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EXPLORING PLANT-BASED MILK ALTERNATIVES: A COMPREHENSIVE REVIEW

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ABSTRACT: The consumption of plant-based milk alternatives has increased substantially in recent years, driven by health concerns, environmental awareness and evolving lifestyle preferences. Many consumers choose these products to manage cow's milk protein allergy (CMPA) or lactose intolerance (LI), while others adopt them as part of plant-forward or vegan dietary patterns. Plant-based milks produced from legumes, oilseeds, cereals and pseudocereals, are typically water-soluble and formulated to resemble the sensory characteristics of cow's milk, making them appealing replacements in a wide range of applications. However, the environmental advantages of these alternatives remain complex and context-dependent. Although plant-based beverages generally require fewer natural resources, their carbon footprint, water consumption and eutrophication potential vary according to crop type, agricultural practices and regional conditions. This review synthesizes current knowledge on the primary motivations for plant-based milk consumption, highlighting key health issues associated with cow's milk, including intolerance, allergy and emerging concerns over saturated fat content. It further compares the environmental impacts of producing plant-based milk substitutes and conventional dairy milk, drawing attention to sustainability trade-offs. Additionally, the nutritional composition of major plant-based milks is examined, noting variations in protein content, micronutrients and fortification practices. The article also addresses significant challenges in producing high-quality plant-based milks, such as flavor optimization, stability, nutrient availability, and processing efficiency. Finally, strategies to enhance the overall quality and acceptability of plant-based milk alternatives are discussed, providing insight into future innovations in this rapidly expanding sector.

INTRODUCTION: In recent times, there has been a growing consumer preference towards adopting a plant-based diet comprising legumes, seeds, fruits, vegetables, nuts and cereals because of varied reasons such as environmental awareness, pursuit of a healthier lifestyle and concerns about animal welfare ¹.

As a results of these factors, various dietary trends such as veganism, vegetarianism, ovo-vegetarianism and lacto-vegetarianism have been emerged. Veganism is defined as entails abstaining from the consumption of dairy, eggs, fish, poultry, meat and their derivatives thereof ².

Plant-based milk alternatives play a very important role in the vegan food sectors, serving as a essential ingredients in various many vegan food products including cheese, butter, ice cream, yoghurt, flavoured milk, etc. In addition, plant-based substitute will be the suitable choice for the people who had cow's milk allergy, lactose intolerance, calorie concern, hypercholesteremic patients and

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also major concerns about saturated fat, sugar level, hormonal contents and antibiotic use in cattle³. Excessive consumption of animal-based food causes cardiovascular diseases, an elevated cholesterol levels, whereas seeds, millets, legumes, nuts and cereals provide antioxidants, dietary fiber, vitamins and minerals, additionally, these foods are classified under nutraceutical and functional foods⁴.

Plant-based diet rich in foods like nuts and soybean can decrease the risk of neurodegenerative disorders such as Alzheimer's disease⁵. Moreover, consuming just two glasses of cow's milk daily can result in a D-galactose intake exceeding 100 mg/kg, potentially contributing to Parkinson's diseases⁶. Consumer's preference for alternatives to cow's milk has surged, with demand for nondairy beverages experiencing a substantial increase of 61% since 2012⁷. In developing countries CMPA (Cow's Milk Protein Allergy) impacts approximately 2 to 7.5% of children, especially in the first month of life. Around 50 to 70% of the population experience cutaneous symptoms while 50 to 60% exhibits gastrointestinal symptoms and 20 to 30% had respiratory symptoms⁸. According to research by the U.S National Library of Medicine (2020), approximately 65% of the global population demonstrates decreased lactose digestion⁹.

