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Article

Sensory, nutritional, and functional characteristics of plant-based milks for lactose-intolerant individuals

Alwi

Faculty of Agricultural Technology, Hasanuddin University, Makassar 90245, Indonesia

Abstract

Plant-based milk has emerged as a prominent alternative for individuals with lactose intolerance who cannot consume cow's milk. The high prevalence of lactose intolerance, particularly in Asian populations, has driven innovation in plant-based functional foods that are more compatible with the digestive system. This literature review examines the potential of plant-based milk as a functional alternative, focusing on its nutritional composition, bioactive compounds, health benefits, and associated technological challenges. The analysis indicates that plant-based milks derived from soybeans, almonds, oats, rice, and coconut contain vegetable protein, fiber, and bioactive compounds such as isoflavones, polyphenols, and beta-glucans, which confer antioxidant, cholesterol-lowering, and metabolic regulatory properties. However, plant-based milks typically exhibit lower protein, calcium, and certain vitamin levels compared to bovine milk, necessitating fortification and technological innovation to enhance their nutritional profile. Given their lactose-free nature, low saturated fat content, and abundance of functional compounds, plant-based milks hold considerable promise as functional food solutions for individuals with lactose intolerance.

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1. Introduction

Bovine milk is a valuable source of protein and calcium. However, individuals with lactose intolerance cannot consume it due to a deficiency in the enzyme lactase, which is required to hydrolyze lactose in the small intestine (1). This enzyme deficiency results in lactose not being completely digested and fermented by microbes in the large intestine leading to symptoms such as bloating, diarrhea, and abdominal pain (2). As over 70% of the Asian population, including that of Indonesia, is estimated to be lactose intolerant, a significant portion of the community experiences adverse effects from bovine consumption. This creates a demand for alternative, lactose-free beverages with high nutritional value (2).

As a solution, plant-based milk has emerged as an effective alternative for individuals with lactose intolerance. It is an oil in water emulsion obtained from plant-based foods such as soybeans, almonds, oats, coconuts, or rice through extraction, grinding, and homogenization (3). This product visually and functionally similar to bovine milk naturally lactose-free, thereby avoiding the digestive symptoms associated with lactose maldigestion (4). Furthermore, these beverages offer additional nutritional benefits, as they contain bioactive compounds that possess antioxidant properties, such as isoflavones, polyphenols, β-glucans, and vitamin E (5).

* Correspondence: **Alwi** alwiarismal24@gmail.com

While a variety of ingredients can serve as bases for plant-based milk, its typically lower protein and calcium content relative to bovine milk presents a significant nutritional challenge (6). Furthermore, variations in chemical composition led to differences in flavor and texture, which can affect consumer acceptance. The production process also requires specific technologies to achieve a stable emulsion that mimics the sensory properties of bovine milk (7). To address these challenges, this review provides a comprehensive analysis of the scientific literature on plant-based milk, with a focus on emulsion stability, proximate composition (including water, protein, fat, and carbohydrate content), and sensory properties such as taste, aroma, color, and texture.

2. Materials and Methods

This literature review synthesizes data from peer reviewed academic research papers. A systematic search was conducted using the keywords “plant-based milk,” “lactose intolerance,” and “vegan milk” across relevant scientific databases. The search was limited to articles published between 2012 and 2025. Following retrieval, each article was critically analyzed and summarized to extract key findings, which were then synthesized to formulate the conclusions presented in this review.

3. Results and Discussion

3.1. Bovine Milk

Bovine milk, a nutrient rich liquid secreted by mammalian mammary glands, has long been a staple of the human diet. Commonly consumed types include cow, goat, sheep, buffalo, and camel milk, each with a distinct chemical composition. Typically, bovine milk consists of approximately 87% water, 3-4% fat, 3-3.5% protein, and 4.6-4.8% lactose, in addition to essential minerals (calcium, phosphorus, magnesium) and vitamins (A, B_2, B_{12}). Its primary proteins are casein (80%) and whey (20%) (8). Casein forms colloidal micelles that are critical for stabilizing the fat in water emulsion, thereby preventing phase separation (9). The fat exists as globules encapsulated by a membrane of phospholipids and proteins, which inhibits oxidation and coalescence. This inherent emulsion stability contributes to the characteristic smooth texture and flavor of bovine milk (10).

