further ↑ particle size, more floating layer, less precipitate	[24]
	Soy milk addition + Homogenization (2-stage) at 40 MPa +HT 120 °C for 10 min	↑ dispersion stability, ↓ particle size, ↓ walnut protein aggregation, inhibition of β-sheet formation in walnut proteins, ↑ essential amino acids, acceptable sensory and textural properties	[24]

Table 1. *Cont.*

Raw Nut	Technological Treatment	Main Results	References
Pine nut (*Pinus pinea* L.)	Soaked rice + pine nuts + Pressure Homogenization at 0, 19.6 and 29.4 MPa (x2) + HT 121 °C for 20 min + pH adjusted to 5.5, 6.5, and 7.5	↑ homogenization pressure and ↑ viscosity, ↓ particle size and stability, non-homogenization and ↑ pH in pH 5.5 samples; good stability and ↓ sedimentation at 4 °C and pH 6.5; initial phase separation at 25 °C; significant sedimentation and phase separation at 40 °C and at pH 7.5	[38]

↑ = indicated an increase; ↓ = indicated a decrease; ↓↓ = indicated a significant decrease.

Conventional thermal treatments, such as pasteurization, high-temperature short-time (HTST) and ultra-high temperature (UHT) treatments, are key in ensuring the microbiological safety, extending shelf-life, and preserving overall quality of the beverages [21,22]. Over the past decade, non-thermal processing technologies such as high-pressure homogenization (HPH), high hydrostatic pressure (HHP), ohmic heating, pulsed electric fields (PEF), hydrodynamic cavitation, and cold plasma have gained significant attention in the food industry [7,23].

Among these, HPH has proven particularly effective in microbial inactivation and enhancing emulsion stability. In plant-based beverages like soy and almond milk, HPH has been shown to increase the bioavailability of certain compounds, although it may lead to some degradation of tocopherols. Vásquez-Rojas et al. [7,23] investigated the use of HPH in Brazil nut beverages for *E. coli* inactivation, applying pressures between 50 and 180 MPa and inlet temperatures ranging from 25 to 75 °C.

These treatments were compared with conventional pasteurization (63 °C for 20 min) and achieved microbial reduction of ≥8 log CFU/mL. The microbiological stability of the HPH-treated beverages remained constant for up to 21 days under refrigeration (5 °C), demonstrating excellent shelf-life potential. Importantly, the overall quality of the beverage was preserved without the use of additives. Only minor compositional changes were observed. Both HPH and pasteurization caused moderate reductions in total phenolic compounds (24–30%), squalene (22.7–26.4%), and γ-tocopherol (28.4–36%), with β-sitosterol levels remaining largely unaffected.

Despite these changes, the oxidative stability of the beverages remained intact during storage, and key physicochemical properties, including pH, titratable acidity, and °Brix values, were stable. Essential minerals and total protein contents were also largely retained, indicating minimal impact on nutritional quality.

Ultra-high pressure homogenization (UHPH) has also emerged as an effective technique for microbial inactivation and improved physical stability, often superior to traditional heat treatments such as pasteurization and UHT treatments. Studies have shown that UHPH at pressures of 200–300 MPa and inlet temperatures of 55–75 °C effectively inactivated microbes, including *Bacillus cereus*, and improved shelf life, particularly when stored at 4 °C [21,22]. UHPH reduces particle size and sedimentation, improving colloidal stability, and inactivates lipoxygenase, reducing the risk of oxidation.

Despite a slight increase in oxidation markers (hydroperoxide index), UHPH-treated beverages have no detectable off-flavors, making them a promising alternative to heat treatments [21,22]. However, Faraloni et al. [26] proposed the use of hydrodynamic cavitation (HC) as an innovative single-step alternative requiring only water, thereby significantly simplifying the process. This emerging technology is considered green, efficient, and scalable, as it eliminates the need for additives and reduces production costs, time, and energy. When both peeled and whole almonds (including skins) were subjected to cavitation at temperatures ranging from 40 °C to 86 °C, the process achieved significant microbial inactivation, with the best results at 74 °C. This temperature was effective in reducing microbial counts without the need for traditional sterilization, preserving heat-sensitive compounds. The process also maintained polyphenol content and inactivated enzymes like polyphenol oxidase and lipoxygenase, contributing to chemical stability and preventing rancidity. In addition, the cavitation process effectively extracted fats, proteins, and carbohydrates, allowing the nutritional composition of the extracts to be comparable to that of a high-end commercial biological product, while showing comparable or better microbiological stability and generally higher availability of bioactive micronutrients. Furthermore, the incorporation of hydrocolloids has been widely employed in tree nut-based beverages as a strategy to enhance physicochemical stability, particularly in terms of phase separation, sedimentation, and viscosity control [10,28,37]. In particular, for macadamia beverage, xanthan and gellan gum were used, obtaining a better homogeneity of the mixture and good physical stability. Instead of coconut beverage, the addition of pectin at different concentrations helped reduce sedimentation, without separating into layers, improving emulsion stability and making it more uniform [10,28].

Fermentation with selected microbial strains has also been identified as a promising tool to enhance the flavor, texture, nutritional value, and shelf-life of these beverages [16,30]. As shown in Table 2, numerous studies have explored the incorporation of different microbial species into various nut-based beverages to improve their quality characteristics [6,8,29,30,39–45].

Almonds, cashews, walnuts, coconuts, and pistachios are among the most studied tree nuts for fermented plant-based beverage production [6,8,30,39–45]. In particular, different lactic acid bacteria (LAB) strains belonging to the species *Streptococcus thermophilus*, *Limosilactobacillus reuteri*, *Lacticaseibacillus rhamnosus*, *Lactobacillus delbrueckii* subsp. *bulgaricus*, *Lactobacillus acidophilus*, and *Lactiplantibacillus plantarum* were employed in the fermentation of almond (*Prunus amygdalus*) beverages [39,46–50]. In addition, yeast species such as *Yarrowia lipolytica*, *Kluyveromyces marxianus*, *Candida antarctica*, *Torula casei* were also assayed for their suitability in almond milk [49].

Table 2. Fermented tree nut-based beverages: microbial species involved and key findings.

Nut Beverage	Microbial Species	Technological Treatment	Storage	Inoculum and Fermentation Conditions	Main Results	References
Almond (*Prunus amygdalus*)	*Streptococcus thermophilus* CECT 986 and *Lactobacillus reuteri* ATCC 55730, used alone	HPH at 172 MPa + inulin + HT at 85 °C for 30 min	28 days at 4 °C	10^8 CFU/mL; 37 °C for 24 h for *L. reuteri*; 42 °C for 24 h for *S. thermophilus*	physical stability; ↑ in particle size; ↓ sugars; *L. reuteri* counts >10^7 CFU/mL; ↓ *S. thermophilus* counts; mannitol production, ↓ acidity, pH ≈ 4.83; ↑ viscosity	[39]
	S. thermophilus CECT 986 and *L. reuteri* ATCC 55730, used alone	HPH at 172 MPa and HT at 85 °C for 30 min	28 days at 4 °C	10^8 CFU/mL; 37–42 °C for 24 h	↑ physical stability; aggregated proteins; ↓ fat globule size; pH ≈ 4.65; ↑ acidity	[46]
	L. rhamnosus CECT 278, *L. plantarum* 3O9, *B. bifidum* CECT 870, *B. longum* CECT 4551, *S. thermophilus* CECT 986, *L. delbrueckii* subs. *bulgaricus*, used alone and in combination	HPH at 172 MPa + HT at 121 °C for 15 min	−22 °C	10^8 CFU/mL; 37 °C until 4.4 < pH < 4.6	↓ fat globule size and pH; ↑ acidity; positive immunomodulatory effects; ↓ TNF-α and IL-6 production; ↑ iron absorption by intestinal cells; no toxic effects on Caco-2 cells	[47]
	L. rhamnosus GR-1	0, 2 and 5% short-chain or long-chain inulin addition	30 days at 4 °C	10^9 CFU/mL; 37 °C for 9 h—anaerobiosis	short-chain inulin addition ↑ viable counts ↓ pH long-chain inulin addition ↓ viable counts	[48]
	L. delbrueckii ssp. *bulgaricus* 27/23, *L. plantarum* ATCC 8014, *L. plantarum* PK 1.1., *Candida antarctica* CAN 0001, Torula casei TCS 0001, *Yarrowia lipolytica* YLP 0001, *Kluyveromyces marxianus* KF 0001, *Candida lipolytica* CLP 0001, used alone	-	-	10^5 CFU/mL for bacteria (30–37 °C for 48 h) and 10^4 CFU/mL for yeasts (30 °C for 48 h)	↑ LAB and yeast counts, *C. lipolytica* showed the lowest growth, ↓↓ pH, ↑↑ viscosity (except *C. lipolytica* beverage), ↓ major fatty acids, ↑ minor fatty acids, enrichment of the aromatic profile (especially in *Y. lipolytica* beverage)	[49]
	S. thermophilus, *L. delbrueckii* subsp. *bulgaricus*, *Lactobacillus acidophilus* (NCFM™), *Bifidobacterium lactis* (HN019™), used alone	HT at 90 °C for 10 min	21 days at 4 °C	≥10^8 UFC/mL; 42 °C ± 1 for 5 h—anaerobiosis	good LAB viability except for *B. lactis*, ↑ fats, ↓ carbohydrates, ↑ total antioxidant activity, ↑ viscosity, stable pH (4.66–4.76), ↓ acidification	[50]