In some cases, novel technologies like ultra sound, pulsed electric fields, ohmic heating and ultra or high-pressure homogenization are employed to enhance the stability without the addition of additives. Moreover, the fortification and enhancement of plant-based milk alternatives with vitamins, minerals and protein enrichment are also a vital issue for consumers who prefer plant-based milk substitutes instead of traditional cow's milk¹⁰. The rise of the plant-based milk substitute industry did not significantly impact the stability of dairy milk sales, making non dairy milk an additional benefit¹¹. Besides the advantages associated with consuming plant-based milk substitutes, the manufacturing of these beverages also brings various environmental impacts, such as reducing water usage footprint and mitigating climate change and ecotoxicity risks¹². Plant-based milk substitutes have positive effects due to their abundant fatty acids and antioxidant activity, which

contributes to reducing the risks of cardiovascular diseases, cancer, atherosclerosis and diabetes¹³.

Milk is considered a complete and irreplaceable food; there is growing recognition of the benefits offered by plant-based milk substitutes compared to traditional dairy products. Factors such as the presence of various bioactive phytochemicals, absence of cholesterol, high energy input required for dairy production, limited availability of milk in certain regions, the rise of vegan diets and constraints on resources like landmass and feed are driving the search for alternative milk sources¹⁴.

The potential for significant growth in the health food market lies in plant-based milk alternatives, which requires thorough exploration through advancements in processing techniques, technological innovations and fortification methods to create a nutritionally balanced beverage that appeals to consumers. To establish plant-based milk as a nutritionally comparable substitute for cow's milk, fortification with suitable nutrients using effective technology is essential, while ensuring the retention of nutrient bioavailability throughout storage¹⁵. These are the some of the reasons consumers shift towards the consumption of plant-based milk substitutes.

Health Issues Related to Cow's Milk Consumption:

Adverse Reaction to Cow's Milk Consumption:

Cow's Milk Protein Allergy: Cow's milk protein allergy arises from an immunological response to cow's milk proteins, which may involve immunoglobulin E (IgE), non-IgE mechanisms, or a combination of both. This particular allergy is predominantly observed in infants and children, with a lower incidence among adults. Dermatological, respiratory, and gastrointestinal symptoms are frequently encountered in cases of cow's milk protein allergy, often leading to poor growth during infancy. The similarity of gastrointestinal manifestations to those seen in individuals with lactose intolerance contributes to the frequent confusion between cow's milk allergy and lactose intolerance¹⁶.

Lactose Intolerance: Lactose intolerance is a contributing factor to the shift from cow's milk to plant-based milk alternative among consumers.

Due to reduction in the expression of the lactase gene, leading to decreased levels of lactase in the small intestine and subsequently reduced lactase activity causes lactose intolerance¹⁷. Individuals with diminished or lacking levels of lactase activity cannot effectively break down lactose in the small intestine, a condition referred to as primary lactase deficiency (PLD). This deficiency is prevalent in an estimated 70% of the global population, albeit with notable variations across different ethnic groups. Undigested lactose travels to the large intestine, where bacterial metabolism occurs, generating significant gas production (e.g., hydrogen, carbon dioxide, and methane) and causing water influx due to lactose's osmotic properties. This process results in symptoms like abdominal discomfort, flatulence and diarrhea. The manifestation and intensity of these symptoms differ among individuals, as lactose tolerance hinges on factors such as lactose intake levels, the presence of lactase in the small intestine, and the nature of accompanying food. Conversely, deficiencies in lactase can also arise from various ailments affecting the small intestine, such as acute gastroenteritis or chronic intestinal inflammation, which induce damage to the intestinal epithelium, leading to varying degrees of lactose maldigestion. This state is termed secondary lactase deficiency¹⁸.