From a nutritional perspective, bovine milk provides a complete protein source, containing all essential amino acids. Lactose serves as an energy substrate and facilitates calcium absorption in the intestines, while minerals such as calcium and phosphorus are vital for bone and tooth development (11). Common derived products include yogurt, cheese, cream, skim milk, butter, and ultra-high temperature (UHT) processed milk. Industrial processing methods like pasteurization and homogenization enhance product safety and shelf life, while also maintaining the stability of the fat emulsion (12). Beyond its complete macro and micronutrient profile, bovine milk contains numerous bioactive compounds that confer physiological benefits. These compounds are derived from milk fat, proteins, and peptides formed during metabolism or processing (13). These compounds exhibit a range of bioactivities, including antimicrobial, immunomodulatory, antihypertensive, anti-inflammatory, and cardioprotective effects. The primary bioactive components in bovine milk and their associated health functions are summarized in the Figure 1 (8).

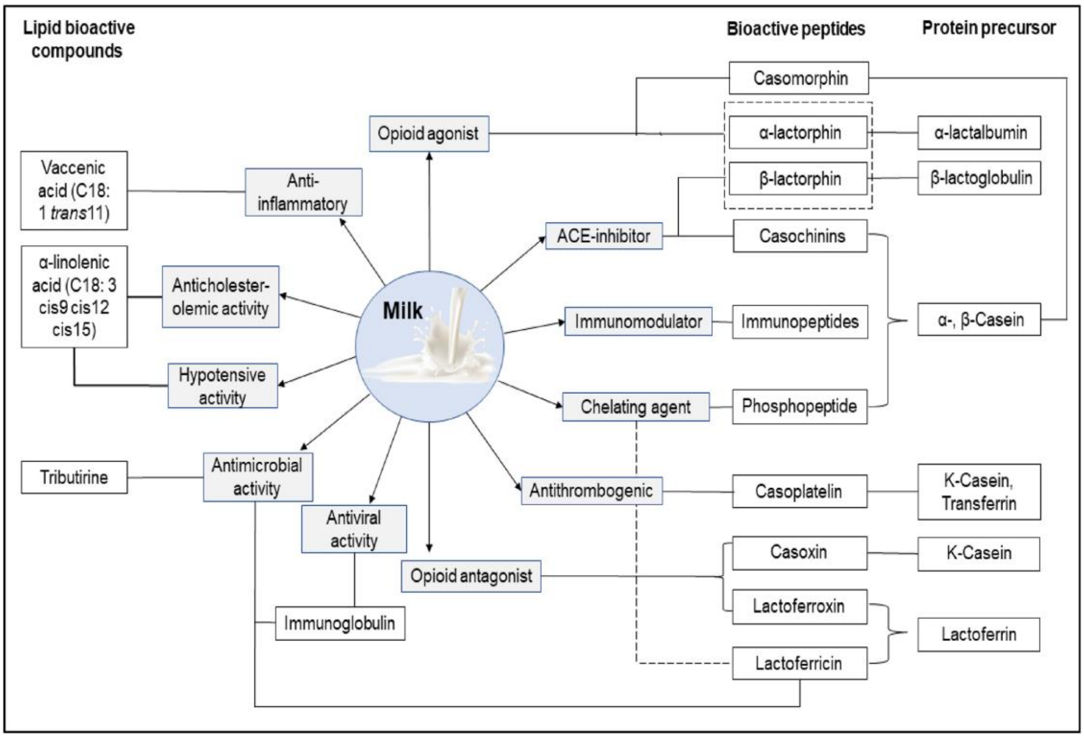

Figure 1. Bioactive compounds of milk and its physiological function (8).

Despite its high nutritional value, bovine milk is not well-tolerated by all individuals. Its primary carbohydrate is lactose; a disaccharide composed of glucose and galactose. The digestion of lactose depends on the enzyme lactase, produced in the small intestine. A deficiency in this enzyme results in lactose intolerance, a condition where undigested lactose is fermented by the gut microbiota. This fermentation produces gas and short-chain fatty acids, leading to clinical symptoms such as bloating and diarrhea (9). The difference between normal lactose digestion and lactose intolerance is shown in the Figure 2.

