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RESEARCH ARTICLE

Emerging Trends in Plant-Derived Milk Alternatives: Nutritional and Environmental Perspectives

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Abstract: Health awareness is growing significantly among modern populations, leading to a notable dietary shift from traditional to health-focused choices. This transition is driven by concerns about environmental sustainability, ethical considerations regarding animal welfare, and the desire to enhance personal health and well-being. One prominent trend is the rise of plant-based milk substitutes, primarily adopted due to lactose intolerance, dairy allergies, digestive issues, and an increasing interest in dietary diversity. Veganism has also played a pivotal role in this shift. Plant-based milk alternatives can be derived from a wide variety of sources, including cereals (e.g., rice, oats, millets), legumes (e.g., soy), nuts (e.g., almonds), and seeds (e.g., flax, sesame). This review explores the types of plant-based milk, modern processing technologies used to improve their shelf life and sensory appeal, and their nutritional and functional bioactive compounds. It also discusses their role in supporting sustainable food systems, improving public health, and promoting dietary diversity in contemporary nutrition.

Keywords: Plant-based milk, lactose intolerance, soymilk, oat milk, almond milk, milk processing technologies.

INTRODUCTION

Milk is widely recognized as one of the most nutrient-rich foods, naturally produced by the mammary glands of mammals during the postpartum period [1]. According to the Food and Agriculture Organization (FAO) and World Health Organization (WHO), milk is an essential source of nutrition for human health [2,3]. Animal-derived milk—commonly obtained from cows, goats, buffaloes, and sheep is known for its comprehensive nutrient profile, including high-quality proteins, healthy fats (such as conjugated linoleic acid and alpha-linolenic acid), minerals (e.g., calcium, magnesium, iron, phosphorus), and vital vitamins [4].

Despite its health benefits, dairy consumption is often associated with several issues. Lactose intolerance is a primary concern, affecting individuals who lack sufficient levels of the enzyme lactase thereby leading to symptoms such as bloating, flatulence, diarrhea, and abdominal discomfort [5]. Additionally, milk allergies often involving an IgE-mediated immune response—can trigger adverse reactions in sensitive individuals [6].

In response to these challenges, plant-based milk alternatives have emerged as a viable substitute for traditional dairy. These non-dairy beverages are created by soaking, grinding, and filtering various plant materials—such as cereals, legumes, nuts, and seeds—combined with water to produce a nutrient-rich liquid that mimics the texture and appearance of cow's milk [5]. Environmental sustainability has also influenced consumer preference for plant-based milk. Animal agriculture is resource-intensive, requiring up to 600–800 liters of water to produce just one litre of dairy milk, whereas plant-based options consume significantly less water and generate fewer greenhouse gas emissions [7]. Though soymilk was initially the most prevalent option, the market has diversified to include almond, oat, coconut, and other plant-derived alternatives, which are now widely available.

From a nutritional standpoint, plant-based milk can serve as functional foods with considerable nutraceutical potential. Although they may lack certain nutrients found in animal milk, fortification and blending with multiple plant ingredients can enhance their nutritional value [8]. This review comprehensively analyzes key plant-based milk substitutes such as soy, oat, coconut, and almond focusing on their production techniques, nutritional properties, functional bioactive components, and their potential benefits in managing various health conditions.

Different Types of Plant-Based Milk Substitutes – A Comparative Overview

Plant-based milk alternatives are liquid extracts obtained from various plant materials such as cereals, legumes, pseudo-cereals, oilseeds, and nuts. These sources are ground and mixed with water to form a slurry, which is then filtered and homogenized to achieve a particle size distribution typically between 5–20 µm. This process produces a stable emulsion that visually and texturally resembles cow's milk, closely mimicking its sensory and nutritional characteristics [9].

Depending on the source material, plant-based milks are classified into five major categories (Figure 1)

- **Cereal-based** (e.g., rice, oats)
- **Pseudo-cereal-based** (e.g., quinoa, teff)
- **Legume-based** (e.g., soy, peanut)

- **Oilseed-based** (e.g., sesame, flax)
- **Nut-based** (e.g., almond, coconut, hazelnut)