A1 Beta Casein and A2 Beta Casein: Caseins (CNs) constitute nearly 80% of the total protein content in milk and can be categorized into four distinct types: α s1-CN, α s2-CN, β -CN, and K-CN. Among these types, the β -CN type encompasses twelve different variations, among which A1 and A2 are the most prevalent. These two genetic variants can be differentiated solely by a single amino acid variation at position 67 - where histidine is found in the A1 variant, while proline is present in the A2 variant. This discrepancy yields implications on the technological properties of milk and its nutritional value for humans, with the A2 variant being considered more favorable compared to the A1 variant. The superiority of the A2 variant is attributed to its advantageous technological characteristics and the enhancement brought to milk digestibility. Additionally, gastrointestinal issues commonly linked to lactose intolerance may stem from the consumption of milk containing the A1 variant, rather than from the body's incapacity to metabolize lactose¹⁹.

Bone Health: Osteoporosis is characterized by a decrease in bone density leading to an elevation in bone fragility. Studies indicate a lack of significant correlation between milk consumption and the likelihood of hip fractures (across all demographics and genders), as well as the prevention of osteoporosis²⁰. Conversely, other studies suggest a negative relationship between the consumption of milk and dairy products and osteoporosis, demonstrating a decrease in the risk of osteoporosis by 22–37% with an increased intake of dairy products and milk (an additional 200 g per day)²¹.

Chronic Diseases: In recent years, there has been a growing scrutiny and examination within the scientific community regarding the involvement of milk and dairy products in human nutrition. This investigation has led to conclusions which suggest that the intake of milk and dairy might provide a safeguarding function against most prevalent chronic illnesses, with only a few harmful effects documented²².

Diabetes: Diabetes is a persistent condition impacting approximately 422 million individuals globally and resulting in 1.5 million fatalities in the year 2019. This ailment can be categorized into Type 1 Diabetes (T1D), characterized by insufficient insulin production by the body, and Type 2 Diabetes (T2D), where the body displays inefficiency in utilizing insulin, representing the primary form of diabetes (WHO, 2021). The onset of T2D can be averted or postponed through adherence to a nutritious diet, regular engagement in physical activities, and the cessation of smoking. Concerning dietary habits, evidence suggests that the intake of dairy items can diminish the susceptibility to T2D, highlighting the advantageous impact of milk consumption on this type of diabetes²³.

Cardiovascular Diseases (CVD): Cardiovascular diseases (CVD) represent a significant public health issue given their status as a primary contributor to global mortality²⁴. The association between the consumption of dairy products and an elevated risk of CVD can be attributed to their fat content and composition, particularly the prevalence of the saturated fatty acid fraction²⁵. Nevertheless, there exists a lack of consensus regarding the impact of diets abundant in SFA on

CVD susceptibility. The daily ingestion of 200 mL of milk does not show any connection to coronary heart disease (CHD), yet this same daily amount of milk consumption is linked to a notable 7% decrease in the likelihood of stroke ²⁶.

Obesity: In the year 2016, an estimation indicated that 13% of the global adult populace was classified as obese, whereas in 2019, an estimation revealed that 38.2 million children under the age of 5 were impacted by this health condition. The consumption of dairy products could serve as a significant factor in managing this health condition owing to their high nutritional value. Epidemiological evidence exists to support the favorable impact of dairy product intake on weight control, with the consumption of full-fat milk being linked to reduced chances of being overweight or obese ²⁷.

Cancer: Cancer is accountable for numerous fatalities globally. The correlation between dairy intake and cancer has been extensively examined; nonetheless, the findings are contentious ²⁸. There is evidence of a potential advantageous impact of milk consumption on the risk of bladder and gastric cancer although this effect varies across different regions and even among various dairy products. Conversely, this does not apply to prostate cancer, as studies have shown that a high milk intake is linked to an increased risk of prostate cancer, its recurrence, progression, and mortality. An escalation in milk consumption by 100 to 200 g/day has been correlated with a significant rise in prostate cancer risk, and a substantial consumption of whole milk can elevate the mortality risk by 50% ²⁹. Conversely, there is insufficient evidence or definitive outcomes concerning the influence of dairy product consumption on lung cancer or liver cancer risk. In terms of breast and ovarian cancer, there is no consensus on the impact of dairy intake on these cancer risks. While some studies suggest no connection between milk consumption (< 450 g/day) and breast cancer risk or between milk/dairy product consumption and ovarian cancer risk a higher milk intake has been associated with an increased susceptibility to these cancer type ²⁸.