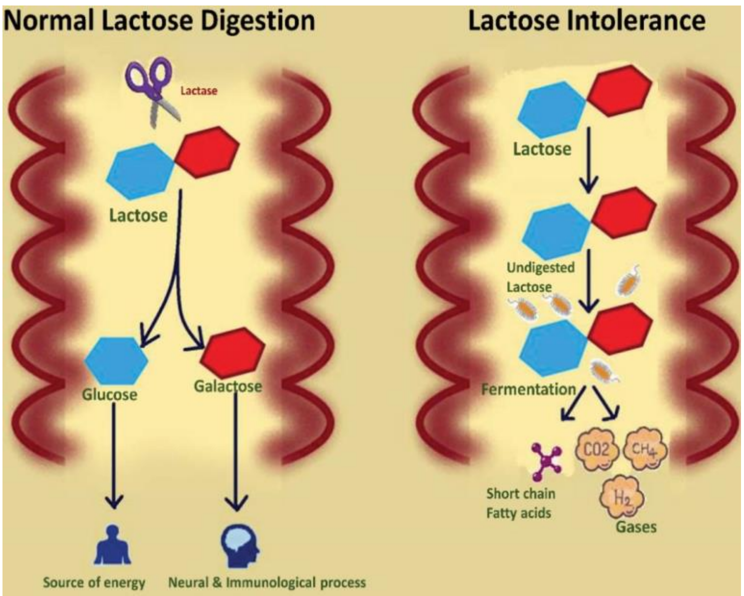

Figure 2. Comparison of milk digestion in lactose-intolerant and normal individuals (9).

3.2. Plant-based Milk

The development of plant-based food innovations has led to the emergence of various alternatives to bovine milk, one of which is plant-based milk. Plant-based milk is an emulsion produced from plant sources through soaking, grinding, extraction, filtration, and homogenization, resulting in a yellowish-white liquid resembling the appearance of bovine milk (14). Common sources include soybeans, almonds, oats, rice, and cashews, each imparting distinct physicochemical and nutritional properties. These ingredients contain natural emulsion-forming components, such as proteins, fats, and carbohydrates which form a stable colloidal suspension after fine grinding and homogenization (15). For instance, soy and almond proteins can form an interfacial layer around fat droplets, stabilizing the emulsion much like casein does in bovine milk. Plant-based fats, particularly polyunsaturated fatty acids, contribute to a smooth texture and nutritional value, while carbohydrates from cereals like oats act as natural thickeners (16).

3.2.1. Soy Milk

Soy milk is the most prevalent plant-based milk and has a compositional profile closest to that of bovine milk. It contains approximately 3-4% protein, with an essential amino acid balance comparable to that of bovine protein. Its primary protein components, β-conglycinin and glycinin, effectively stabilize emulsions by forming an interfacial layer around fat globules (17). The fat content ranges from 1.5 to 2.5%, predominantly comprising polyunsaturated fatty acids (PUFAs) such as linoleic and linolenic acid, which are associated with cardiovascular benefits (18). Soy milk is also a rich source of isoflavones, phytoestrogen compounds with antioxidant properties linked to a reduced risk of heart disease and breast cancer (19). In terms of physical stability, its emulsion is relatively robust due to the capacity of its proteins to inhibit phase separation during storage (20). However, the presence of oligosaccharides, such as raffinose and stachyose, can cause flatulence in some individuals (21).

3.2.2. Almond Milk

Almond milk is produced by soaking and finely grinding almonds in water. Its composition is characterized by high content of monounsaturated fats (MUFAs), predominantly oleic acid, and vitamin E (tocopherol), a potent antioxidant (22). However, its protein content is relatively low (~1%), making its nutritional profile less balanced compared to alternatives like soy milk. To address this, almond milk is frequently fortified with plant-based proteins, vitamin B_{12}, and vitamin D (23). The low protein content also results in a thin interfacial layer between fat and water, leading to inherently low emulsion stability. Consequently, phase separation often occurs unless stabilizing agents are incorporated. In commercial production, emulsifiers such as soy lecithin or gellant gum are therefore commonly added to enhance stability and maintain product homogeneity during storage (24). The product’s appeal is driven by its lactose-free nature, low calorie content, and the presence of bioactive compounds such as flavonoids, phenolics, and tocopherols (25). These compounds provide antioxidant activity, offering health benefits to regular consumers by neutralizing free radicals.

