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Review Article

Benefits and challenges in plant-based milk alternatives

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Plant-based milk alternatives have become increasingly popular as a replacement for traditional dairy milk, largely due to rising consumer interest in healthier, environmentally friendly and allergen-free choices. These alternatives are produced from various plant sources, including grains (such as oats and rice), legumes (like soy and pea), nuts (including almond and cashew) seeds (such as flax and hemp), and pseudocereals (like quinoa and amaranth). Each type of plant-based milk presents unique nutritional benefits and bioactive compounds that may contribute to health advantages, including lower cholesterol levels, anti-inflammatory properties, better heart health and improved gut microbiome diversity. One major benefit of plant-based milk is its compatibility with individuals who are lactose intolerant or allergic to dairy, as well as those adhering to vegan or plant-based diets. Additionally, these alternatives generally have a smaller environmental impact than conventional dairy milk, requiring fewer natural resources like land and water while producing lower greenhouse gas emissions. However, the widespread acceptance of plant-based milks faces challenges. Many products do not match the protein content or essential micronutrients (such as calcium, vitamin D and vitamin B12) found in dairy milk, which often necessitate fortification to improve their nutritional profile. Furthermore, differences in taste, texture and mouth feel compared to traditional milk can influence consumer preferences. This review highlights on these aspects in detail. Future research should aim at refining formulations, enhancing nutrient absorption, and investigating new plant sources to improve both the functional attributes and sensory experiences of plant-based milks.

Keywords: *soy milk, almond milk, peanut milk, coconut milk, sustainability, dairy alternatives, nutritional benefits*

Introduction

Milk and dairy products have long been considered essential for human nutrition, ranking among the top food groups due to their rich macronutrient and micronutrient profiles (Jemaa et al., 2021). They provide high-quality proteins, essential fatty acids, calcium, vitamin D, and bioactive compounds that support overall health and development (Haug et al., 2007). However, in recent years, the demand for plant-based milk alternatives has surged, driven by multiple factors, including lactose intolerance, dairy allergies, gastrointestinal discomfort, ethical and environmental concerns and shifting dietary preferences (Reyes-Jurado et al., 2023). Additionally, the rising prevalence of veganism and flexitarian diets has further fueled the shift towards non-dairy alternatives (Jeske et al., 2018). Plant-based milk alternatives are derived from a variety of plant sources, including legumes (soy, pea, peanuts), cereals (oats, rice), oilseeds (flax, sesame), and nuts (almond, cashew, coconut). The production process generally involves raw material selection, soaking, grinding, and blending with water, followed by homogenization and filtration to achieve a fluid consistency that resembles conventional dairy milk (Mäkinen et al., 2016; Thakur et al., 2022). Advanced processing techniques, such as enzymatic hydrolysis, fermentation, and thermal treatments, are often applied to enhance the stability, nutritional profile, and sensory attributes of these products (Silva et al., 2020; Karoui & Bouaicha, 2024). One of the key advantages of plant-based milk alternatives is their potential health benefits. They are naturally cholesterol-free, often lower in saturated fats, and can provide beneficial bioactive compounds such as polyphenols, phytosterols, and antioxidants (Sethi et al., 2016). Moreover, their suitability for individuals with lactose intolerance or dairy allergies makes them an essential dietary option for a growing segment of the population. Additionally, compared to conventional dairy production, plant-based milk alternatives have a lower environmental footprint, requiring fewer natural resources and producing fewer greenhouse gas emissions, making them a more sustainable choice (Poore & Nemecek, 2018). Despite these benefits, several challenges hinder the widespread adoption of plant-based milk alternatives. Many formulations lack the protein quality and quantity of dairy milk, requiring fortification with essential nutrients such as calcium, vitamin D, and vitamin B12 (Vanga & Raghavan, 2018). Furthermore, undesirable sensory attributes, such as grainy textures, off-flavors, and phase separation, often affect consumer acceptability. To improve the taste, texture, and stability of these products, food additives such as emulsifiers, stabilizers, and flavor enhancers are commonly used (Karoui & Bouaicha, 2024). As consumer demand for plant-based milk alternatives continues to rise, research and innovation are essential to optimizing their nutritional composition, sensory attributes, and functional properties. This review explores the production methods, nutritional benefits, and challenges associated with plant-based milk alternatives, providing insights into their role in sustainable diets and future advancements in food technology.