Neurological Diseases: Dementia, a syndrome leading to the decline in cognitive and behavioral functions, impacts an estimated 50 million

individuals globally, with 10 million new cases reported annually ³⁰. Alzheimer's disease (AD) stands out as the most prevalent type, representing 60 to 70% of the instances. Studies have shown an inverse relationship between milk consumption and the susceptibility to cognitive disorders like AD. Conversely, the intake of dairy products appears to significantly elevate the risk of Parkinson's disease (PD). For instance, an increase of 200 g/day in milk consumption is associated with a 17% rise in the risk of PD, despite the unclear mechanism behind this correlation ³¹.

Environmental Effects of the Production of Plant-Based Milk Substitutes and Cow's Milk:

The food system significantly impacts the environment through various channels such as hastening climate change, intensifying water and land utilization, generating eco toxicity, promoting eutrophication and contributing to biodiversity loss ³². Researchers reported that the environmental burdens associated with dairy cattle, including land use and greenhouse gas emission, are significantly higher compared to pea production, with ratios of 36 and 6 times greater, respectively. Highlighting the substantial environmental pressures attributed to animal products, particularly greenhouse gas emissions, which appear to escalate over time ³³.

The majority of environmental concerns associated with the production of milk include soil degradation, as well as air and water pollution, along with the loss of biodiversity ³⁴. Environmental impact of milk production can be quite variable, depending on factors such as the livestock population on the farm, the environmental conditions in which they are housed, and the level of milk production ³⁵. Greenhouse gas emissions from this sector primarily consist of CO₂, CH₄, and N₂O, which are emitted from multiple stages in the life cycle ³⁶.

Impact on climate, eutrophication, acidification risk, and ecotoxicity of a conventional Swedish dairy farm was assessed during the production of oat milk substitute instead of cow's milk. Plant-based milk waste contains significant levels of bioactive compounds, antioxidants, essential oils, and an antimicrobial agent. Additionally, valuable substances such as a surface-active agent, dietary fiber, and a colorant are extracted from this waste

product. Repurposing plant-based waste aids in reducing environmental issues³⁷.

TABLE 1: MEAN GREENHOUSE GAS EMISSIONS FOR ONE GLASS (200G) OF DIFFERENT MILKS³⁸

Milk Types	Green house gas Emissions (kg CO ₂ -Ceq per 200g)
Cow's milk	0.62
Rice milk	0.23
Soy milk	0.21
Oat milk	0.19
Almond milk	0.16

TABLE 2: MEAN WATER FOOTPRINT FOR ONE GLASS (200G) OF DIFFERENT MILKS³⁸

Milk Types	Water Use (L per 200g)
Cow's milk	131
Rice milk	74
Soy milk	56
Oat milk	9
Almond milk	2

Plant based milk requires less energy input per unit of milk produced compared to animal milk.

Green house gas emission, land use and water footprints of plant-based milks vary, due to differences in region of production, transportation, production process, crop water needs and farming practices.

Plant-Based Milk Market Value: The plant-based milk alternatives market has been forecasted to expand at a CAGR of 15% from 2013 to 2018, with an anticipated value of \$14 billion.

Meanwhile, the global dairy industry, which was valued at USD 12.8 billion in 2018, is projected to grow to USD 25.18 billion by 2026, exhibiting a CAGR of 9.79% during the 2019 to 2026 period³⁹.

