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Plant-based Dairy Alternatives: A Review on Product Diversity and Processing Techniques

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Abstract : This review highlights the emerging field of plant-based dairy alternatives with focus on plant-based curd, yogurt, cheese, and ice cream. Consumer interest in plant-dairy increasing, as a result of expansion of vegan ideology, rising health concerns (lactose intolerance, allergy to dairy products), and sustainability issues. Derived from several sources like almonds, soy, coconuts, oats, peanuts, and hemp seeds, each plant-based dairy alternative has unique nutritional and sensory qualities depending on the source material. The product is formulated through techniques like soaking, germination, fermentation, and blending the plant-based milk to replicate the texture, and nutritional qualities to conventional dairy products. Though advancement has been made in this sector, achieving desirable taste, texture, and nutrients continue to be a challenge. This review emphasizes the current advancements in dairy substitutes and explores their role in shaping a sustainable global food system.

Key words: *plant-based dairy alternatives, sustainable foods, lactose intolerance solutions, alternative proteins.*

1. INTRODUCTION

Veganism, as a dietary lifestyle, is the complete avoidance of all the products that come from animals. This includes eggs, meat, fish, dairy, as well as honey [1]. The increased popularity in vegan diets is attributed by health concerns, ethical beliefs, and environmental awareness.

One of the leading health drivers is lactose intolerance—a condition where a person experiences symptoms like bloating, gas, and diarrhoea upon consumption of lactose, the sugar present in milk and milk products [2] Additionally, dairy allergies – an immune response to milk proteins, provide another significant reason as to why some choose to eliminate or never consume milk and milk products [3].

Ethical and environmental issues are also steering consumer awareness beyond personal health. People are now paying attention to food products that align with sustainability goals and animal welfare ethics. With regard to the environment, plant-based diets are critical because of the impact of the emissions produced by animal-based foods on the entire food system. In terms of food-related greenhouse gas emissions, animal-based foods account for about 57%, compared to plant-based products which account for about 29% [4].

This growing shift is clearly reflected in the market trends. For instance, worldwide production of plant-based milk was 8.7 million tonnes in 2019 and the market is projected to be over USD 300 billion by 2025, showing robust consumer interest and attractive business opportunity [5]. Similarly, the world dairy alternatives market was USD 32.77 billion in 2024 and projections have a 12.7 percent CAGR (Compound Annual Growth Rate) by 2030 [6] Considering that 65% of the people in the world are lactose intolerant [7], availability to nutritious non-dairy alternatives is very crucial.

Higher dietary fiber, phytochemicals, and antioxidants derived from plant-based diets also link with a lower prevalence of chronic diseases including heart disease, diabetes, and certain types of cancers [8]. They hence have huge potential and are fueling demand for readily accessible dairy alternatives.

2. CONVENTIONAL DAIRY VS PLANT-BASED DAIRY ALTERNATIVES

Bovine milk, is the natural mammary secretion collected from healthy animals like cows, goats, or camels through full milking [9]. It’s a well-known source of lipids, protein of high biological value, vitamins and minerals like calcium [10]. Yet, for an increasing number of consumers, dairy presents problems mainly in the form of gastrointestinal discomfort, allergies, ethical or environmental concerns, and so on.

This provides an opportunity for plant-based milk alternatives to serve as a suitable option. Plant-based milk alternatives (PBMAs) are water-soluble extracts derived from cereals, pseudo cereals, legumes, vegetables, oilseeds, and nuts. These extracts form emulsions that mimic cow's milk in both appearance and texture. While they are sometimes marketed as drinks, beverages, or dairy alternatives rather than "milk", [11] there is a debate over it's appropriate naming conventions [12].