Need for plant-based milk alternatives

The increasing global consumption of animal-derived products has significant health and environmental impacts. The adoption of Western-style diets has exacerbated these concerns, driving the need for sustainable and health-conscious dietary shifts (Pointke et al., 2022). Approximately 75% of the global population experiences some form of lactose intolerance, making plant-based milk alternatives an essential dietary option (Makinen et al., 2016). These alternatives are lactose-free, cholesterol-free, and low in trans fats, providing an ideal substitute for individuals with dietary restrictions. The impact of dairy production on the environment is considerable, with cow’s milk contributing significantly to greenhouse gas emissions and water consumption. Plant-based milk alternatives have a global warming potential two to three times lower than dairy milk (Geburt et al., 2022). Additionally, the production of cow’s milk requires nearly four times more water than plant-based alternatives. Plant-based diets are increasingly recognized for their environmental sustainability, public health benefits, and balanced nutrition at both individual and societal levels (Makinen et al., 2016).

Categories of plant-based milk

Plant-based milks are non-dairy alternatives derived from various plant sources, including nuts, seeds, grains, and legumes. They serve as substitutes for traditional cow's milk and are widely consumed by people who show lactose intolerance, are allergic to dairy or are keen vegan diet followers. Additionally, plant-based milks have gained popularity due to their lower environmental impact compared to dairy production (Poore & Nemecek, 2018). These milks vary in taste, texture, and nutritional content, depending on the source from which they are derived. One of the most well-known categories of plant-based milk is nut-based milk, which includes almond, cashew, macadamia, hazelnut, and walnut milk. Almond milk is among the most widely consumed due to its light, nutty flavor and low calorie content. It is particularly rich in vitamin E, an antioxidant known for promoting skin health (Singar et al., 2024). Cashew milk, on the other hand, has a creamier texture and is often preferred for cooking and coffee applications. Macadamia milk is another creamy and rich alternative, known for its high content of heart-healthy monounsaturated fats. Hazelnut milk has a naturally sweet, nutty taste and is often used in desserts, while walnut milk stands out due to its high omega-3 fatty acid content, which supports brain and heart health (Ros, 2010). Another category is seed-based milks, which include hemp, flaxseed, and sunflower seed milk. These plant-based milks are rich in essential fatty acids and are often consumed by individuals looking for nutrient-dense alternatives. Hemp milk, made from hemp seeds, has a slightly earthy taste and is high in polyunsaturated fatty acids (omega-3 and omega-6), which show proven benefits for cardiovascular health. Flaxseed milk is a mild and neutral-tasting option, known for its high omega-3 content. Similarly, sunflower seed milk is a lesser-known but valuable alternative, offering high levels of vitamin E and serving as a nut-free option for those with allergies.

Grain-based milks, including oat, rice, and quinoa milk, are another popular category. Oat milk has gained significant popularity due to its naturally creamy consistency and mild sweetness, which comes from the natural breakdown of oat starches into simple sugars during processing. It is also a good source of beta-glucans, a type of soluble fiber that helps lower cholesterol levels (Whitehead et al., 2014). Rice milk, on the other hand, is one of the most hypoallergenic plant-based milk options, making it suitable for individuals with multiple food allergies. However, it is relatively high in carbohydrates and low in protein. Quinoa milk is a less common but nutritionally dense option as it comprises of all nine essential amino acids and making it a wholesome protein source (Vega-Gálvezet al., 2010). Legume-based milks, particularly soy, pea, and chickpea milk, are valued for their high protein content. Soy milk is nutritionally similar to that of dairy milk as it contains similar protein levels and a balanced amino acid profile. It is also rich in isoflavones, plant compounds that may have beneficial effects on heart health and hormone regulation (Messina, 2014). Pea milk, made from yellow peas, is another protein-rich alternative with a creamy texture and a neutral taste, often fortified with essential nutrients such as vitamin D and calcium. Chickpea milk, though less common, provides a good source of plant-based protein and fiber, making it a nutritious addition to the legume-based milk category. Coconut-based milk, derived from the flesh of coconuts, is a unique plant-based milk due to its distinct tropical flavor and high content of medium-chain triglycerides (MCTs). MCTs are a type of fat that is rapidly metabolized by the body for energy, making coconut milk a popular choice in keto and paleo diets. It is also widely used in cooking, especially in Southeast Asian and Indian cuisines. However, coconut milk has less protein compared to other plant-based milks and is often combined with other ingredients to enhance its nutritional profile (Dayrit, 2014).