Table 2. *Cont.*

Nut Beverage	Microbial Species	Technological Treatment	Storage	Inoculum and Fermentation Conditions	Main Results	References
Brazil nut (*Bertholletia excelsa*)	*Lactobacillus casei*	High-speed omogenization + Inulin and pectin addition + HT at 80 ± 1 °C for 20 min	28 days at 4 °C	6.5 log CFU/g; 37 °C for 12 h—anaerobiosis (fermentation); 4 ± 1 °C for 24 h (maturation)	↓↓ dietary fiber, ↓ total carbohydrates, minerals and pH, no yeasts and mould counts, no *Salmonella* spp. detection, Total and thermotolerant coliforms: within legal limits, good *Lactobacillus casei* stability during storage	[51]
Macadamia (*Macadamia tetraphylla*)	*L. rhamnosus*	Omega-3 fatty acids addition	-	-	↑ MUFA LAB count >10^6 CFU/mL, good sensorial acceptance	[52]
Cashew nut (*Anacardium occidentale*)	*B. animalis* BB-12®, *L. acidophilus*, *L. plantarum* Lyofast SP-1, used alone	Colloidal mill for 4 min + HT at 140 °C for 4 s	30 days at 4 °C	10^8 CFU/mL	LAB count > 10^7 CFU/mL, ↓ pH, coliforms, *Staphylococcus aureus*, yeasts, molds count < safe limits, no *Salmonella* spp.	[40]
	Lactobacillus paracasei ATCC 334	*L. paracasei* + cashew nut + HT at 72 °C ± 2 °C for 20 min	4 °C	10^7 CFU/mL; 35 °C for 6 h—anaerobiosis	↑ protein content, ↑ higher sensory acceptability, if ↑ cashew nut amount →↓ LAB amount ↑ sensorial acceptance	[41]
	L. plantarum (LAC 1), *Pediococcus acidilactici* (LAC 2), used alone and in combination	Tiger nut (*Cyperus esculentus*) milk and cashew nut milk (80:20 ratio) + HT at 82 °C for 10 min	-	10^7 CFU/g; room temperature	EPS production, ↓ pH, ↑ titratable acidity, proteins, fats and minerals, flavouring and sensory enhancement, ↑ antioxidant and/or anti-inflammatory activity in LAC 1 sample. LAB count > 10^6-10^7 CFU/mL, LAC 2 beverage had the highest overall preference	[53]

Table 2. *Cont.*

Nut Beverage	Microbial Species	Technological Treatment	Storage	Inoculum and Fermentation Conditions	Main Results	References
Cashew nut (*Anacardium occidentale*)	*Weissella paramesenteroides* TC6 and *Enterococcus faecalis* A4, used alone and in combination	Soy milk + cashew nut milk (80:20 ratio) + HT at 82 °C for 10 min	-	10^7 CFU/g; room temperature	↓ pH, bile salt resistance, ↑ titratable acidity, antioxidant and/or anti-inflammatory activity, EPS production, LAB count > 10^6–10^7 CFU/mL, TC6 + A4 milk → sensorial appreciation, TC6 milk → most preferred, A4 milk → least preferred, TC6 + A4 milk → sensory appeal and bioactivity	[54]
Coconut (*Cocos nucifera* L.)	*L. reuteri* DSM 17938 or LR 92	Homogenization + HT at 95 °C for 5 min	30 days at 4 °C	10^6 CFU/mL; 34–37 °C for 48 h	↓ pH and ↓ LAB viability during storage; DSM17938> acidification, reuterin production, more efficient use of fructose and glucose (DSM17938), build-up of fructose and use of sucrose (LR92), degradation of malic acid	[44]
	S. thermophilus, *L. delbrueckii* subsp. *bulgaricus*, *L. acidophilus*, *B. lactis* used in combination	Low/Full fat addition + Homogenization for 20 min + HT at 85 °C for 10 min	28 days at 6 °C	45 °C for 5h anaerobiosis	↓ *L. delbrueckii* subsp. *bulgaricus* and *B. lactis* count, ↓ pH, ↑ and ↓ hardness and adhesiveness in Low- and Full-fat samples, respectively. ↑ functional fatty acids and sterols	[45]
	Pediococcus acidilactici W3	HT at 90 °C for 30 min—3% yogurt starter culture, EPS, 1.5% LAB strain	14 days at 4 °C	1.5 × 10^6 CFU/mL; 44 °C for 6 h—anaerobiosis	↓ probiotic viability after 7 days of storage, ↑ lactic acid, significant antioxidant potential, viscosity, bioactivity and prebiotic potential of EPS produced by LAB strain	[55]

Table 2. *Cont.*

Nut Beverage	Microbial Species	Technological Treatment	Storage	Inoculum and Fermentation Conditions	Main Results	References
Walnut (*Juglans regia*)	*L. plantarum*	Homogenization + 95 °C for 10 min + papain hydrolysis	−80 °C	10^8 CFU/mL; 37 °C for 24 h	↓ pH,↑ LAB count, ↑ fermentation speed, ↑ antioxidant activity, ↑ *L. plantarum* growth	[42]
	L. plantarum LP56	Colloidal mill + 2 homogenization steps (35 and 40 MPa) + HT at 121 °C for 10 min	24 h at 4 °C	10^9 CFU/mL; 37 °C for 4–16 h	↓ pH, ↑ TA, ↑ free amino acids and unsaturated fatty acids; ↓ aldehydes, ↑ alcohols, esters, ketones → fruity, milky, roasted notes	[43]
	L. plantarum NBIMCC 3447, *L. gasseri* NBIMCC 2450, used alone	FOS addition (1–4%) + 121 °C for 15 min + Freeze-drying	30 days at 4 °C	~10^6 CFU/mL; 37 °C for 16–18 h pH < 4.5.	↑ LAB count, 4% FOS ↑ LAB survival after lyophilization, *L. plantarum* > *L. gasseri*. resistance to freeze-drying	[56]
	Lact. plantarum ZS2058, *Lact. casei* FZSSZ3-L1, *Lact. rhamnosus* JSWX-3-L2, *Limos. reuteri* FXJCJ4-2, *B. breve* CCFM683, used alone	Colloidal mill + lipase from *Aspergillus oryzae* addition + HT at 85 °C for 20 min	24 h at 4 °C	7 log CFU/mL; enzymatic hydrolysis at 37 °C for 3 h, 37 °C for 20–30 h	↓ pH, ↑ *B. breve* count and production of CLA and CLNA, slower growth for *Lact. casei* and *Lim. reuteri*, lipase-enhanced fatty acid bioavailability	[57]
Hazelnut (*Corylus avellana*)	*L. rhamnosus* GG, *S. thermophilus*	Inulin + xanthan gum + HT at 90 °C for 10 min	28 days at 4 °C	~10^9 CFU/mL; 37 °C for 3–5 h—anaerobiosis	↓ pH, ↑ acidity, stable colloidal properties, probiotic survival > 10^8 CFU/mL, overall good sensory acceptability	[58]
	L. delbrueckii subsp. *bulgaricus*, *S. thermophilus*	Ultrasonic homogenization at 100 W, 20 kHz for 10 min	4 °C for 12 h	~8–9 log CFU/mL 42 °C for 5 h	↑ acidity, ↑ fat content, slightly ↓ protein, ↓ pH, low viscosity, better dispersion and stability, ↓ consistency, and overall acceptability	[59]