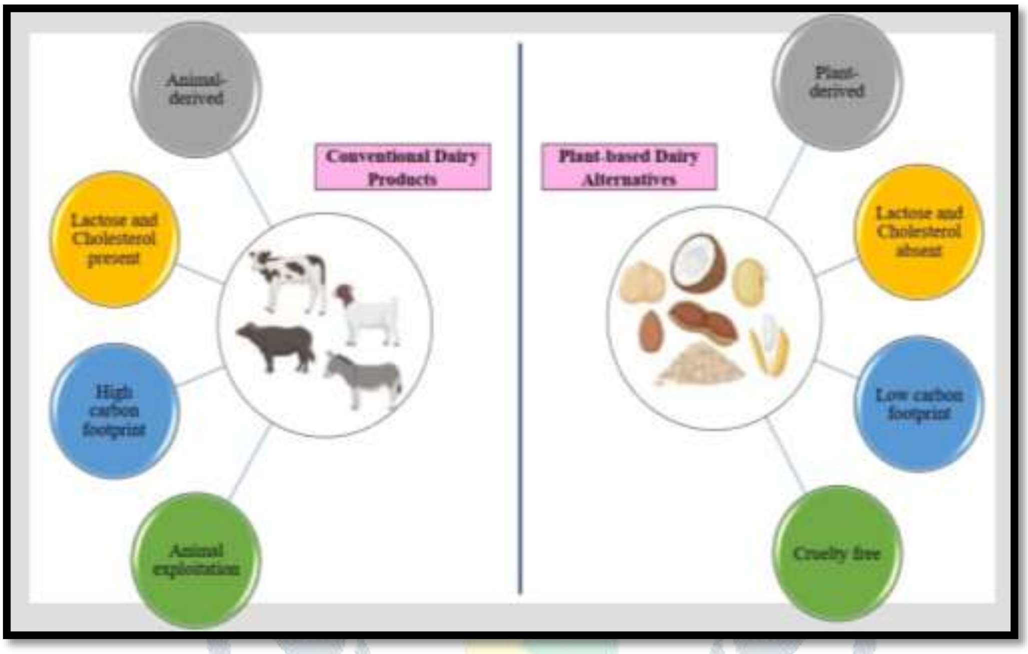

Figure.1. Difference between conventional dairy products and Plant-based dairy alternatives

In February 2023, the U.S. Food and Drug Administration (FDA) released draft guidance that recognized that terms like, "soy milk" and "almond milk," are established by common usage. The guidance recommends that PBMAs that use the term "milk" in their names should also provide a voluntary statement of the nutrients present, if their composition is different from cow's milk, under United States Department of Agriculture (USDA's) criteria for fluid milk substitutes [13]. For plant-based dairy substitutes such as cheese or yogurt, the FDA in 2025, went on to recommend that the plant source be indicated in bold and conspicuous labelling. This was developed along with the rationale that providing clear labelling for plant-based products avoids any misrepresentation of the product to consumers [14].

Vegan milk can be made from a variety of sources such as cereal (eg. millets, oats, rice), legumes (eg. soybean, peas, chickpeas), nuts (eg. almond, cashew, coconut), and oilseeds (eg. sesame, groundnut). In addition to replicating the flavor and texture characteristics of dairy, these raw materials also provide functional and nutritional benefits11. However, due to significant differences in the chemical compositions of plant-derived milk and bovine milk, replicating the nutritional and sensory profile of conventional dairy products continues to be a major hurdle in the development of dairy alternatives [15].

Almond milk has become the most consumed and widely accepted plant-based milk worldwide. In 2023, it represented 53% of the global plant-based milk market largely attributed to the fact that it is low in calories and a rich source of vitamin E [16]. Its popularity indicates that there is a larger shift occurring among consumers towards healthier and sustainable options.

3. PLANT-BASED MILK AS A FOUNDATION FOR DAIRY ALTERNATIVES

Plant-based milk serves as a foundation for development of vegan curd, yogurt, cheese, and ice cream. This review draws attention to recent developments concentrating on novel ingredients, manufacturing techniques, nutritional advantages, taste enhancement, and developmental obstacles. Unlike bovine milk, which is just milked and pasteurized, plant-based milk involves several processing steps to obtain the extract.