Pseudo-cereal based plant milk is derived from grains such as amaranth, teff etc. and represents a growing segment of the plant based beverage industry. These are valued for their high nutritional content, their gluten-free nature and environmental sustainability. All the pseudo cereals are rich in proteins, dietary fibres, bioactive compounds and essential amino acids, making them suitable for health conscious consumers and individuals with dietary restrictions. Pseudo-cereal such as amaranth and quinoa contain complete proteins with all essential amino acids and like many traditional cereals, they are also a rich source of vitamins, especially B group vitamins and minerals, such as calcium, magnesium and iron. The presence of phenolic compounds and antioxidants contributes to their anti-inflammatory and hypoglycemic effects (Li et al, 2025). The production process of Pseudo-cereal based plant milk involves the cleaning and soaking of the grains followed by grinding to get a smooth slurry. Heating is done to inactivate the enzymes and filtration helps to remove any solids. Sometimes fortification is also done with certain vitamins and minerals. They are also subjected to lactic acid bacteria fermentation to reduce any anti-nutritional factors and increase the bioavailability of nutrients so they help in improving digestive health, making them a suitable choice for consumers seeking suitable sustainable alternatives (Deziderio et al., 2023).

Additionally, some plant-based milks are created as blends or fortified versions to enhance their taste, texture, or nutritional value. For example, almond-oat blends combine the creaminess of oats with the mild nuttiness of almonds. Many commercially available plant-based milks are fortified with calcium, vitamin D and vitamin B12 to make them more comparable to dairy milk in terms of nutrition. Protein-enriched versions also exist, where manufacturers add pea or soy protein to improve the overall protein content of the milk. As per Sharma et al (2020), the plant-based milk can be categorized into the following categories tabulated under Table 1.

Table 1. Categories of Plant-based milks

Categories (based on)	Examples of milks
1. Cereal	Rice milk, Oat milk, Corn milk.
2. Legume	Soy milk, Peanut milk, Lupin milk.
3. Nut	Almond milk, Coconut milk, Hazel nut milk, Walnut milk, peanut milk.
4. Seed	Sesame milk, Flaxseed milk, Hemp milk, Sunflower milk.
5. Pseudo-cereal	Quinoa milk, Teff milk, Amaranth milk.

Nutritional and Bioactive Properties

1. Soy milk

Soy milk obtained from soybeans (*Glycine max*) is one of the most widely consumed plant-based milks. It contains appreciable content of MUFAs and PUFAs that promote cardiovascular health. Additionally, it is rich in bioactive compounds such as isoflavones, which offer protective effects against cancer and osteoporosis, and phytosterols, which help reduce cholesterol levels (Thakur et al., 2022). Soy milk gives better viscosity with higher protein and fat content when we go for alkaline soaking of soy grains (Giri & Mangaraj, 2012). Further, the blanching of soy grains helps in reducing the trypsin inhibitor activity up to 50 per cent which helps in improving its digestibility (Yuan et al., 2008).

2. Almond milk

Almond milk is considered a "brain food" due to its high content of vitamin E and essential fatty acids. It contains bioactive compounds such as arabinose, which helps regulate blood sugar levels and improves cholesterol profiles (Velangi & Savla, 2022). Sobhy et al. (2021) reported that almond milk has high nutritive value due to its high antioxidant activity. Its consumption helps in decreasing body weight, body mass index and waist and hip circumference (Al Tamimi, 2016). Almond milk has a glycemic index of 57 as compared to dairy milk which has a GI of 47 as studied by Jeske et al. (2017). The nutritional composition of almond milk can be altered by the inclusion of stabilizers, preservatives and by following different processing methods (Kundu et al., 2018). The digestibility score of almond milk was reported to be 85.8 % (Khamzaeva et al., 2024). Balbino et al. (2023) prepared almond drinks with added concentrated aqueous herbal extracts of myrtle, bay leaf and fennel seeds which resulted in increased antioxidant activity by up to 12-fold. To further enhance the health promoting properties of almond milk Bernat et al. (2015) went for its fermentation with probiotic strains which resulted in its increased viscosity values as well. Likewise, fermented almond milk tea was developed by Kannan et al (2021) which was found to act as a prophylactic anti-diabetic drink.