Table 2. *Cont.*

Nut Beverage	Microbial Species	Technological Treatment	Storage	Inoculum and Fermentation Conditions	Main Results	References
Pistachio (*Pistacia vera* L.)	43 different LAB strains	Grinding (Thermomix) + HT at 70 °C for 30 min	30 days at 4 °C	~6 log CFU/mL; 30 °C for 24 h	↓ pH, good acidification, good LAB growth, sensory acceptability confirmed	[6]
	Starters used: MA400: *S. thermophilus* + 3 different *Lactococcus lactis* (subsp. *lactis*, *cremoris*, and *diacetylactis*) MY800: *S. thermophilus* + 2 *L. delbrueckii* (subsp. *lactis*, and *bulgaricus*)	Grinding (Thermomix) + HT at 70 °C for 30 min	30 days at 4 °C	30 °C for 12 h (MA400) and 42 °C for 5 h (MY800)	LAB count > 7 log CFU/g, ↓ pH, ↑ acidity, more complex volatile profile in conventional pistachios fermented with MY800, highest total volatiles in MY800-fermented conventional pistachio beverages: terpenes > aldehydes > alcohols	[60]
	S. thermophilus, *L. bulgaricus*, *L.acidophilus*, *L. gasseri*, *B. bifidum*, used alone or in combination	4 probiotic combinations: Homogenization at 10,000 rpm for 10 min + 4% inulin + HT at 85 °C for 30 min	4 °C o/n	10^7 CFU/mL; 42 °C until pH 4.6	↓ pH, 4% inulin produced ↑acetate, butyrate and lactate →↓ Caco-2 cell viability. *B. bifidum* + inulin →↑ SCFA production, acetate, and exerted strong anti-cancer effects	[61]
	Leuconostoc pseudomesenteroides D4 and *Companilactobacillus paralimentarius* G3, used alone	Colloidal mill for 5 min at room temperature + HT at 70 °C for 30 min	30 days at 4 °C	~6 log CFU/mL; 28 °C for 24 h	↓ pH, ↑ lactic and acetic acid production, ↑↑ LAB count, ↑ free amino group and antioxidant activity, 31 potentially bioactive peptides, ↓ 2S albumin, 7S and 11S globulins, ↓ IgE-binding capacity	[30,62]
	Leuc. pseudomesenteroides PD4, *Lact. plantarum* PT1, *Comp. kimchi* PU2, *Lact. plantarum* PV2, *Comp. alimentarius* PG3, and *Lact. paraplantarum* PN4, used alone	colloidal mill 3000 rpm for 10 min + HT at 70 °C for 30 min	30 days at 4 °C	~6 log CFU/mL; 28 °C for 24 h	↑ glutamic acid (Glu), arginine (Arg), and serine (Ser), GABA, LAB counts > 10^8 CFU/mL, terpenoids, acetoin and 2,3-butanedione production, contaminating microbial count < 1 log CFU/mL, ↑ alcohol production in presence of *Leuc. pseudomesenteroides* PD4	[8,17]

↑ = indicated an increase;↓ = indicated a decrease; ↑↑ = indicated a significant increase; ↓↓ = indicated a significant decrease; GABA = gamma-aminobutyric acid.

In general, both lactic acid bacteria and yeast strains demonstrated strong growth potential during fermentation, maintaining high viable loads even after cold storage, especially when probiotic strains were used. As a result, the plant-based beverages remained microbiologically stable, nutritionally rich, and enhanced in both texture and functionality [63]. Furthermore, da Cunha et al. [51] developed a fermented, symbiotic Brazil nut-based beverage using *Lacticaseibacillus casei* and inulin. Microbiological tests confirmed its safety, with no spoilage detected in the fermented version, unlike the control. *Lacticaseibacillus casei* maintained microbial stability through acid production and remained viable above the probiotic threshold throughout storage (28 days, 4 °C), with only a slight decline. Although inulin offered limited protection, probiotic levels stayed effective.

Microencapsulation is recommended to further improve the survival of probiotics and their targeted release in the intestine. Trinidad et al. [52] developed a functional macadamia-based beverage incorporating encapsulated *Lacticaseibacillus rhamnosus*, a probiotic known for its resilience under gastrointestinal conditions. The final product was nutritionally rich, microbiologically safe, and sensorially acceptable, aligning with current dietary trends and demonstrating potential for market introduction.

In recent years, cashews have garnered increasing attention in the development of nut-based beverages. Bruno et al. [40] assessed the potential of cashew nut milk as a carrier for probiotics, specifically evaluating the viability of *Bifidobacterium animalis*, *Lactobacillus acidophilus*, and *Lactiplantibacillus plantarum* over 30 days of refrigerated storage (4 °C). Their findings indicated high probiotic viability, favorable sensory properties, and preservation of the beverage's original color.

Recent studies have explored the use of cashew nuts in probiotic plant-based beverages. Sousa et al. [41] examined the impact of different concentrations of *Lacticaseibacillus paracasei* (1–2%) and cashew nut content (100–300 g) on the composition and sensory properties of cashew-based beverages. After fermentation, *Lact. paracasei* remained viable, reaching concentrations sufficient for probiotic benefits [48,64] and confirming the suitability of cashew milk as a non-dairy probiotic matrix. Assamoi et al. [53] further advanced this research by developing two innovative plant-based fermented beverages, combining cashew nuts with tiger nut milk and soy milk [54], respectively. The tiger nut–cashew blend was fermented with *Lactiplantibacillus plantarum* and *Pediococcus acidilactici*, while the soy–cashew blend was fermented with *Weissella paramesenteroides* and *Enterococcus faecalis*.

The results confirmed the feasibility and health potential of cashew-based and blended plant-based milks fermented with indigenous LAB strains.

Coconut milk has also been fermented using various LAB strains such as *L. reuteri*, *S. thermophilus*, *L. delbrueckii* subsp. *bulgaricus*, *L. acidophilus*, *Pediococcus acidilactici*, used either individually or in combination, as reported in Table 2. In particular, Adebayo-Tayo et al. [55] demonstrated the efficacy of *Pediococcus acidilactici* as a starter culture for coconut-based probiotic beverage. The strain's ability to synthesize heteropolymeric exopolysaccharides (EPS) with notable antioxidant activity supports the development of natural, functional, and nutraceutical beverages suitable for lactose-intolerant consumers. Several strains of lactic acid bacteria have also been successfully used in the production of fermented walnut and hazelnut beverages, highlighting the broad applicability of microbial fermentation across diverse tree nut matrices to enhance nutritional value, safety and consumer appeal [42,43,56–59].

Various studies have employed *L. plantarum* strains for the production of fermented walnut beverages [42,43,56,57]. In particular, it has been shown that fermentation with *L. plantarum* can improve the sensory and functional qualities of walnut milk by increasing umami and sweet amino acids, as well as polyunsaturated fatty acids [43]. Flavor quality was also improved by decreasing aldehydes and increasing alcohols, acids, esters, and ketones [43].

Similarly, several authors have successfully applied lactic acid fermentation in the development of pistachio-based beverages [6,8,60]. These investigations confirm the feasibility and potential of using pistachios as a matrix for the production of fermented functional beverages. Moreover, Garzón et al. [17] demonstrated that LAB fermentation enhances mineral bioaccessibility, primarily by reducing antinutrients like phytic acid and increasing ascorbic acid content, which in turn promotes iron bioavailability. Finally, Marulo et al. [30] developed a novel pistachio beverage fermented with strains *Leuconostoc pseudomesenteroides* and *Companilactobacillus paralimentarius*, highlighting that fermentation generated numerous bioactive peptides associated with antioxidant activity and inhibitory effects on enzymes of physiological relevance. These findings underscore the potential of fermented pistachio beverages as functional foods with promising health benefits.

Overall, the growing body of literature emphasizes the importance of adopting rational and systematic approaches in the selection and combination of microbial strains, aiming to promote synergistic interactions that enhance both the predictability and quality of tree nut-based fermented products.

3. Nutritional Characteristics

As previously discussed, the development and consumption of PBBs is driven by various factors, including their potential as culinary substitutes for cow’s milk or other mammalian milk. However, consumers should be aware that PBBs differ significantly from cow’s milk in terms of nutritional composition [4,11]. In particular, there are notable differences between the nutritional profile of raw materials, such as nuts, and the beverages derived from them.