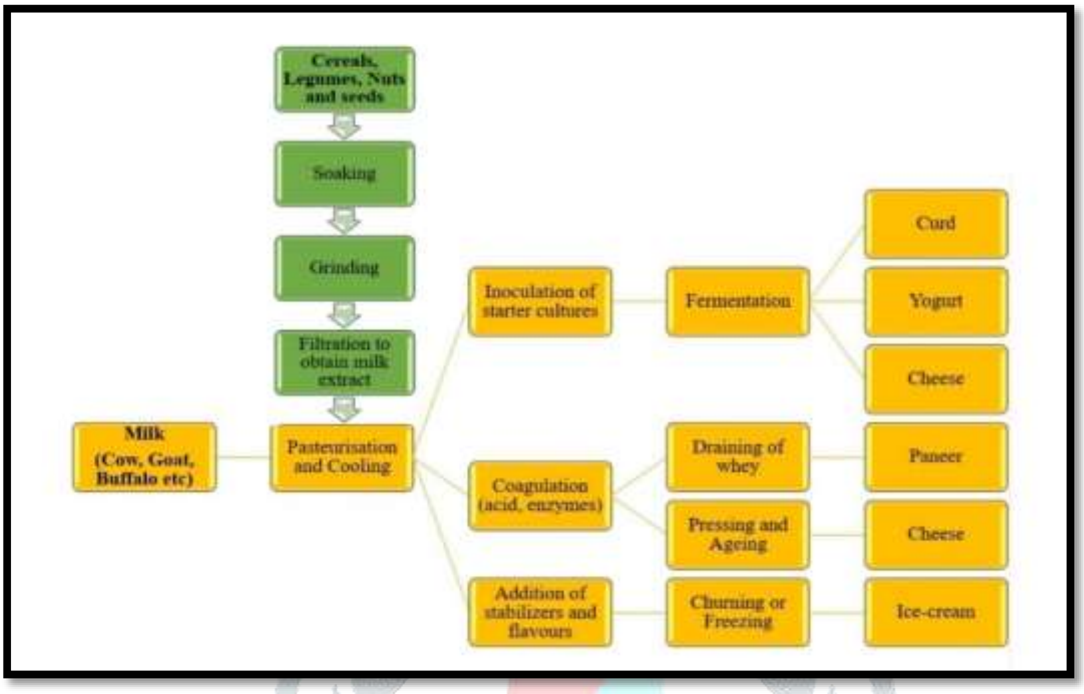

Figure.2. Flowchart depicting Dairy and Plant-Based Milk processing pathways into value-added products

3.1. Plant-Based Curd

Curd (also known as *Dahi*) is a fermented product made by fermentation of boiled or pasteurised milk using either an innocuous lactic acid culture or any other harmless bacterial culture, either naturally or via controlled souring [9].

Millets are becoming more popular because they have abundant nutrients, are low in fat, and have a low glycaemic index. This makes them a suitable choice to develop dairy alternatives [17]. Curds were made using a blend of millets which included barnyard, sorghum, finger millet, amaranth, and buckwheat milks. These were fermented with a mix of *Lactococcus lactis*, *Streptococcus thermophilus* and *Lactobacillus acidophilus*. These curds exhibited higher mineral content (magnesium, potassium, iron), but had slightly lower protein, carbohydrate and fat content compared to curd of dairy origin [18].

Similarly, Curds were also made with a range of minor millets, including foxtail, Proso, barnyard, little and kodo millet, and fermented with NCDC 261, a starter culture. The curds developed had a pH and acidity level comparable to that of dairy curd, however the flavor could not be maintained due to the organoleptic properties of the grains [19]. In both the studies, soaking and germination of the grains were used, followed by milk extraction, pasteurization, and fermentation, which is a promising approach to provide plant-based curd with nutritional benefits [18,19].