3. Oat milk

Oat milk (*Avena sativa*) is rich in β-glucan, vitamins A, D, E, and B1, and essential minerals such as calcium and potassium. It offers significant health benefits, including cholesterol reduction, improved blood sugar regulation, and enhanced digestive health (Karoui & Bouaicha, 2024). The world's first oat milk brand, Oatly was made by using 200 grams of oats and 35 grams of rapeseed oil to get a smooth milk like taste (Röös et al, 2016). The selection of suitable cultivars is very important for maintaining the stability and flavour of the oat milk (Zhou et al, 2023). The optimum time for soaking of oats for making oat milk was reported to be 8 h for maximum extraction of oat milk (Syed et al., 2020). The shelf life of the oat milk can be effectively increased by inhibiting the vegetative cells by subjecting it to high pressure processing at 600 MPa which also resulted in better sensorial acceptance as compared to heat treated samples (Ahmad et al, 2025). The emulsion stability of the oat milk can also be improved by adding emulsifiers, colloid milling and sterilization (Paul et al., 2020). The problem of undesirable flavors in the oat milk which are caused by lipid oxidation can be worked by the addition of various additives (diacetyl, limonene, cinnamaldehyde) as well as employing novel non thermal techniques like cold pressure (Han et al., 2019).

4. Peanut milk

Peanuts (*Arachis hypogaea*) are one of the richest sources of protein among nuts, making peanut milk an excellent plant based protein option that aids in muscle recovery and overall bodily functions. This milk is rich in saturated fats including monounsaturated and polyunsaturated fats which contribute to heart health by reducing levels of harmful LDL cholesterol and boosting beneficial HDL cholesterol. Additionally, peanut milk contains vitamin E, an antioxidant that shields cells from damage caused by free radicals and supports heart health. Vitamin B6 plays a crucial role in the production of hemoglobin and helps lower the risk of cardiovascular issues. Further, it is a good source of magnesium and calcium, collectively these nutrients promote better heart health, effective weight management, improved digestive health and sustainability. In a normal soaking method of peanut milk preparation, the values of proteins, carbohydrates, fat and ash were reported to be 3.68%, 4.70%, 2.16% and 0.24% respectively. On the other hand, in soaking in 1% $NaHCO_3$ method of peanut milk preparation, proteins, carbohydrates, fat and ash were found to be 3.11%, 5.58%, 1.86% and 0.26% respectively. In the roasting method of peanut milk preparation, proteins, carbohydrates, fat and ash were 3.23%, 3.78%, 3.53% and 0.18% respectively (Yadav et al., 2018).

Sakthi et al. (2020) extracted the peanut milk by different processing methods and found the best pre-treatment was roasting of peanuts before soaking. The application of microfluidization at 120 MPa yielded peanut milk with good physical stability (Dai et al., 2022). It was also reported that peanut milk prepared from variety M-522 after pressure blanching at 121°C for 3 min was most appropriate for the preparation of peanut milk beverage (Jain et al., 2013). It has versatile culinary applications and can be used in smoothies, coffee, savoury dishes, deserts and offers a creamy texture and flavour while being a dairy free alternative (Singh & Singh, 2020). Peanut milk can be further utilised for making yogurt with high protein and fat content as well as good water holding capacity (Isanga & Zhang, 2009). Peanut milk yogurt analogs for also prepared by using an exopolysaccharides starter culture which yields yogurt with better firmness, creamy texture and less syneresis (Bulca & Büyükgümüs, 2024). While it is nutritious, it can’t be consumed in more amounts due to the excessive calorie intake.

Production of plant-based milk alternatives

1. Nut based-coconut milk

Coconut (*Cocos nucifera* L.) is used to make coconut milk, desiccated coconut and coconut oil. It contains lauric acid which helps to arrest the occurrence of cardiovascular diseases and contains phenolic components and has antioxidant properties (Karoui & Bouaicha, 2024). It contains 50cal, 2g CHO, 5g of fats in per 236g of coconut milk (Sharma et al., 2020). Considering sustainability, the waste from coconut can be reincorporated in biomass for energy and save the resource for the environment (Tulashie et al., 2022). The Flow diagram for the production of plant-based milk alternatives is presented in Figure 1.

The general process for manufacturing plant-based milk alternatives includes several key steps:

1. **Raw material selection:** Cleaning and selecting high-quality plant ingredients.