3.2.3. Oat Milk

Oat milk is derived from oat grains (*Avena sativa*) and is distinguished as a milk alternative rich in complex carbohydrates and soluble fiber, particularly β-glucan. This β-glucan contributes high viscosity, enhancing both the emulsion's texture and stability, while also reducing serum LDL cholesterol levels (26). Oat milk contains 1–1.5% protein, which is lower than soy milk but sufficient to aid emulsion stability, especially when combined with stabilizers or natural emulsifiers. Its fat content is relatively low (0.5–1.5%) and consists predominantly of unsaturated fatty acids, which are associated with cardiovascular benefits (3). Furthermore, oat milk provides essential minerals such as iron, magnesium, and phosphorus, alongside B-complex vitamins that support energy metabolism. This nutritional profile renders oat milk suitable for individuals with lactose intolerance, bovine milk allergy, or those seeking to manage cholesterol and support digestive health (27). The water-binding and gelling properties of β-glucan are responsible for oat milk's characteristically smooth texture and rich mouthfeel. These desirable sensory attributes, combined with its nutritional profile, have established oat milk as a favored choice in modern cuisine (28). Its ability to produce a stable, fine foam similar to bovine milk makes it especially popular as a "barista milk" and a base for coffee blends, all while remaining vegan and suitable for individuals with lactose intolerance (29).

3.2.4. Coconut Milk

Coconut milk is a plant-based milk extracted by blending ripe coconut meat (*Cocos nucifera* L.) with water, yielding a viscous, white liquid rich in vegetable fat. Its primary composition includes water (50–60%), fat (20–25%), protein (1–2%), and minor quantities of carbohydrates, vitamins, and minerals (30). The lipid fraction is dominated by medium-chain saturated fatty acids, such as lauric acid (C12:0), capric acid (C10:0), and caprylic acid (C8:0), which are readily digested and rapidly metabolized for energy (31). This property makes coconut milk a quick energy source and a viable option for individuals with lactose intolerance. In terms of physical structure, coconut milk is a natural oil-in-water (O/W) emulsion. Proteins and phospholipids on the surface of its fat globules act as natural emulsifiers, maintaining homogeneity between the oil and aqueous phases. However, due to its high fat content, the emulsion is prone to destabilization through creaming during storage (30). Consequently, industrial production typically incorporates stabilizers such as carboxymethyl cellulose (CMC), guar gum, or lecithin to ensure long-term product stability (32). Coconut milk provides essential micronutrients including iron, magnesium, phosphorus, potassium, and vitamins C, E, and several B vitamins. Beyond its nutritional value, coconut milk contains bioactive compounds with health-promoting properties (33). Lauric acid, for instance, exhibits antimicrobial and antiviral activity; within the body, it is converted to monolaurin, a compound known to inhibit the growth of pathogens such as *Candida albicans* and *Staphylococcus aureus* (34). Additionally, the natural phenolic and flavonoid content derived from coconut meat contributes antioxidant activity, which may help reduce oxidative stress and support cardiovascular health.

3.3. Chemical and Sensory Properties of Plan-based Milk

The compiled data encompassed the types of plant-based ingredients used, proximate composition analyses, and sensory evaluations. Sensory analyses testing was primarily conducted using hedonic scales to assess panellists' preference for sensory attributes, including color, flavor, aroma, and texture. The referenced studies predominantly employed a 9-point scale (1 = strongly dislike, 9 = strongly like), with one study using a 5-point scale.