Classification of Plant-Based Milk Based on its Origin:

Cereal Based –	Legume Based –	Nut Based –	Pseudo cereal based –	Other based
Oats, Rice, Corn, Rye, Kamut milk	Soybean, Peanut, Groundnut, Kidney bean, Pea, Chick pea	Almond, Cashew, Coconut, Hazelnut, Walnut, Pistachio, Tiger nut	Quinoa, Teff, Amaranth milk	Potato, Moringa, colocynth (<i>Citrullus colocynthis</i>) seeds, cantaloupe seeds

Nutritional Composition of Cow and Plant-Based Milk:

Nutritional Properties: The nutritional composition of plant-based milk alternative exhibits variations mainly in the levels of sugar, fat, and protein. Cow's milk possesses a nutritional equilibrium that makes it a high-value product, serving as a rich reservoir of protein, calcium, phosphorus, potassium, and vitamin D. Due to the variability in raw materials and the formulation of plant-based milk alternatives, the task of establishing a comprehensive nutritional comparison among these products proves to be challenging. While plant-based milk do not match

the nutritional profile of cow milk, they are commonly supplemented with a variety of nutrients including calcium, phosphorus, as well as vitamins A, E and D. Nonetheless, a complete nutritional breakdown is lacking across all products, with manufacturers often only listing the essential nutrients on their packaging. Certain plant based milk offer vital nutrients necessary for human consumption. For example, soybean, peanut, hemp, and almond milk substitutes are abundant in essential fatty acids like linoleic and oleic acids, potentially playing a significant role in enhancing human nutrition⁴⁰.

TABLE 3: NUTRITIONAL COMPOSITION (ENERGY EXPRESSED AS KCAL/100 ML AND MACRONUTRIENTS (G/100ML)⁴¹

Nutritional parameters	Cow's milk	Soy milk	Peanut milk	Coconut milk
Total energy content (Kcal)	34.0–65.8	32.0–58.0	72.0- 76.0	19.0–178.0
Carbohydrates (g/100g)	4.58–5.33	0.20–7.08	4.7- 4.9	0.42–5.00
Fiber (g/100g)	0.2- 0.3	0.40–0.80	-	0.10–0.42
Glucose (g/100g)	2.06	0.01–0.52	0.08-0.09	0.81
Fructose (g/100g)	4.5 – 5	0.06–1.27	1.00- 1.2	-

Lactose (g/100g)	2.55	-	-	-
Protein (g/100g)	3.15–3.70	2.08–3.70	1-3	0.08–1.60
Lipids (g/100g)	3.5- 4	1-2	4-6	7-8
SFA (g/100g)	0.06 – 2.35	0.17 – 0.42	0.5- 1.5	1.67 – 12.6
MUFA (g/100g)	0.02 – 1.09	0.35	3- 5	-
PUFA (g/100g)	0.00 – 0.20	1.00	1- 2	-

TABLE 4: VITAMINS CONTENT IN COW'S MILK AND SOME PLANT-BASED MILK ⁴²

Vitamins	Cow's milk	Soy milk	Peanut milk	Coconut milk
Vitamin C (mg)	-	-	-	-
Thiamine (B1)mg	0.1	0.1	-	-
Riboflavin (B2) mg	0.3	0.2	-	-
Niacin (B3) (mg)	0.3	0.3	-	-
Pyridoxamine, (B6) (mg)	0.0	0.1	-	-
Folate (B9) (µg DFE)	0.0	34	-	19
Cobalamine (B12) (µg)	1.3	0.7	-	0.8
Vitamin A (µg)	80	33	80	60
Vitamin E (mg)	0.1	4.0	-	-
Vitamin D (µg)	2.4	-	1.5	2.9
Vitamin K(µg)	0.0	1.9	-	-