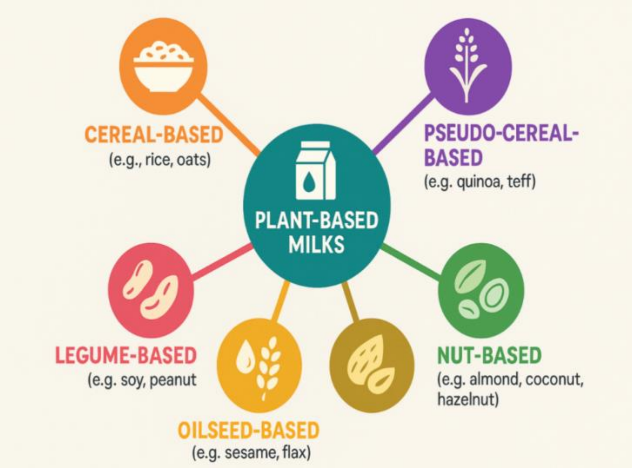

Figure 1: Classification of Plant-Based Milk and Their Sub-types

Oat Milk

Oat milk, developed in the 1990s by Swedish scientist Rickard Öste (founder of Oatly) was designed as an eco-friendly and lactose-free alternative to dairy milk . It has gained substantial commercial acceptance due to its creamy texture and mild flavor.

Nutritionally, oat milk contains β-glucan, a soluble dietary fiber known to reduce LDL cholesterol and regulate blood glucose levels [9]. Oats are also rich in unsaturated fatty acids and essential amino acids, which enhance their health benefits, particularly for individuals with metabolic disorders such as hyperlipidemia or type 2 diabetes.

Soymilk

Soymilk, derived from whole soybeans, is a protein-rich beverage widely recognized as the first mainstream plant-based milk substitute. Originating in China, it is nutritionally comparable to cow's milk, particularly in its protein content. This justifies its designation as "soymilk" rather than merely "soy extract", Beyond protein, soymilk contains bioactive compounds such as isoflavones, phytosterols, and saponins, which offer notable health benefits.

However, processing challenges remain—especially in removing anti-nutritional factors and the beany flavour (associated with lipoxygenase activity). Modern techniques such as lipoxygenase inhibition and ultrafine homogenization are employed to improve its taste and mouthfeel [10].

Sesame Seed

Sesame seeds are a valuable source of plant-based protein and have the potential to serve as an alternative protein option due to their nutritional benefits. In addition to being a rich source of oil, sesame seeds contain a significant amount of protein [11]. Sesame seed protein is rich in sulphur-containing amino acids like methionine and cysteine and exhibits high thermal stability [12].

Although sesame protein contains slightly lower levels of essential amino acids compared to soy protein, recent findings suggest that sesame seed meal still provides adequate amounts to meet daily nutritional requirements. It has been proposed as a viable plant-based alternative to dairy, as it provides a nutrient power pack of essential amino acids, low-cholesterol fats, and calcium . The calcium content specifically supports its role as a potential substitute for animal-derived milk [13].

Sesame can be consumed in the form of pastes or plant-based milk, delivering a blend of proteins, healthy fats, and calcium. Despite its nutritional potential, sesame remains underutilized for its protein content. One of the primary limitations is the presence of allergens, which can trigger adverse reactions such as skin irritation, abdominal discomfort, itching, difficulty in swallowing, and swelling in individuals with sensitivities [14].

Almond Milk

Almond milk is prepared by blending soaked almonds with water, followed by filtration. It has a light texture, a nutty flavour, and is naturally free of lactose and cholesterol. Almond milk is low in calories and saturated fat, making it ideal for weight-conscious individuals and those with lactose intolerance [15]

Commercial versions are often fortified with calcium, vitamin D, and vitamin B12 to improve nutritional equivalency with cow's milk. Almond milk also contains high levels of vitamin E and monounsaturated fatty acids, contributing to its antioxidant and cardioprotective properties [16].

Coconut Milk

Coconut milk is produced by grinding the mature coconut kernel (endosperm) and mixing it with water. It is rich in lauric acid, a medium-chain fatty acid known for its antimicrobial, antiviral, and antioxidant properties [17].

Unlike coconut water, coconut milk is high in fat but offers benefits such as improved immune function, cardiovascular support, and skin nourishment. It also contains essential nutrients like folate, iron, and amino acids, making it a valuable alternative for those seeking dairy-free options [18].

Quinoa

Quinoa is classified as a pseudo-cereal and is often referred to as the "mother grain" due to its exceptional nutritional profile. It is widely recognized for its high nutritional value, with the Food and Agriculture Organization (FAO) of the United Nations comparing its nutrient composition to that of dried whole milk, identifying it as an excellent source of essential nutrients.