2. Soaking: Enhances extraction efficiency by softening plant materials (Daryani et al., 2024).

3. Blanching: Reduces microbial load and removes off-flavors (Sethi et al., 2016).

4. Grinding and filtration: Extracting and separating the milk component.

5. Homogenization: Ensuring a uniform texture and stability.

6. Fortification (if needed): Adding essential vitamins and minerals to enhance nutritional value.

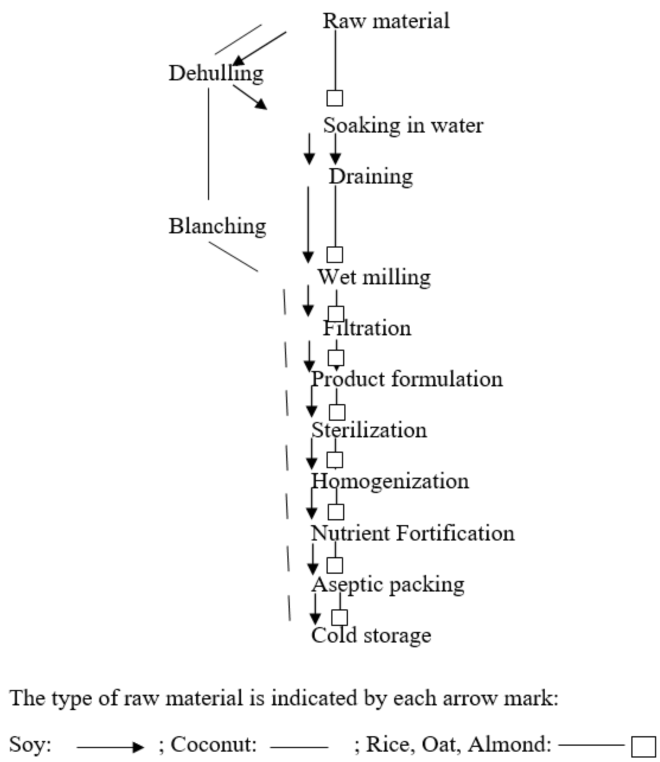

Figure 1. Flow diagram for production of plant-based milk alternatives (Adapted from: Reyes-Jurado et al., 2023, Aydar et al., 2020).

2. Cereal based rice milk

Rice (*Oryza sativa*) is the most popular cereal consumed worldwide (Padma et al., 2018). Rice is rich in carbohydrates but low in protein, lipids, vitamins and minerals and needs fortification. Rice milk is lactose-free and not allergic. It contains Phytosterol and c-oryzanol which reduce cholesterol, anti-diabetic, anti-inflammatory and anti-oxidative in nature (Velangi & Savla, 2022). The nutritional composition of plant-based milk alternatives is presented in Table 2 as under. The various bioactive compounds present in plant-based milk and their health benefits are tabulated in Table 3 as under.

Table 2. Nutritional composition of plant-based milk alternatives

Plant-based milk	Calories (cal)	Total CHO (g)	Total fats (g)	Protein (g)
Almond milk	16.95	0.4	1.27	0.85
Soya milk	33.90	1.69	1.69	2.97
Rice milk	50.85	9.32	0.85	0.00
Coconut milk	21.19	0.85	2.12	0.00

Table 3. Bioactive compounds present in plant-based milk and their health benefits (Adapted from Sethi et al., 2016, Velangi & Salva, 2022)

Plant-based milk (sourced from)	Bioactive compound	Health benefits
Almond	Arabinose, β-sitosterol	Powerful antioxidant, high in vit E.
Rice	Phytosterol, c-oryzanol	Reduce cholesterol, anti-diabetic, anti-inflammatory.
Oat	β-glucan	Maintain and reduce weight and cholesterol, anticancer properties.

Coconut	Lauric acid	Anti-bacterial, anti-viral, protective against degenerative diseases.
Soya	Phytosterol, isoflavones, saponins, phytic acid	Lipid lowering, protective against several diseases like osteoporosis, cancer, diabetes, Blood Pressure.