Peanut-based curd was made using peanut milk where sodium bicarbonate was used to neutralize the strong peanut flavor prior to fermenting with green chili. This formulation offered high antioxidant and antimicrobial activity [20]. Soy curds were prepared with blanched soybeans and fermented with *Lactobacillus acidophilus*. These curds showed probiotic properties, tolerance to phenol, bile salt and acidic pH, as well as antimicrobial effects against *E. coli*, *Shigella flexnerii* and *Listeria monocytogenes*. Soy-curds have tended to be accepted in the marketplace, mainly for their functional health properties, including a contribution to gut health [21].

Table 1. Summary of research studies on plant-based curds

Sl.No.	Plant-Milk Base	Processing Steps	Fermentation Method	Findings	Reference
1	Millet milk - Barnyard, Sorghum, Finger millet, Amaranth, Buckwheat and Coconut milk	Soaking (6 hrs), germination (24 hrs), blanching (80 °C, 10-20 mins), grinding, homogenization	2% mix of *L. acidophilus, l. lactis, S. thermophilus* (1:1:1), incubated at 32-34 °C, 10-12 hrs	High mineral content (iron, potassium, magnesium), lower carbohydrate, protein, fat and calcium compared to dairy-based curd.	[18]
2	Millet milk - Foxtail, Little, Kodo, Proso, Barnyard	Soaking (16 and 24 hrs), germination (24 hrs), grinding, filtration	NCDC 261, incubated at 30 °C, 6 hrs	Improved nutritive value and reduced anti-nutritional compounds upon soaking and germination	[19]

Overall, the development of plant-based curds derived from millets, legumes, and nuts demonstrates their ability to provide promising alternatives to conventional dairy products. While sensory properties present some challenges, these products fit in with

3	Peanut milk	Sodium bicarbonate treatment (1%), grinding, straining, boiling (80 °C, 5-6 mins)	Green chilli, incubated at room temp, 14-15 hrs	High antioxidant and antimicrobial activity	[20]
4	Soy milk	Soaking (12-16 hrs), blanching (98 °C, 30 mins), grinding, filtering, boiling (10-15 mins)	*L. acidophilus* (1%), incubated at 45 °C, 24-48 hrs	Probiotic properties, antimicrobial effect against (*E.coli*, *L.monocytogenes*l, antibiotic resistance (neomycin, gentamycin)	[21]

current trends towards healthier and more sustainable eating patterns. Optimization of fermentation techniques will likely result in broader acceptance, providing a variety of probiotics, minerals, and antioxidants diversifying the plant-based food spectrum.

3.2. Plant-Based Yogurt

Yogurt refers to a dairy product which is developed as a result of fermentation of pasteurized milk or cream using *Lactobacillus delbrueckii subsp*. *Bulgaricus* and *Streptococcus thermophilus.* These bacteria create plenty of live active cultures [9]. During fermentation, the milk's lactose turns into lactic acid. This acid gives yogurt its unique taste and texture. As plant-based dairy alternatives are becoming popular, non-dairy yogurts are also being explored.

Plant-based yogurt was developed from a blend of almond milk (AM) and Jerusalem artichoke milk (JAM). Jerusalem artichokes are excellent source of inulin and are high in antioxidant properties. They are utilized in powdered form, after ultrasonication, and drying with hot air dryer, to create a milk substitute. The mixture with 67.5% JAM and 32.5% AM was fermented with starter culture (Vivo Active) showed better water holding capacity an lower syneresis, as well as higher phenolic content, suggesting that JAM could improve the texture and antioxidant properties in plant-based yogurts. Addition of almond milk helped provide the color and overall sensory acceptability [22].

Expanding the idea of improving the nutritional value of plant-based yogurts, chickpeas were explored as a base for yogurt production. The results of chickpea-based yogurt showed promise especially when enhanced with honey to improve polyphenol and antioxidant activity. The research reported that chickpea milk was a great source of protein and had the potential to deliver high nutrient density when fermented with particular starter cultures (kefir and Vegurt). Chickpea yogurt offered nutritional benefits but more work is required in product processing to make it an equivalent alternative to dairy-based yogurt [23].