Raw nuts are mainly known for their high fat content, especially their richness in monounsaturated and polyunsaturated fatty acids (MUFA and PUFA, respectively). Additionally, they are valuable sources of protein, dietary fiber, and essential minerals such as potassium, calcium, and magnesium. They also contain certain prebiotic compounds that can support gut health [65,66].

In contrast, nut-based beverages are typically prepared by dehulling the nuts, blending them with water, and filtering the mixture. This process significantly dilutes the nutrients found in whole nuts [67–69]. Consequently, the final beverage often contains lower concentrations of proteins, fats, and micronutrients compared to the raw nut.

Table 3 summarizes the nutritional composition of different raw nuts and their corresponding beverages. For comparison, the composition of whole cow’s milk, considered as the most common dairy milk, is also included. When assessing the nutritional composition of nut-based beverages, it is important to consider not only the type and quality of the raw ingredients used, but also the specific processing methods applied. Steps such as soaking, roasting, milling, or de-oiling can significantly alter the nutritional composition of the final product [29,69].

Table 3. Nutritional composition of raw nuts and beverages derived from them.

Nut	Product	Energy [1]	Lipids	Proteins	CarboH	Fiber	Ashes	References
Almond (*Prunus amygdalu*)	Raw almond	584	51.4	21.4	20.0	10.8	3.2	[70]
	Beverage made with soaked (12 h) almonds, then blended with water 1:5 (almond/water) and filtered	68	5.4	2.5	2.4	-	-	[71]
	Beverage made with 4% (*w*/*w*) almond in water at 80 °C, milled, filtered and homogenized. Lecithin (0.03% *w*/*w*) was added	26	2.2	0.9	0.6	-	0.2	[72]
	Sweetened beverage made with almonds mixed with water (4 °C—6 h), drained, milled (1:3 nut/water *w*/*v*) and strained. Sugar syrup was added and the filtrate was homogenized	55	3.4	1.7	4.5	1.3	3.0	[73]
	Beverage made with almond, unsweetened, plain	15	1.2	0.6	0.3	0.5	0.5	[70]
Brazil nut (*Bertholletia excels*)	Raw Brazil nut	669	58.5	16.0	19.6	-	3.4	[74]
	Beverage made with ground Brazil nuts, homogenized with water at 75 °C, ratio of 7:1 (water/Brazil nut, *v*/*w*), filtered and partially defatted	41.3	2.9	1.3	1.1	-	0.1	[75]
	Beverage made with ground Brazil nuts, homogenized with water at 75 °C, ratio 7:1 (water/raw material, *v*/*w*), and filtered	60.6	5.2	1.4	1.9	-	0.3	[74]
	Beverage made with Brazil nut (40%), macadamia nut (10%), and water (50%)	-	-	7.4	4.0	-	1.5	[76]
Cashew nut (*Anacardium occidentale*)	Raw cashew nut	533	38.9	17.4	36.3	4.1	2.6	[70]
	Beverage made with soaked (12 h) cashews, then blended with water 1:5 (cashew/water) and filtered	60	4.5	1.8	3.1	-	-	[71]
	Sweetened beverage made with ground cashew mixed 1:10 with water, 3% sugar, and heat-treated (140 °C—4 s)	65	4.0	1.8	5.4		0.3	[25]
	Commercial hazelnut beverages	55	-	1.1	0.8	-	-	[77] [2]
Hazelnut (*Corylus avellana*)	Raw hazelnut	602	53.5	13.5	26.5	8.4	2.2	[70]
	Beverage made with soaked (12 h) hazelnuts, then blended with water 1:5 (hazelnut/water) and filtered	74	7.3	1.0	1.0	-	-	[71]
	Commercial hazelnut beverages	70	-	1.0	7.3	-	-	[77] [2]

Table 3. *Cont.*

Nut	Product	Energy [1]	Lipids	Proteins	CarboH	Fiber	Ashes	References
Macadamia nut (*Macadamia integrifolia*)	Raw macadamia nut	669	64.9	7.8	24.1	7.6	1.4	[70]
	Beverage made with macadamia nut (40%), Brazil nut (10%), and water (50%)	-	-	4.8	5.7	-	0.9	[76]
Pistachio (*Pistacia vera*)	Raw pistachio	598	45.0	20.5	27.7	7.0	2.8	[70]
	Beverage made from roasted or soaked pistachios and hot water 1:5 (pistachio/water) and sugar (5%)	-	5.0–6.0	3.0–4.4	-	-	-	[29]
	Beverage made from soaked pistachios and hot water 1:5 (pistachio/water) and filtered	-	-	1.6–1.7	-	-	0.2–0.3	[60]
	Fermented beverage made with soaked pistachio (25 °C—5 h), ground, filtered, and heat-treated	50	4.6	2.0	0.2	2.9	0.3	[6]
	Fermented beverage made with ground pistachios (1:5 pistachio/water) in a colloidal mill (10 min)	99	8.3	4.2	1.9	2.1	0.6	[8]
Walnut (*Juglans regia*)	Raw walnut	690	62.1	16.1	16.0	-	1.2	[78]
	Soaked walnut (60 °C—2 h) and homogenized 1:8 with water at 60 °C and filtered	-	66.2	2.9	-	-	-	[79]
	Beverage made with boiled walnuts (1 h), blended with water (1:2 *w*/*v*) and filtered	92	7.4	1.7	4.8	-	0.2	[80]
	Beverage made with soaked (12 h) walnuts, then blended with water 1:5 (walnut/water) and filtered	72	7.5	0.8	0.4	-	-	[71]
	Beverage made with soaked (10 h) walnuts, then blended with water 1:7 (walnut/water), filtered and mixed with fructose	73	5.0	2.3	4.7	-	0.7	[81]
Cow's milk (whole)		61	3.2	3.3	4.63	-	0.8	[70]

f.w.= fresh weight; CarboH = Carbohydrates; [1] Energy content was calculated according to Atwater Factors and express as kcal/100 g; lipids, proteins, CarboH, fiber and ashes are expressed as g/100 g f.w.; [2] Average values of seven (cashew) or three (hazelnut) commercial beverages from Australia, France, Spain, United Kingdom or United States.

3.1. Energy Content

Raw nuts are nutrient-rich foods with a high fat content and, therefore, a high energy value. According to the U.S. Department of Agriculture (USDA) food database, most nuts provide over 500 kcal/100 g, with some varieties reaching 700 kcal/100 g [70]. On the other hand, nut-based beverages such as almond, cashew, or walnut drinks typically contain less than 100 kcal/100 mL, with some products delivering as little as ~20 kcal/100 mL [71,72,80]. This significantly lower caloric content may benefit individuals aiming to reduce their overall energy intake [82]. The transformation of nuts into beverages leads to a substantial dilution of their caloric density. In some cases, the reduction exceeds 90%, as observed by Vasquez-Rojas et al. [74], who reported that raw Brazil nuts contain 669 kcal/100 g fresh weight (f.w.), whereas a beverage prepared from them contained only 60.6 kcal/100 g f.w. When comparing cow's milk to nut-based beverages, the energy content is often similar, particularly among commercial formulations [70].

3.2. Lipids and Fatty Acid Composition

As previously mentioned, lipids represent one of the most important components of nuts, with values around 39–73 g/100 g fresh weight (f.w.). However, when nuts are processed into beverages, the fat content is substantially reduced, typically falling within the range of 1.2 to 2.2 g/100 g f.w [70,72]. Notable exceptions have been reported by Bolarinwa et al. [80] and Gocer & Koptagel [71], who found higher lipid concentrations in walnut (7.4–7.5 g/100 g f.w.) and hazelnut beverages (7.3 g/100 g). In terms of fatty acid composition, Gocer & Koptagel [71] observed that the highest value of MUFA was found in hazelnut beverages, while the highest content of PUFA was found in walnut beverages. Similarly, Eshonturaev et al. [83] evaluated the fatty acid composition of almond beverage and found that the unsaturated fatty acids represented 92.5% of the total lipids, while saturated fatty acids accounted for only 7.5%. In general, nut-based beverages can contain higher fat levels than cow's milk, leading in some cases to a higher energy content, as observed in a study carried out by Gocer & Koptagel [71]. This highlights the importance of evaluating the type of nut and processing method used when assessing the nutritional and caloric properties of these beverages.