One of quinoa's most unique features is that it provides all nine essential amino acids, making it a complete protein. It is also rich in iron, magnesium, and vitamin B6—similar to dairy milk. When fortified with calcium, vitamin A palmitate, vitamin D2, and vitamin E (D-alpha tocopherol), quinoa milk can offer a more balanced nutritional profile than traditional cow's milk. Although plain quinoa milk may lack certain nutrients naturally present in dairy, fortification significantly enhances its value. This makes it a suitable alternative for individuals seeking nutrient-dense, plant-based beverages. Quinoa milk is naturally high in protein and free from artificial additives or preservatives. It can be used in the same way as regular dairy milk, including in tea and coffee. In addition to beverages, quinoa is also utilized in a variety of food products such as bread, cookies, soups, and more [19].

Innovations in Plant-Based Milk and Its Processing Technologies

The processing of plant-based milk alternatives has seen significant advancements through the application of both thermal and non-thermal emerging technologies. These include Pascalization (High-Pressure Processing), high-intensity ultrasound, pulsed electric fields, ohmic heating, and microwave heating. These methods not only enhance product safety and shelf life but also help preserve the nutritional and sensory qualities of the final product [20]. The effects of these novel processing techniques on plant-based milk substitutes are summarized in Table 1.

Table 1: Impact of Novel Technologies on Plant-Based Milk Substitutes

Technology	Plant Source	Process Conditions	Outcome	Reference
Enzymatic Hydrolysis	Oats	Protease used to hydrolyze proteins into polypeptides and amino acids	Increased oat protein isolate solubility, improved emulsion stability, and enhanced uniformity of oil droplets	[21]
Ultrasound	Almond	130 W, 80%, 20 kHz, 8 min, 6 s pulse	Reduced *E. coli* O157:H7 from 5.12 to 3.81 log CFU/mL and reduced *Listeria monocytogenes* by 1 log CFU/mL	[21]
	Almond	300 W, 100%, 20 kHz, 0–5 min	Increased °Brix, improved physical stability, reduced viscosity, and smaller suspended particle size	[22]
	Coconut	50–55 W, 40%, 20 kHz, 13 min	Reduced concentrations of methyl tetrahydrofuran, octanoic acid ethyl ester, decanoic acid, and hexadecanoic acid methyl ester	[23]
High-Pressure Processing	Soy	200 & 300 MPa at 55°C, 65°C, 75°C	Enhanced enzymatic activity; 300 MPa at 75°C achieved total sterilization	[24]
Pulsed Electric Field	Soy	18–22 kV/cm, 25–100 pulses, 0.5 Hz, 26°C	Increased viscosity and notable color changes with increased intensity and number of pulses	[25]
Ohmic Heating	Soy	220 V, 50 Hz, 0–15 min	Reduced thiol loss; effective inactivation of trypsin and chymotrypsin	[26]

ADVANCEMENTS IN COLD STERILIZATION TECHNOLOGIES

Pascalization (High-Pressure Processing – HPP)

Pascalization, or High-Pressure Processing (HPP) is a non-thermal preservation method involving pressures ranging from 100 to 1000 MPa. One of its key advantages is minimal impact on sensory and nutritional attributes. HPP helps preserve volatile compounds, proteins, vitamins, and antioxidants by maintaining the integrity of covalent bonds, thereby retaining the product's original flavour, texture, and nutrient profile [26].

Additionally, HPP reduces colloidal particle size, enhancing beverage stability and homogeneity [27]. However, pressures above 400 MPa may lead to colloidal aggregate formation, negatively affecting quality. Therefore, pressures below 400 MPa are generally preferred to maintain consistency and prevent aggregation in plant-based drinks [28].

High-Intensity Ultrasound (HIU)

High-intensity ultrasound effectively inactivates spoilage organisms, pathogenic microbes, and endogenous enzymes in plant-based beverages with minimal nutritional degradation. Moreover, it improves rheological properties such as texture and stability . When combined with heat (thermosonication) or pressure (manosonication), ultrasound significantly enhances microbial safety and shelf life [29].

Pulsed Electric Field (PEF)
PEF is a widely adopted non-thermal method for microbial and enzymatic deactivation in liquid plant-based foods. It typically operates at low temperatures (30–40°C) to avoid heat-induced degradation . During PEF, electric fields of 5–55 kV/cm are applied for microseconds to induce transmembrane potentials in microbial cells, leading to pore formation and cell inactivation [30].