TABLE 5: RECOMMENDED DIETARY ALLOWANCES -ANIMAL BASED AND PLANT-BASED MILK PER 100G OF PRODUCT

Vitamins	Gender	RDD for adults	Animal milk	Plant milk	Sources for RDD
Vitamin A	M	900µg	0.00 – 7.67%	0.00 – 20.00 %	43
	F	700µg	0.00 – 9.86 %	0.00 – 25.71 %	
Vitamin B1	M	1.2 – 1.5 mg	0.67 – 56.67%	0.00 – 8.33%	44
	F	1.0 – 1.1 mg	0.91 – 68.00%	0.00 – 10.00%	
Vitamin B2	M	0.9 – 1.1 mg	0.01 – 41.78 %	0.00 – 36.67%	45
	F	1.1 – 1.3mg	0.01 – 34.18 %	0.00 – 30.00 %	
Vitamin B3	M	16 mg	0.50 – 2.61 %	0.44 – 3.98 %	46
	F	14 mg	0.57 – 2.98%	0.50 – 4.55 %	
Vitamin B6	M	1.3 – 1.7 mg	0.65 – 3.85 %	0.00 – 295.38%	47
	F	1.3 – 1.5 mg	0.73 – 3.85 %	0.00 – 295.38	
Vitamin B9	M/F	400 µg	0.15 – 2.13 %	0.25 – 12.00 %	48
Vitamin B12	M/F	2.4 µg	0.00- 33.33 %	0.25 – 321.4	49
Vitamin C	M	90mg	0.00 – 5.56 %	0.00 – 1.11 %	44
	F	75mg	0.00 – 6.67 %	0.00 – 1.33 %	
Vitamin D	M/F	15 – 20 µg	0.10 – 8.67 %	0.00 – 22.20 %	50
Calcium	M/F	1000- 1200 mg	2.67 – 20.00 %	0.00 – 49.50 %	51
Iron	M	8 mg	0.09 – 3.75 %	0.00 – 82.25 %	52
	F	8 – 18 mg	0.04 – 3.75 %	0.00 – 82.25 %	
Magnesium	M	400 – 420 mg	1.90 – 7.75 %	0.13 – 17.50 %	53
	F	310 – 320 mg	2.50 – 10.00 %	0.17- 22.58%	
Phosphorus	M/F	700 mg	2.00 – 26.43%	0.29 – 36.62 %	54
Potassium	M	3400 mg	1.50 – 6.00 %	0.77 – 18.79	55
	F	2600 mg	1.96 – 7.85%	1.01 – 24.58 %	
Sodium	M/F	2300 mg	0.65 – 2.58 %	0.00 – 8.83 %	55
Zinc	M	11 mg	0.54 – 6.79 %	0.00 – 8.55 %	56
	F	8-9 mg	0.66 – 9.34 %	0.00 – 11.75 %	

RDA and per cent of the daily value of animal based and plant-based milk per 100g of product. M- Male; F- Female.

Bioactive Compounds of Selected Plant-Based Milk Alternatives and Their Health Benefits:

Bioactive compounds are found in foods in minor amounts and are often referred to as non-essential nutrients that offer various health advantages. Typically abundant in plant based foods, these compounds have been shown to provide protective

effects against cancer, lower the likelihood of coronary heart disease, and support brain development. Moreover, the accessibility of diverse bioactive compounds such as isoflavones and phenolic compounds in the initial substance can be enhanced through natural or induced fermentation.

Peanut milk contains phenolic compounds which has a protective role against heart diseases and stroke⁵⁷. Soymilk possesses isoflavone, Phytosterol and alpha tocopherol. It has the ability to bind with estrogen receptors and lowers cholesterol properties. Medium chain lauric acid in coconut milk promotes brain development and immune system⁵⁸.

Challenges in the Development of Plant-Based Milk Alternatives: In the production and enhancement of Plant-Based Milk Alternatives (PBMAs), there are four main focus areas: enhancing stability, removal of unpleasant flavours, neutralizing or eliminating antinutrients, and extending shelf life.