Table 1. Proximate and Sensory Properties of Plant-Based Milk

Plant-based Milk	Proximate Composition	Sensory Properties	Reference
Soy Milk	Protein: 3.61% Fat: 2.54%	Color: 7.5/9 Flavor: 7.8/9 Aroma: 7.2/9 Texture: 7.6/9	(35)
Almond Milk	Protein: 0,5–1% Fat: 2–3% Carbohydrate: 0,5–1%	Color: 7.0/9 Flavor: 7.4/9 Aroma: 7.0/9 Texture: 7.2/9	(25)
Oat Milk	Protein: 1–1,5% Fat: 1,5–2%; Carbohydrate: 6–8%	Color: 7.2/9 Flavor: 7.6/9 Aroma: 7.3/9 Texture: 7.5/9	(36)
Almond + Sprouted Soybean Milk	Water: 81,15% Protein: 15,01% Fat: 1,99% Carbohydrate: 1,11%	Color: 7.6/9 Flavor: 7.8/9 Aroma: 7.4/9 Texture: 7.7/9	(37)
Coconut + Tiger Nut	Water: 53,93% Protein: 14,59% Fat: 12,90-21,49% Carbohydrate: 2,81-10,72%	Overall acceptability: 7,3–7,9/9	(38)

As summarized in Table 1, soy milk exhibited the highest protein content (3.61%), substantially exceeding that of almond (0.5–1%) and oat (1–1.5%) milks. Consequently, among the plant-based options, soy milk most closely approximates the protein nutritional value of bovine milk. It also received high sensory scores (flavor: 7.8; texture: 7.6), indicating strong consumer acceptance (35) . Almond milk was rated favourably for aroma (7.0) and taste (7.4), despite its low inherent protein content, a deficit often addressed through fortification (25). Oat milk, characterized by a higher carbohydrate content (6–8%), also achieved a favourable taste score (7.6), making it suitable for consumers preferring a naturally sweet profile (36,37). Milk derived from coconut and tiger nuts was distinguished by its creamy texture and savory taste, with overall scores ranging from 7.3 to 7.9 (38). In summary, soy milk most closely resembles bovine milk in both protein content and overall sensory acceptance. However, formulations combining ingredients like coconut and almond may further enhance consumer appeal by optimizing flavor and texture profiles.

3.4. Emulsion stability

Emulsion stability is a critical determinant of plant-based milk quality, directly influencing product texture, appearance, and shelf life. Soy milk demonstrates superior stability when processed via high-pressure homogenization, maintaining a homogeneous emulsion without sedimentation for over seven days (35). This stability supports a sensory quality closely resembling that of bovine milk. A blend of almond and soy milk retains stability for up to five days, albeit with minor sedimentation that can affect visual appeal and mouthfeel (37). Oat milk exhibits favorable stability, characterized by a high stability index (SI) and a viscosity of 0.0035 Pa·s, which corresponds to a stable emulsion and a characteristically thick texture (36). In contrast, coconut milk shows moderate inherent stability; its high fat content necessitates the addition of emulsifiers to inhibit phase separation (38). Emulsion instability can lead to detrimental changes in texture and flavor, ultimately lowering sensory scores. Therefore, processing technologies such as homogenization and the strategic use of emulsifiers are essential for preserving the quality and consumer acceptance of plant-based milk products.

The stability of plant-based milk emulsions is governed by three principal factors: emulsifier type, homogenization method, and particle size distribution. Emulsifiers such as gum arabic or soy lecithin adsorb at the oil-water interface, forming a protective barrier that prevents phase separation and maintains a homogeneous appearance and texture (39). High pressure homogenization plays a critical role by reducing fat droplet size, thereby inhibiting droplet coalescence (4). This process enhances the product shelf life and prevents the colloidal system from separating. Furthermore, a small mean particle size (typically <1 µm) increases physical stability by minimizing gravitational sedimentation (40). Optimal emulsion stability directly translates to superior product quality, yielding a creamy texture, uniform appearance, and high sensory scores. Conversely, instability leads to sedimentation, reduced shelf life, and diminished consumer acceptance (41). Consequently, a synergistic approach combining effective homogenization with appropriate emulsifiers is essential for maintaining the overall quality of plant-based milk

4. Conclusions

Plant-based milk holds significant promise as a functional food alternative for individuals with lactose intolerance, being inherently lactose-free and a source of beneficial bioactive compounds. Research indicates that varieties such as soy, oat, almond, and coconut milk can contribute to cardiovascular health, digestive function, and metabolic regulation. While challenges such as lower inherent protein and calcium content persist, these can be effectively mitigated through fortification and bioprocessing techniques like fermentation. As consumer preference shifts towards plant-based diets, these products are poised to become integral components of a more sustainable and nutritionally inclusive food system.

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Data Availability Statement

Available data are presented in the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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