However, PEF alone cannot eliminate spores, as it does not initiate spore germination. Therefore, combining PEF with additional treatments is necessary to stimulate germination and ensure complete microbial safety [31].

THERMAL-ELECTRIC TECHNOLOGIES

Microwave Heating
Microwave processing employs electromagnetic radiation (typically 10^3 to 10^4 MHz) to uniformly heat plant-based beverages by targeting the dipole rotation of water molecules. It enables rapid and volumetric heating with minimal processing time, preserving nutritional and organoleptic properties . Unlike ionizing radiation, microwave energy does not break molecular bonds, ensuring the integrity of vitamins, proteins, lipids, and carbohydrates [32].

Ohmic Heating
Ohmic heating is a thermal process that generates heat within the product by passing electrical current (50–60 Hz) through the food matrix. Heat is generated due to the electrical resistance of the material, which causes ion rearrangement and molecular agitation [33]

This method is energy-efficient, easy to operate, and effective for both solid and liquid components. However, it has high setup costs and a risk of overheating, which may cause protein aggregation and reduce the nutritional and sensory quality of plant-based beverages [34].

Nutritional Composition and Bioactive Compounds in Various Plant-Based Milk Substitutes

Table 2: Nutrient Composition of Various Non-Dairy Milk Alternatives (per 100 mL)

Plant Milk Source	Energy (kcal)	Protein (g)	Carbohydrates (g)	Total Fat (g)	Total Sugars (g)	Fibre (g)
Oats (Whole)	66	1.9	4.44	4.65	1.27	0.8
Soybean (Whole)	43	2.6	4.92	1.47	3.65	0.2
Almond (Unsweetened)	15	0.59	0.58	1.10	0.00	0.0
Coconut (Whole)	54.17	1.67	10.00	1.04	7.92	-

Note: kcal = kilocalorie; g = gram

Table 2 illustrates the nutritional composition of selected plant-based milk alternatives, adapted from references [35]. The nutrient profile of these beverages varies considerably based on the plant source and processing techniques. For instance, oat milk is typically higher in energy due to its carbohydrate-rich composition, whereas soy milk tends to offer higher protein content, sometimes comparable in quality to dairy milk.

In contrast, cow's milk is a complete protein source, containing all nine essential amino acids, which is generally not the case for plant-based substitutes unless they are fortified or blended. Low-calorie options such as almond, rice, and coconut milk are often preferred by individuals seeking weight management or lower energy intake. Additionally, the flavour and sweetness of these milks may vary based on added sugars and flavouring agents, tailored to consumer preferences and health considerations.

Fortification plays a crucial role in improving the nutritional profile of plant-based milk. Essential micronutrients such as calcium, vitamin D, and vitamin B12 are often added to mimic the nutrient density of cow’s milk. However, not all commercially available products offer transparent or comprehensive labelling, leading to variability in nutritional quality. Some plant-based milk sources, such as soy, almond, hemp, and peanut (groundnut), naturally contain bioactive compounds including linoleic and oleic acids—essential fatty acids that contribute to cardiovascular health and overall nutrition. Almond milk, in particular, is a notable source of vitamin E and calcium [36,37].

Table 3: Vitamin Composition in Selected Plant-Based Milk Alternatives (per 100 mL)

Milk Source	Vitamin A (µg)	Vitamin B1 (mg)	Vitamin B2 (mg)	Vitamin B3 (mg)	Vitamin B6 (µg)	Vitamin B9 (µg)	Vitamin B12 (µg)	Vitamin C (mg)	Vitamin D (µg)	Vitamin E (mg)	Vitamin K (µg)
Oat Milk	–	25.2	14.0	–	5.0	–	–	–	–	5.13	–

Milk Source	Vitamin A (µg)	Vitamin B1 (mg)	Vitamin B2 (mg)	Vitamin B3 (mg)	Vitamin B6 (µg)	Vitamin B9 (µg)	Vitamin B12 (µg)	Vitamin C (mg)	Vitamin D (µg)	Vitamin E (mg)	Vitamin K (µg)
Soy Milk	32.57	0.08	0.24	0.28	0.10	33.60	0.68	0.0	1.86	4.00	–
Coconut Milk	60.00	–	–	–	–	19.20	0.75	0.0	2.92	–	–
Almond Milk	77.14	–	0.19	–	–	19.20	1.00	0.0	2.32	3.84	–

Note: mg = milligram; µg = microgram

Table 3 presents the vitamin content of various plant-based milk substitutes, adapted from references [38]. Among the listed alternatives, almond milk is notable for its high vitamin A content. Soy milk also offers considerable levels of B-complex vitamins, including B2, B6, and folate (B9), making it nutritionally robust compared to other plant-based options. Unlike cow's milk, which is routinely fortified with vitamin D to prevent deficiencies, many plant-based milk products are either not fortified or inconsistently fortified. This lack of standardization can lead to potential health risks, such as rickets or impaired bone health, particularly in populations relying heavily on plant-based beverages without appropriate supplementation. Therefore, consistent and regulated fortification strategies are essential to ensure plant-based milks serve as adequate nutritional alternatives to dairy [39].