3.3. Protein Content

Protein content of raw nuts typically ranges between 7.8 and 21.4% (f.w.). In contrast, PBBs made from nuts generally contain between 1% and 2.5% protein. Exceptions include a pistachio beverage with 4.4% protein, reported by Shakerardekani et al. [29], and a walnut beverage with 2.9% protein made by Zhai et al. [79]. A Brazil nut beverage evaluated by Vasquez-Rojas et al. [74] showed a 90% reduction in protein content compared to the raw nut. Craig & Fresán [77] evaluated nut beverages from different countries, finding that none of the samples met a suggested nutrient guideline of at least 5 g of protein per serving. However, combining nuts with protein-rich ingredients such as legumes has been proposed as a promising strategy to enhance the protein content of these beverages. Compared with cow's milk, which contains 3.3% protein, most nut-based beverages have a significantly lower protein content. This nutritional difference should be considered by individuals following a plant-based diet. While raw nuts are recognized as good sources of protein, the beverages derived from them fall short of delivering equivalent amount.

3.4. Carbohydrates, Fiber and Sugar Composition

Content of carbohydrates in raw nuts is approximately 12–36 g/100 g f.w. Similarly to other nutrients, carbohydrates undergo significant dilution during the processing of nuts into beverages, leading to products with 0.3–5.4 g/100 g f.w. On the other hand, fiber represents an important part of the raw nuts, with some varieties providing almost 11 g of fiber per 100 g. However, in nut-based beverages, fiber content is usually very low or not reported, as it is often removed during processing (e.g., filtration) or not determined experimentally. When evaluating carbohydrate and sugar content of PBBs, it is important to differentiate between unsweetened and sweetened products. Many commercial nut beverages include added sugars, sugar syrups, or other mono- or disaccharides to enhance flavour. For example, Craig and Fresan [77] found that 46% of the almond milk samples they evaluated contained more than 5g of sugar per serving. Gocer & Koptagel [71] evaluated the sugar composition of different nut beverages and reported notable findings, such as 1.9 g/100 mL. of fructose in cashew nut beverages and 1.2 g/100 mL in almond beverages. Despite the health benefits of consuming PBBs, there should be regulations on the maximum amount of sugar allowed in these products since sugar is often used to improve their sensory qualities. With high sugar levels, these beverages become unhealthy foods, which represents a problem for those who use them as a replacement for cow's milk, for example. Dhaver et al. [84] compared the effects of almond and cow's milk on postprandial glycemia of diabetic individuals, finding no significant differences.

One important distinction between cow's milk and nut-based beverages lies in their fiber content. Unlike bovine milk, which contains negligible fiber, nut beverages, especially those that are non-filtered, can retain small amounts of dietary fiber, offering a potential benefit for individuals seeking fiber-rich alternatives.

3.5. Mineral and Vitamin Content

Ash content, an indicator of total mineral content of raw nuts or their derived beverages, is usually lower than 3 g/100 g f.w. Alozie Yetunde & Udofia [73] evaluated the mineral content of almond milk and reported an ash content of 3.04 g/100 mL. The predominant minerals were phosphorus (75.2 mg/100 mL), potassium (65.3 mg/100 mL), and magnesium (42.0 mg/100 mL). Brazil nuts are an important source of selenium, as determined by Vasquez-Rojas et al. [74], who found selenium levels of 36 μg/100 g f.w. in raw Brazilian nuts. However, this concentration was significantly reduced in the corresponding beverage, which contained only 15 μg/100 g f.w [74,85]. Calcium can represent a controversy between consumers of dairy and plant-based beverages. Cow's milk naturally contains around 120 mg of calcium per 100 mL. To match this level, many commercial nut beverages are fortified. Craig & Fresán [77] evaluated 148 PBBs from three different countries and found that 115 of them were fortified with calcium, with concentrations ranging from 100 to 450 mg/serving. In addition to fortification, processing techniques such as lactic acid bacteria fermentation of PBBs may improve mineral bioaccessibility. Garzón et al. [17] found that fermenting a pistachio-based beverage with lactic acid bacteria not only increases calcium bioavailability, but also significantly reduces phytic acid content, an antinutritional factor known to inhibit mineral absorption. While PBBs can be valuable sources of certain essential minerals, it is also important to consider their sodium content. High sodium intake is associated with adverse health outcomes. Craig & Fresán [77] assessed the compliance of different nut beverages with a suggested nutrient guideline of these products in having no more than 115 mg of sodium per serving. These authors found that only half of the almond beverages fulfilled this characteristic, while other cashew-based beverages showed better compliance, reaching values of more than 70%.

3.6. Other Nutritional Aspects of Nut Beverages

Besides their macro- and micronutrient composition, nut-based beverages offer potential health benefits for individuals with lactose intolerance or cow's milk protein allergy, as well as being an alternative for those who follow a vegan or plant-based diet [68,86].

In this sense, optimizing the formulations of PBBs is of great importance, as it allows for the production of safe alternatives for individuals who cannot consume dairy products. Optimization strategies include avoiding cross-contamination between dairy products and tree-nut beverages and ensuring correct labeling, as well as having policies that regulate these aspects. Regarding the vegan population or for those who choose PBBs as an alternative to dairy for other reasons, it is important that a minimum nutritional and sensory quality be achieved so that products can truly replace dairy. On the other hand, it is important to consider that nut allergies are a concern for some individuals, as certain nuts can trigger severe allergic reactions [87]. In this regard, it is of vital importance to correctly identify the possible allergens in PBBs. Jonas da Rocha Esperança et al. [11] commented on the importance of monitoring allergens in tree-nut beverages. In many cases, manufacturers may intentionally modify these products by adding undeclared nut mixtures, or they may unintentionally cross-contaminate them with different nuts. These factors can lead to the unidentified presence of potentially fatal allergens for those individuals with allergen sensitivities. In addition, as in other sectors of the food industry, allergen detection is often expensive and complex and may not be effective in all cases. It is imperative to correctly declare allergens on the labels of these products and adapt to each country's regulations. In some countries, allergen declarations are based on phrases such as "This food may contain nuts or their derivatives." This type of labeling provides general information for individuals with nut allergies and eliminates the need for specific allergen screening. Another important consideration is the lack of regulation in some countries regarding the minimum amount of nuts or other ingredients that PBBs must contain. As noted by Scholz-Ahrens et al. [68], the absence of standardized requirements may lead to significant variability in the nutritional composition of commercial nut-based beverages [4]. Another important aspect that can be considered is the use of food additives in order to enhance the sensory quality of PBBs and to extend the shelf-life. Although the controlled use of additives should not reduce the nutritional quality of products or represent a problem, consumers who prefer healthy products may disagree with the use of these additives. In this sense, manufacturers may benefit from applying techniques that help preserve PPBs without the use of additives.

Beyond the above-mentioned composition of nut-based beverages, different authors have taken a step forward in improving the nutritional quality of these types of products. In this regard, several probiotic nut-based beverages have been developed using different bacterial strains [60,66]. Lipan et al. [67] evaluated an almond milk enriched with *Lactobacillus plantarum*, which resulted in a product with improved mineral and fatty acid content. Similarly, some authors demonstrated that lactic acid bacteria fermentation led to the release of certain bioactive peptides of health interest [30]. Plant-based beverages are increasingly recognized as suitable matrices for the development of probiotic products, since they naturally contain non-digestible compounds (such as certain fibers and oligosaccharides) that can support the growth and viability of different bacterial cultures [60].

4. Sensory Aspects of Nut-Based Beverages

When considering sensory aspects of nut-based beverages, it is important to distinguish between regular and non-regular consumers of such products. It can be assumed that certain consumers, such as vegans, value sensory attributes differently from non-vegans. However, much of the scientific literature on nut beverages lacks detailed demographics or dietary information about the individuals involved in sensory evaluations. This gap poses challenges for both interpreting results and designing effective sensory testing protocols. Producers of nut-based PBBs should carefully consider the characteristics of their target market and conduct sensory trials with panels tailored to these specific profiles.

Understanding consumer expectations is essential for developing products that are both appealing and acceptable.

Like other foodstuffs, nuts exhibit a distinctive volatile compound profile that contributes to their aroma and flavor. These include acids, alcohols, aldehydes, ketones, esters, and aromatic compounds. For instance, benzaldehyde, known for its sweet, almond-like aroma, is a common compound in almond-based beverages, while hazelnut beverages often contain pyrazines, which contribute roasted or nutty notes [88]. However, some volatile compounds identified in nut beverages, such as pentanal and hexanal, can result in the development of off-flavors, negatively affecting consumer acceptance [89,90].