The chronological order of published research on plant-based milks is presented in Table 4 as under:

Table 4. Chronological order of published research on the plant-based milks

S.No.	Research	Conclusions	Reference
1.	Elaborated on the process of making a beverage from whole soybeans focusing on temperature and pressure conditions.	• Homogenization at 200ºF and 3500 psi showed zero separation after 2 months of storage.	Nelson et al. (1976)
2.	Study of soymilk made from lipoxygenase free and normal soybeans	• Soymilk had less cooked beany flavor and less astringency and more yellow in color as compared to the control.	Torres-Penaranda et a 1998)
3.	Ultra-high-pressure homogenization of soy milk was conducted	• This treatment increases the stability of soy milk • 200-300 MPa increases the microbial quality of soy milk.	Cruz et al. (2007)
4.	Soy milk was prepared by incorporating different levels of sugar	• Soy milk stored at 4°C with added sugar gave the best quality soy milk with retention of major volatiles.	Achouri et al. (2007)
5.	Soybeans stored varying conditions of temperature and humidity for preparing soy milk	• Best storage conditions: Temperature: <22°C and RH: 55-60% • Soybeans stored under optimum conditions (4°C) yielded better quality of soy milk.	Kong et al. (2008)
6.	Estimation of beany flavor. Hot water blanching and grinding was employed.	• The soaking and blanching of soybeans followed by grinding with hot water for 2-6 min helped in decreasing lipoxygenase activity.	Lv et al. (2011)
7.	Examined the effect of processing on the composition of soymilk and its powder.	• Soaking, blanching, fermentation, homogenization, filtration, etc. affect the composition, anti-nutrients, sensory acceptance and stability of liquid and powdered milk.	Giri & Mangaraj (2012)
8.	The sensory quality of soybeans and soymilk was tested.	• Selecting the desired seeds affects the chemical quality traits in the soybean breeding programme.	Ma et al. (2014)
9.	Established models that shed light on the protein aggregation and lipid-protein interaction.	• Heat affects the characteristics and behaviour of soymilk particles	Peng et al. (2016)
10.	Soy and almond milk combinations were prepared and tested	• Prepared soy and almond milk samples showed the best acceptability with the better nutritional profile.	Kundu et al. (2018)
11.	Fermentation of plant-based milk alternatives was employed to improve flavor and nutritional value.	• Enhance the flavor and nutritional profile of plant-based milk alternatives by using fermentation methods and mixed-culture fermentation.	Tangyu et al. (2019)
12.	Developed next generation plant-based milk substitutes by employing fortification.	• Structural design principles facilitated the development of higher quality and more stable plant-based products.	McClements (2020)
13.	Analysis of Bioactive Constituents in Plant-Based Milk Alternatives in the United States Market	• Analyzed the presence of bioactive polyphenols in plant based milk alternatives and their impact on human health.	Grainger et al. (2024)

Purchasing intent

Various studies were conducted to determine the consumer perception regarding plant-based milk alternatives and the factors affecting the purchasing of plant-based milk. In one study, a total of 895 participants comprising 796 women and 99 men participated and were questioned about the factors that drove them to purchase. Most people consumed almond milk, soy milk, and coconut milk. The frequent reason behind consumption was "Non-Dairy milk contains good fat" (Cakir-Bicer et al., 2023). Consumer perception and choice are affected by many factors like price, characteristics, producer, product composition, and quality of the product (McCarthy et al., 2017). Per capita, cow's milk consumption in North America has decreased. Retail market sales in the USA were observed at $6 billion in 2017 and estimated at $28 billion in 2021. In Canada per capita consumption of cow's milk decreased from 89.14L to 69.48L between 1997 and 2016 (Chalupa-Krebzdak et al., 2018).

Challenges of plant-based milk alternatives

Despite their advantages, plant-based milk alternatives face several challenges:

- **Sensory Characteristics:** Legume-based milk often exhibit a beany taste, while nut- and seed-based alternatives may have chalky textures or off-flavors (Sethi et al., 2016; Moss et al., 2022).
- **Nutritional Equivalence:** Many plant-based milks have lower protein and mineral content compared to dairy milk, necessitating fortification (Ramsing et al., 2023).

Production Costs: The multiple processing steps required for plant-based milk contribute to higher costs compared to dairy milk (Sethi et al., 2016).

Conclusion

Plant-based milk alternatives represent a crucial advancement in food science, offering sustainable and health-conscious choices for consumers worldwide. They provide a viable solution for individuals suffering from lactose intolerance, milk allergies, and those following plant-based diets, contributing to enhanced dietary diversity. Their role in promoting environmental sustainability by lowering greenhouse gas emissions and water consumption compared to traditional dairy production and promoting public health underscores their importance in the future of food systems. While challenges such as sensory appeal and nutritional balance remain, technological advancements in processing and fortification are addressing these issues.

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JR and PK-inception; AT and JR-literature collection; JR, PK, AT- compilation; JR and PK-editing.

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