Table 4: Bioactive Compounds in Plant-Based Milk Substitutes and Their Health Benefits

Plant-Based Milk Source	Bioactive Compounds	Health Benefits
Oat Milk	β-glucan	Helps in weight management, controls blood glucose and cholesterol levels, supports gut health, beneficial in IBS, exhibits anticancer properties
Soy Milk	Phytosterols, genistein, phytic acid, saponins, isoflavones	Lowers lipid levels, provides antioxidant protection, helps prevent CVD, diabetes, hypertension, cancer, renal problems, and osteoporosis
Coconut Milk	Lauric acid	Antiviral, antimicrobial, antibacterial, antioxidant, anti-aging, anti-cancer, prevents oxidative stress and degenerative diseases, promotes skin health
Almond (Badam) Milk	Arabinose compound	Enhances immune function, regulates blood pressure, supports vision and bone health, improves kidney function

Bioactive Compounds and Their Health-Promoting Roles in Plant-Based Milk Alternatives

Table 4 summarizes the key bioactive compounds present in commonly consumed plant-based milk substitutes and highlights their associated health benefits. Oat milk is a notable source of β-glucan, a soluble fiber known for its ability to manage body weight, regulate blood glucose and cholesterol levels, and support gastrointestinal health. It is especially beneficial in managing Irritable Bowel Syndrome (IBS) and may exhibit anticancer effects. Soy milk stands out due to its rich content of phytosterols, genistein, phytic acid, saponins, and isoflavones, which offer strong antioxidant protection and play a preventive role against cardiovascular diseases (CVD), diabetes, high blood pressure, cancer, renal complications, and osteoporosis. Coconut milk contains lauric acid, a medium-chain fatty acid recognized for its antiviral, antimicrobial, and antibacterial effects. It contributes to delaying aging, preventing degenerative diseases and oxidative stress, and is beneficial for skin nourishment and immune support. Almond milk, enriched with arabinose and vitamin E, helps strengthen the immune system, supports blood pressure regulation, improves vision, aids in bone development, and promotes healthy kidney function. Collectively, these plant-based milk substitutes not only offer nutritional benefits but also provide functional bioactive compounds that support long-term health and disease prevention [5].

CONCLUSION

The growing significance and popularity of plant-based milk substitutes are increasingly evident in modern diets. These products cater to diverse dietary needs, offering viable options for people who have milk allergy or intolerance to lactose, while also addressing broader health and environmental concerns. Plant based milk substitutes such as oat, soy, coconut, and almond, yield an enduring and health-conscious replacement for conventional dairy, reflecting a switch in consumers perception towards eco-friendly as well as nutritionally adaptable options. Nutritionally, plant based milk may lack certain components found in animal-based milk, they act as practical alternative for those with dietary restrictions. Furthermore, reduced water usage and lower greenhouse gas emissions, sustainable products are added eco-friendly practices which motivate the individuals to consume plant source milk. The growing market presence contributed by innovative processing techniques such as microwave and electro conductive heating (ohmic heating), which enhances the quality, safety and sensory appeal of these beverages.

Future perspective of the potential innovation in product development is extensive. Efforts to create plant-based milk products with improved flavours, textures, and nutritional profiles through the blending of various plant sources and advanced processing techniques can attract a vast consumer base. Industries prioritizes not only on advanced processing but also in nutritional aspects such as essential micronutrient fortifications to introduce the best product in the market for consumers to meet their dietary needs, especially those transitioning from conventional dairy.

Sustainability exists as a key driver of growth for plant-based milks. Future research evidences towards optimizing production and technological processes, reducing water use, presence of bioactive components assists in betterment of health. Simultaneously, expanding consumer education efforts is vital in addressing misconceptions and fostering informed choices. As market expands transparency and consumer trust are ensured by standardized regulatory guidelines and labelling practices.

Conflict of interest

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