Removal of Unpleasant Flavor: The presence of unsaturated fatty acids and lipooxygenases responsible for off flavours in plant-based milk. Removal of off flavours by deodourization, inactivation of enzymes and masking of off flavour by addition of natural or artificial flavourings⁵⁹. Lipooxygenases catalyze the production of nonvolatile hydroperoxides from unsaturated fatty acids, which subsequently break down into medium-chain aldehydes and alcohols like n-hexanal and n-hexanol. These compounds are linked with attributes of beany or off-flavor. The deactivation of lipooxygenase through heat treatment represents the predominant technological approach for enhancing the flavor profile of plant-based milk, a method that has been employed over numerous decades⁵⁹. Alteration of the conventional processing technique through the inclusion of procedures such as roasting, blanching, and soaking in alkaline conditions has been recognized for its ability to diminish the beany taste in legume-derived milk, consequently enhancing the product's level of acceptance. Moreover, the incorporation of flavorings and sugar has been demonstrated to elevate the overall acceptability of alternative milk derived from plants. Furthermore, the combination of legume milk with cereal milk and nut milk has proven beneficial in enhancing the quality and expanding the acceptance of plant-based milk⁶⁰.

Removal or Inactivation of Anti-Nutritional Factors: By dehulling, soaking, fermenting, or thermal treatment (cooking), the majority of

antinutrient chemicals are fortunately eliminated from seeds. The antinutrients can be reduced or eliminated more effectively by combining this method, and this is frequently the case when producing plant-based milk⁶¹.

Various techniques and methods, including fermentation, germination, debranning, autoclaving, soaking, among others, are employed for the purpose of diminishing the presence of antinutrients in foods. Through the utilization of different methods either individually or in conjunction, it becomes feasible to lower the concentration of anti-nutrients in food items⁶².

Plant-based milk contain Trypsin Inhibitor activity was reduced by 13% of traditional and steam injection to 100°C for 20 minutes, 25 to 50% was reduced by blanching method, Ultra High Treatment increasing both temperature and duration reduces residual trypsin inhibitor activity⁶¹. Phytates have stability to heat and cannot be degraded by cooking process, it will reduce the bioavailability. It can be reduced or eliminated by the action of enzyme phytase. Germination and sprouting are one of the non chemical, non thermal process to increase the protein content, milk yield, improve organoleptic acceptability and also reduces trypsin inhibitor, fat and phytic acid⁶³.

Improvement of Shelf Life: UHT processing comprises of direct heating techniques such as steam injection and steam infusion, as well as indirect heating using plate or tubular heat exchangers. Subsequent to any of the aforementioned processes, packaging under aseptic conditions is imperative to uphold sterility. Following pasteurization, the product must be refrigerated, whereas after in-container sterilization or UHT treatment, the product can be stored at room temperature for a limited duration. Thermal treatments have been effectively utilized in the processing of plant-based milk varieties such as soy milk and peanut milk. Consequently, alternative non-thermal processing techniques are required to enhance the shelf-life of these particular types of plant-based milk. Various non-thermal methods, ultra-high-pressure homogenization (UHPH), and high-pressure processing, have been examined for their efficacy in prolonging the shelf-life of plant-based milk.

Therefore, further exploration is warranted to investigate the preservative effects of pulsed light, ultrasound, and other non-thermal technologies on plant-based milk⁶⁴.

Stability Improvement: Various processes like homogenization and thermal treatments are crucial for enhancing the suspension and microbiological stability of the final product, ensuring its safety for consumption. However, emerging non-thermal processing methods such as ultra-high-pressure homogenization (UHPH) and pulsed electric field processing are being explored to address issues like shelf life extension, emulsion stability, nutritional preservation, and sensory appeal without relying on high temperatures or additives. High-pressure homogenization, UHPH, and ultrasound are the most extensively researched methods, showing promising outcomes²⁸. Fresh or pasteurized plant-based milk, when not packaged or packaged without aseptic conditions, have a short shelf life, lasting only hours at room temperature or 2-3 days under refrigeration (4°C to 5°C). Pasteurized plant based milk, when aseptically packaged and stored refrigerated, exhibit stability for 12-30 days. Those that undergo ultra-pasteurization and aseptic packaging can last 90-170 days at room temperature. Thermal treatment is commonly employed for preservation as it effectively deactivates microorganisms and enzymes responsible for product deterioration.