The study conducted by Vaikma et al. [88] provided noteworthy findings related to the sensory attributes of nut-based PBBs, offering insights into both consumer preferences and potential areas for product optimization.

According to Vaikma et al. [88], beverages made from almonds, Brazil nuts, and cashew nuts exhibited a salty taste, while umami notes were also detected in the latter two. These flavor characteristics may influence consumer perception and acceptance. In support of this, Moss et al. [91] reported that nutty flavors, in particular, can enhance the overall acceptability of nut-based beverages among the general consumers.

Furthermore, Vaikma et al. [88] observed that the intensity of nutty flavors, especially in hazelnut beverages, can be increased through specific heat treatments. These processing methods may enhance the release of desirable volatile compounds, contributing positively to the sensory profile. Additionally, combining different types of nuts in a single formulation has been shown to enhance both aroma and flavor complexity, potentially improving consumer appeal [11]. The majority of plant-based beverages can be classified as oil-in-water emulsions [72,75,88], making them prone to instability phenomena such as syneresis, coalescence, creaming, and flocculation. These issues can impact the sensory acceptability of the products [72,92]. To mitigate these issues, the use of emulsifiers has been suggested as an effective strategy to improve the stability of these beverages [10] (Figure 2).

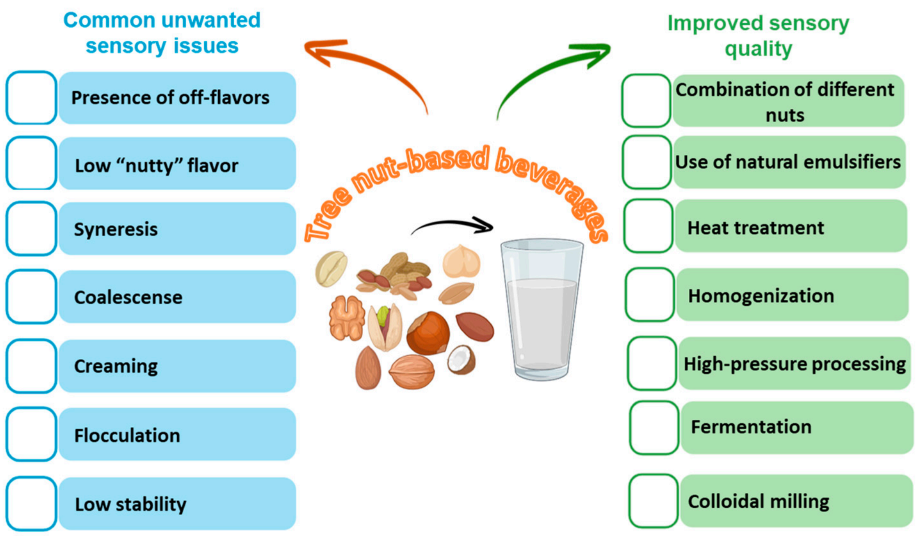

Figure 2. Common sensory issues in nut-based beverages and possible strategies to improve sensory quality. The figure was created with Biorender.com.

The sensory evaluation of plant-based beverages (PBBs), particularly those derived from nuts, is a critical factor influencing consumer acceptance and product success. Both formulation strategies and processing methods play a significant role in shaping sensory properties such as appearance, flavor, mouthfeel, and overall acceptability.

Emulsifiers and stabilizers are commonly employed to enhance the stability and sensory appeal of nut-based beverages. For instance, Hasan et al. [72] investigated the effect of lecithin in almond milk and found that it successfully prevented sedimentation and enhanced the overall stability of the product after seven days of storage. Similarly, Camacho-Teodocio et al. [10] explored the combined use of soy lecithin and xanthan gum in a macadamia nut beverage. Their findings showed that this combination improved both physical stability and sensory attributes over a two-month period.

Beyond additives, processing technologies such as high-pressure processing (HPP) and homogenization have also been recognized as effective methods for improving the sensory characteristics of plant-based beverages, including color and palatability [11,23].

Additionally, external factors like storage temperature can influence product stability and, by extension, sensory performance [93]. Among nut-based beverages, almond milk appears as one of the most consumed and studied [11]. In a study conducted by Moss et al. [91], 323 participants were surveyed regarding their preferences for nut-based drinks. The results revealed that almond beverage was the most preferred, selected by 19% of consumers, compared to cashew drink, which was preferred by only 6%.

When evaluated on a 9-point hedonic scale, almond milk scored around 7 for both appearance and mouthfeel, whereas cashew drink received significantly lower scores (4.1 for appearance and 5.7 for mouthfeel). Notably, the addition of chocolate flavoring to almond beverage increased its overall acceptance by enhancing its appearance, flavor, and overall liking.

Similarly, the sensory properties of sweetened almond milk were assessed by Alozie Yetunde & Udofia [73], using a consumer panel of individuals familiar with such products. Their study yielded positive results, with almond milk receiving scores around 2 on a 9-point hedonic scale (where 1 = Excellent and 9 = Very Poor) for attributes like color, mouthfeel, flavor, taste, and overall acceptability. Furthermore, almond milk outperformed a soy-based control drink in all sensory parameters.

In contrast, different commercial and formulated almond milks were evaluated by Ong et al. [94], providing further insights into the sensory characteristics of this widely consumed beverage. The authors found significant differences not only between the two main sample types but also among the different commercial almond milk brands. Some panelists detected a roasted flavor, likely associated with pasteurization process. Similarly, Vaikma et al. [88] analyzed over 20 almond milk samples and reported the presence of volatile compounds such as alcohols, aldehydes, and ketones, which contributed to sweet sensory notes. However, they also noted substantial variability in the sensory properties across the different almond beverages.

Despite previously reported negative sensory outcomes for cashew-based beverages, Bruno et al. [40] developed a plant-based beverage (PBB) from cashew and found promising results using a hedonic scale: 75% of the sensory scores ranged between "like slightly" and "like extremely." The authors also evaluated specific sensory attributes, reporting favorable results for color, and noted that no particles were perceived in the mouth, indicating good product homogeneity. Additionally, the beverage maintained good sensory acceptance and shelf stability over a 60-day period. Sen and Kahveci [95] assessed two hazelnut-based beverages formulated with either 2% or 4% (w/v) hazelnut protein, using a 9-point hedonic scale. Their findings showed that the 2% formulation received lower scores for appearance and higher ratings for bitterness and sourness compared to the 4% sample. Regarding mixed nut beverages, Machado et al. [76] conducted a sensory evaluation of beverages made with varying proportions of macadamia and Brazil nut. None of the formulations achieved the highest scores on the 9-point hedonic scale; instead, all evaluated sensory attributes received moderate ratings between 5 and 7. Sensory evaluations of other nut-based beverages have also included pistachio products. Shakerardekani et al. [29] reported favorable sensory results for a pistachio beverage composed of roasted and milled pistachios blended with hot water and sugar. Using a hedonic test, the beverage received a score of 8.2 on a 9-point scale, indicating high acceptability. In contrast, Tavakoli et al. [96] assessed a beverage formulated with pistachio hull and stevia, evaluated by a semi-trained panel. This product received lower overall acceptability scores compared to a control beverage without pistachio. Furthermore, the study found that increasing the concentration of pistachio hull led to decreased sensory acceptance, with the 6% (w/v) formulation receiving the lowest ratings.

Regarding fermented pistachio beverages, Sánchez-Bravo et al. [60] conducted a sensory analysis using a trained panel and reported moderate scores for pistachio-related attributes. On a 1–10 scale, the pistachio flavor scored approximately 6, while pistachio odor received a score of around 4. These findings highlight the potential loss or alteration of original nut characteristics during processing into fermented beverages.

Several studies have also examined the sensory acceptance of walnut-based beverages. Zhai et al. [79] reported low overall acceptability (score of 2 on a 0–5 scale) for plain walnut milk; fermentation significantly improved scores, especially for texture and flavor.

In contrast, Bolarinwa et al. [80] found better results for 100% walnut milk, which received an overall acceptability score of 6.4 on a 9-point scale, with all individual attributes (color, taste, flavor, and mouthfeel) rated above 5. Moreover, substituting 10% of the walnut milk with soy milk significantly improved overall acceptability, attributed to enhanced flavor and mouthfeel.

These findings suggest that nut-based beverages formulated with multiple ingredients may offer a promising strategy for improving sensory attributes and consumer acceptance.

When comparing nut-based beverages to cow's milk, sensory differences are undeniable. Nonetheless, among PBBs, nut milks tend to more closely resemble the taste of dairy milk in terms of taste and color. A particularly comparable attribute is the white appearance of nut milks, which contrasts with the darker hues often in cereal-, legume-, or seed-based beverages- colors that may negatively influence consumer acceptance [88,97]. Despite these sensory differences and the potentially lower acceptance of PBBs relative to cow's milk, it is essential to consider the broader context in which consumers make purchasing decisions, including nutritional value, ethical concerns, economic factors, and marketing influences.

5. Potential Health Benefits of Nut Plant-Based Beverages

Tree nuts are well recognized for their nutritional value and bioactive properties. They are rich sources of essential fatty acids, vitamin E, and diverse bioactive compounds, including sterols and polyphenols, which contribute to their health-promoting effects. Polyphenols, in particular, have been noted for their protective roles against cardiovascular dysfunction, metabolic syndrome, diabetes, inflammation-related conditions, and cancer [98].

The retention of bioactive compounds in tree nut-based beverages depends largely on two factors: (i) the incorporation of all parts of the nut into the beverage without generating waste, and (ii) the extent to which food processing preserves or degrades these compounds. On the other hand, some processes, such as fermentation, can enhance the bioaccessibility of bioactive compounds. Therefore, the health-promoting potential of nut-based beverages results from a balance between the degradation and enhancement of these compounds during production. Table 4 shows the bioactive or health-related properties investigated in different tree nut-based beverages produced under different processing conditions, along with the bioactive compounds associated with these benefits.

Table 4. Bioactive compound content and health properties of tree nut-based beverages.

Nut Beverage	Process	Health Property	Bioactive Compound Content	References
Almond (*Prunus amygdalus*)	Fermented with *Lactobacillus* spp. and stored for 21 days	In vitro antioxidant (DPPH, FRAP and FIC).	TPC (30.7–90.1 µg GAE/mL) TFC (16.0–27.3 µg/g)	[18]
	Pulsed electric field treatment and stored for 28 days	In vitro antioxidant activity (DPPH and TEAC).	TPC (748.3 µg GAE/g) TFC (420.7 µg CE/g)	[99]
	Thermosonication (45 °C for 40 min)	In vitro antioxidant (DPPH, TEAC, hydroxyl radical scavenging).	TPC (766.3 µg GAE/g) TFC (429.2 µg GAE/g)	[99]
	Spray-dried almond milk, enriched with probiotic (*L. plantarum* ATCC 8014)	In vitro antioxidant activity (ABTS, DPPH and FRAP).	TPC (710 µg GAE/kg)	[67]
	Microfluidization in a HPH + Fermentation with *Lactobacillus* spp. + simulated gastrointestinal digestion	Positive immunomodulatory effects on macrophages. Increase iron uptake by intestinal epithelial cells.	-	[47]
	Processing with kitchen blender, boiling for 20 min, and straining fermented with *L. plantarum* L42g	DPPH radical scavenging activities (%) decreased from the initial 43.2% to 29.2% at 12 h fermentation, then sharply increasing to 62% at 24 h.	GABA (~1500 mg/L at 12 h and 2500 mg/L at 24 h fermentation)	[100]
	-	Clinical study (30 volunteers) of daily consumption (240 mL) of almond milk for 4 weeks: decreased body weight, body mass index and waist and hip circumference, without effect on.	-	[82]
Baru almond (*Dipteryx alata*)	High-intensity ultrasound and probiotic fermented (*L. casei*-01), stored for 28 days	In vitro antidiabetogenic (α-amylase and α-glucosidase inhibition). In vitro antioxidant (ABTS and DPPH scavenging).	Gallic acid (2300 µg /L, BI 33%) Procyanidin B1 (2960 µg/L, BI 79%) Quercetin 3-glucoside (3870 µg/L, BI 71%) Procyanidin A2 (6390 µg/L, BI 64%)	[19]

Table 4. *Cont.*

Nut Beverage	Process	Health Property	Bioactive Compound Content	References
Pistachio (*Pistacia vera* L.)	-	In vitro antioxidant (DPPH)	Gallic acid (0.2–2.5 μg/g) Catechin (19.4–80.2 μg/g) Ferulic acid (0.2–3.9 μg/g) Quercetin (0.9–2.3 μg/g)	[101]
	Fermented with *L. pseudomesenteroides* D4 and *C. paralimentarius* G3	In silico bioactive peptides identified: ACE inhibitor, Renin inhibitor, DPP-IV inhibitor, antioxidant.	Bioactive peptides (494 endogenous peptides identified by LC-MS/MS)	[30]
	Fermented with *Lactobacillus* spp.	Cytotoxicity and apoptotic cell death against colon carcinoma cells (Caco-2), through the microtubule disruption and nuclear damage mediated by caspase-3 (potential for treatment of colon cancer).	-	[61]
Hazelnut (*Corylus avellana*)	-	In vitro antioxidant activity (DPPH and FRAP).	TPC (51.4 μg/mL)	[102]
	Fermented with kefir grains	In vitro antioxidant activity (DPPH, reducing power, and ferrous-ion chelating ability).	TPC (917 μg GAE/mL)	[103]
Brazil nut (*Bertholletia excelsa*)	Nuts were ground, homogenized with water and filtered with stainless mesh	In vitro antioxidant activity (DPPH, TEAc and ORAC).	TPC (795–3140 μg GAE/g d.b.)	[74]
	High-pressure homogenization treatment and storage for 21 days	In vitro antioxidant activity (ABTS and DPPH).	TPC (69.2 μg GAE/mL)	[7]
	Mineral enrichment: 25 mg of calcium plus 0.35 mg of iron (5% DRIs of minerals)	In vivo studies: beverage administration on Wistar rats: decreases in retroperitoneal adipose tissue, total cholesterol, and triglycerides.	TPC (50 μg GAE/g)	[12]
Macadamia (*Macadamia integrifolia*)	Formulated with xanthan gum and soy lecithin	In vitro antioxidant (ABTS and DPPH).	-	[10]

TPC: total phenolic content; TFC: total flavonoid content; BI: bioaccessibility; GAE: gallic acid equivalent; CE: catechin equivalent; FIC: ferrous ion chelating ability; GABA: gamma-aminobutyric acid.

Almond (*Prunus dulcis*) beverages have been produced using various processing methods, including thermosonication [15], pulsed electric field treatment [99], and microfluidization via high-pressure homogenization [47], with or without fermentation. Additionally, probiotic almond milk powder has been developed through spray drying [67]. These processing techniques influenced total phenolic and flavonoid content, as well as antioxidant capacity, typically assessed using DPPH and FRAP assays. Furthermore, antidiabetogenic potential was assessed via α-amylase and α-glucosidase inhibition assays. Bernat et al. [47] reported that almond milk fermented with *Bifidobacterium bifidum* or *Bifidobacterium longum* enhanced intestinal energy metabolism and reduced pro-inflammatory production, suggesting potential benefits for allergy and intolerance management.

Buatong et al. [100] prepared fermented almond beverages using *Lactoplantibacillus plantarum* L42g. After 24 h of fermentation, gamma-aminobutyric acid (GABA) levels reached ~2500 mg/L, along with increases in antioxidants and antibacterial activity.

In a clinical study involving 30 volunteers, Al Tamimi et al. [82] demonstrated that daily consumption of 240 mL of almond milk for four weeks led to reductions in body weight, body mass index, and waist and hip circumference, without affecting blood pressure. Dhaver et al. [84] found that almond milk elicited a similar postprandial glycemic effect to carbohydrate- or caloric-matched 2% milk in patients with overweight, obesity or type 2 diabetes. However, insulin and glucagon secretions were significantly lower following almond milk intake.

Abd-elmonsif et al. [104] reported that almond milk exhibited good remineralization capacity and protection of tooth enamel, increasing surface calcium and phosphorus levels and reducing morphological alterations compared to soy, oat, bovine, and cocoa milks.

Baru almond (*Dipteryx alata* Vogel) beverages, produced using high-intensity ultrasound [19], demonstrated improved bioaccessibility of phenolic compounds when probiotics were added prior to ultrasound treatment. Fermented beverages also exhibited higher α-amylase and α-glucosidase inhibitory activities compared to non-fermented, untreated, or pasteurized samples. These enhanced activities were attributed to elevated levels of phenolic compounds with strong antioxidant properties, due to elevated levels of epicatechin, cis-resveratrol, and bioactive peptides.