Positive Health Effects of Plant-Based Milk Substitutes: Plant-based milk especially nut and seed milk are abundant in antioxidants, leading to a decreased susceptibility to conditions such as cardiovascular diseases, cancer, atherosclerosis and diabetes through the inhibition of free radicals that cause oxidation of nucleic acids, proteins, lipids, and DNA. It is imperative to acknowledge that plant-based milk, despite its richness in protein, dietary fiber, fatty acids, vitamins, and phytochemicals from nuts and cereals, may contain lower levels of these beneficial bioactive compounds due to losses incurred during processing. The reduction in overall phenolic compounds observed in the majority of plant-based milk options can be attributed to their lower content of hydrophilic phenolics. Sesame milk, which is a source of lignans, has been associated with improved liver detoxification, decreased tumor

formation, protection of neuronal cells from oxidative stress, as well as possessing anti-hypertensive, anti-inflammatory, and anti-allergic properties⁶⁵.

Plant-based milk contains phytosterols and it is structurally similar to cholesterol, via with cholesterol for solubilization in the digestive tract. This competition leads to reduced cholesterol absorption in the small intestine, consequently lowering blood cholesterol levels. Elevated low-density lipoprotein (LDL) cholesterol levels are linked to a higher risk of coronary heart disease. The reduction in cholesterol absorption facilitated by phytosterols mitigates this risk⁶⁶.

The levels of water-soluble glycosidic phytosterols, such as β -sitosterol, β -sitosterol- β -D-glucoside, stigmasterol, campesterol, brassicasterol, and ergosterol, were measured in different plant-based beverages like coconut-rice, rice, soy, cashew, unroasted and roasted almond, and oat milk alternatives⁶⁷.

CONCLUSION: Plant-based milk substitutes represent a growing segment within the plant-based food industry, their appeal broadening due to factors such as increased lactose intolerance, diverse dietary preferences, health consciousness, ethical considerations for animal welfare, and environmental awareness. Aside from the advantages of consuming plant-based milk substitutes, their production contributes positively to the environment through various means, such as reducing water usage, and offering potential for mitigating climate change and ecotoxicity. The growing acceptance among consumers, driven by diverse dietary trends such as vegetarianism, lacto-vegetarianism, and ovo-vegetarianism, along with the significant potential for minimizing environmental impact during production, indicates a promising expansion for the plant-based milk substitute market. Plant-based water-soluble extracts can serve as alternatives to cow's milk, but they require fortification to match the composition and nutritional quality of cow's milk. This fortification can involve the addition of additives or the combination of multiple plant-based milk substitutes. Due to their nutritional composition, dairy products present a favorable effect on obesity control, type 2 diabetes, and Alzheimer's disease

and decrease the risk of stroke and elevated blood pressure. In recent times, innovative technologies such as ultrasound, pulsed electric field, ohmic heating, high-pressure, and ultra-high-pressure homogenization have been utilized to enhance the stability of plant-based milk substitutes. These advancements hold promise for further refinement in large-scale production. Despite the beneficial antioxidant activity and cardiovascular disease prevention properties of plant-based milk, stemming from its rich content of fatty acids, challenges arise from inadequate protein levels, low bioavailability of minerals and vitamins, and the inclusion of added sugars, posing a dilemma for consumers.

In summary, the market for plant-based milk alternatives is positioned for ongoing expansion, fueled by rising consumer interest, ongoing product innovation, and advancements in technology. With more individuals adopting plant-based diets and seeking healthier, environmentally sustainable food choices, the demand for plant-based milk alternatives is projected to surge substantially.

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