Similarly, pistachio (*Pistacia vera* L.) beverages have also demonstrated promising functional properties. Lim et al. [61] prepared pistachio extracts by soaking, de-skinning, and grinding the kernels, followed by blending with hot distilled water, filtration, homogenization, and pasteurization. Beverages were then fermented with *Lactobacillus* spp., known for their ability to produce short-chain fatty acids (SCFAs). The study concluded that fermented pistachio extracts rich in acetate may have potential as functional foods with anti-colon cancer properties. In another study, Mertdinç et al. [101] produced pistachio milk using a multi-food processor and subsequent filtration, identifying catechin and gallic acid as the predominant phenolic compounds. Remarkably, they reported bioaccessibility values of approximately 200% for both total phenolic content and antioxidant activity, highlighting the enhanced functional potential of pistachio-based beverages following processing. Further supporting the functional potential of nut-based beverages, Marulo et al. [30] developed a pistachio beverage by de-hulling the seeds, mixing them with water, and grinding the mixture in a colloidal mill. The resulting whole-nut beverage was fermented using selected strains of lactic acid bacteria, specifically *Leuconostoc pseudomesenteroides* and *Companilactobacillus paralimentarius*. The study identified 31 potentially bioactive peptides, primarily associated with antioxidative activity and the inhibition of angiotensin-converting enzyme (ACE) and dipeptidyl peptidase-IV (DPP-IV). Notably, fermentation started with *L. pseudomesenteroides* produced the highest concentration and diversity of bioactive peptides.

Similarly, hazelnut (*Corylus avellana*) beverages have shown promising bioactive potential. Aysu et al. [102] prepared hazelnut milk by roasting shelled hazelnuts, soaking them in water overnight, and wet-grinding them in a blender, followed by filtration through double-layered cheesecloth. A comparable method was used by Maleki et al. [103], who fermented the hazelnut milk with kefir cultures. Both preparations demonstrated in vitro antioxidant activity, attributed to their total phenolic content.

Other milk analogs have been developed using Brazil nut (*Bertholletia excelsa*). In one study, the nuts were ground, homogenized with water, and filtered through a stainless-steel mesh to obtain the beverage [74]. This Brazil nut beverage contained flavonoids such as catechin, epicatechin, and their derivatives. However, phenolic acids, including protocatechuic acid, gallic acid, and ellagic acid, which are primarily concentrated in the nut skin, were largely retained in the solid waste post-filtration. The beverage demonstrated an antioxidant capacity of 8 μmol TE/100 g fresh weight in the DPPH assay, a value within the reported range for commercial plant-based milks (4.7–30.5 μmol TE/100 mL) [74].

In a subsequent study, the same beverage was subjected to high-pressure homogenization (HPH) [7]. The untreated (control) beverage contained a predominance of flavonoids (57.9 mg/L), followed by phenolic acids (26.7 mg/L) and phenolic aldehydes (0.8 mg/L). The most abundant individual phenolic compounds included catechin, epicatechin, catechin gallate, and ellagic acid, with concentrations ranging from 13 to 17 mg/L. However, several of these compounds, particularly gallic acid, catechin, epicatechin, catechin gallate, and ellagic acid, were sensitive to HPH processing. This treatment significantly reduced total flavonoid content (from 46.9 to 43.5 mg/L) and total phenolic acids (from 16.9 to 15.4 mg/L), alongside a 30–37% decrease in antioxidant capacity, as measured by both ABTS and DPPH assays.

In another study, Ribeiro de Oliveira et al. [12] prepared a Brazil nut (*Bertholletia excelsa*) beverage by grinding the nuts in distilled water using a blender, followed by filtration through cheesecloth to remove the solid residue. The resulting beverage was then heat-treated via pasteurization (60 °C for 20 min). The effects of this beverage, standardized to 1 g of protein per 100 mL and administered at a dose of 1 mL/100 g body weight, were evaluated in Wistar rats over a 28-day period. Rats consuming the Brazil nut beverage showed significant reductions in retroperitoneal adipose tissue, total cholesterol, and triglyceride levels, suggesting a potential hypolipidemic effect.

Macadamia nuts (*Macadamia integrifolia*), valued for their rich sensory characteristics and nutrient content, have also been used to produce nut-based beverages. Camacho-Teodocio et al. [10] developed a macadamia beverage by blending ground nuts with water and stabilizing the mixture with soy lecithin and xanthan gum. The formulation was homogenized using a blender and subjected to heat treatment at 85 °C for 15 min. The selected beverage formulations exhibited high antioxidant capacities, with values of 100.48 ± 13.61 μmol TE/100 mL (ABTS assay) and 92.4 μmol TE/100 mL (DPPH assay), indicating strong potential as a functional beverage.

Although the bioactive profiles of nuts are well-documented, far less is known about the final concentration and activity of these compounds in nut-derived beverages. Processing steps commonly used in beverage production, such as filtration, dilution, fermentation, and heat treatment, can substantially modify both the concentration and bioavailability of bioactives, potentially affecting their health-promoting properties. Therefore, future studies must prioritize direct assessment of functional and health-related effects of nut-based beverages, rather than extrapolating from whole-nut data.

6. Conclusions

Tree nut-based beverages are rapidly emerging as attractive dairy-free alternatives, driven by growing consumer demand for plant-based products. These beverages not only offer unique and desirable sensory attributes, such as a distinctive nutty flavour, creamy texture, and pleasant aromas, but they also provide a host of nutritional benefits, including healthy fats, vitamins, minerals, and bioactive compounds. Their cholesterol- and lactose-free nature makes them particularly suitable for people with dietary restrictions, such as those with lactose intolerance, dairy allergies, or those adhering to vegan or vegetarian diets. Despite their growing popularity, microbiological safety remains a critical issue, mainly due to the high moisture content and nutrient density of these beverages, which create favourable conditions for microbial growth. Therefore, rigorous processing techniques, including pasteurization, high-pressure processing (HPP), and aseptic packaging, are essential to ensure both safety and shelf stability.

To further enhance the nutritional and functional value of tree nut-based beverages, manufacturers often resort to fortification strategies, incorporating key micronutrients such as calcium, vitamin D, vitamin B12, and iron, to fill nutritional gaps commonly found when replacing dairy products. In addition, advances in formulation technologies, including the use of stabilizers, emulsifiers, and fermentation, are being explored to optimize mouthfeel, taste, shelf life, and digestibility. In response to changing market preferences, there is a growing focus on low-calorie, functional, and healthy formulations enriched with probiotics, prebiotics, antioxidants, and natural plant extracts.

These innovations are supported by a growing research interest in using new raw materials, optimizing processing methods, and adapting products to the diverse needs of consumers, from athletes to health-conscious people and those with chronic diseases. Looking forward, the future success of tree nut-based beverages will depend on a multidisciplinary approach that integrates expertise from food science, microbiology, nutrition, and sensory evaluation. Continued efforts are needed to address challenges related to standardization of fermentation protocols, shelf life, and sustainability of raw materials. Through collaboration between research and innovation, tree nut beverages have the potential to play a central role in the future of functional and plant-based nutrition.

Author Contributions: Conceptualization, T.D.R. and A.R.; resources, T.D.R.; writing—original draft preparation, T.D.R., A.G.G., S.N., P.M., A.D.C., M.C.P., S.R.D. and A.R.; writing—review and editing, T.D.R., M.C.P., S.R.D. and A.R.; supervision, T.D.R.; project administration, T.D.R. and A.R.; funding acquisition, T.D.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Bilateral project between ISA-CNR e Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CONICET-UNLP-CIC) entitled "Development of functional pistachio-based fermented beverage" (SAC.AD002.001.024) and was partially supported by the European Commission—NextGenerationEU, Project SUS-MIRRI.IT "Strengthening the MIRRI Italian Research Infrastructure for Sustainable Bioscience and Bioeconomy", code n. IR0000005.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BI	bioaccessibility
CE	catechin equivalent
CLA	conjugated linoleic acid
CLNA	conjugated linolenic acid
d.w.	Dry weight
EPS	Exopolysaccharides
FOS	Fructooligosaccharides
f.w.	Fresh weight
GAE	Gallic acid equivalent
LAB	Lactic acid bacteria
MUFA	Monounsaturated Fatty Acids
PUFA	Polyunsaturated Fatty Acids
TFC	total flavonoid content
TPC	total phenolic content

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