The nutritional and physicochemical properties of walnut-based yogurt produced using *Lactiplantibacillus plantarum*, was compared with conventional dairy yogurts. The walnut yogurt had more protein, fat and total solids. The fermentation process significantly increased lactic acid, improved the taste, and reduced bitter amino acids by 92%. Glucose was added to support fermentation, but contributed to the higher sugar levels. A darker pinkish-yellow color was developed, due to maillard reaction during fermentation. Volatile compound profiles showed a richer aroma, due to higher levels of esters and alcohols that improved the sensory quality. Though there was a slight difference in texture and colour, sensory evaluation showed the acceptability of the product, suggesting walnut yogurt could be a nutritionally advanced and sustainable plant-based option to dairy yogurt [24].

Another novel approach involved developing yogurt using jackfruit seed milk and coconut milk. The formulation also included strawberry crush and probiotic cultures, with the sensory evaluation showing that a higher strawberry content resulted in the most sensory favorable attributes. The yogurt had a balanced nutritional profile, a creamy mouthfeel, and a lower fat content, this appealing to the vegan market. Jackfruit seed milk has shown to be a sustainable food ingredient, and has potential to be further used the development of plant-based yogurt [25].

A mixture of peanut, oats and coconut milk was also developed in food experimentation to create yoghurt – the product formulation was optimized via simplex-lattice mixture design. The best formulation consisted of 7.13 ml peanut, 10 ml oats, and 7.86 ml coconut milk. The product exhibited improved viscosity, low syneresis, and high sensory acceptability. The peanut and oats milk contributed to the increased viscosity of the product due to higher protein. Coconut milk gave acceptable flavor to the yogurt. Stabilizers such as corn starch, xanthan gum and pectin substantially enhanced texture of the yogurt as well as flow patterns. The yogurt had desirable nutritional and physicochemical properties as an alternative option for the lactose intolerant individuals. Peanut milk was kept minimal to avoid off-flavor [26].

Yogurt analogues were made by using peanut milk, microbial transglutaminase (mTGase), and two starter cultures (one producing exopolysaccharides (EPS) and one not producing EPS) for optimizing texture of the yogurt. To compensate for the low viscosity and poor texture of peanut milk products, peanut pulp was incorporated in the formulation. Cultures producing EPS improved the microstructure but reduced viscosity, whereas cultures that do are non-EPS had better texture and higher sensory acceptability. mTGase intrinsically improved gel strength and reduced syneresis by forming protein cross-links in the gel network.

The yogurt made with EPS showed significantly better levels of firmness. Peanut milk also contributed to high bacterial viability, which indicates the potential suitability of peanut milk to be used as a fermentation substrate. However, the shelf life was restricted to 14 days due to growth of moulds over time [27].

Table 2. Summary of research studies on plant-based yoghurts

Sl. No.	Base Ingredients	Functional Additives	Starter Culture	Processing Techniques	Fermentation Process	Findings	Refere-nce
1	Almond milk and Jerusalem artichoke milk	Tapioca starch (0.02%), Locust bean gum (0.01%)	1% Vivo Active starter culture which contains *B. lactis, S. thermophilus, L. delbruckii ssp. Bulgaricus, L. acidophi*lus,	Jerusalem artichoke - ultrasonicated (10 min, 25 kHz), dried (60 °C), powdered, reconstituted, blended with almond milk	Pasteurized (85 °C,15 secs), inoculated (1.5% culture), fermented at 40 °C for 24 hrs	High phenolics, improved water holding capacity, reduced syneresis	[22]
2	Chickpea milk	Linden honey (1-2 %)	Vegurt, PROBIO YOGURT, Kefir	Chickpeas soaked (1-3 days, 20 °C), ground filtered, pasteurized (70 °C, 10 min)	Fermented at 35 °C for 14 hrs	High protein, fiber, antioxidant activity and polyphenolic content	[23]
3	Walnut milk	Glucose (9.34%), Sodium carboxymethyl cellulose (0.3%)	*Lactiplantibacillus plantarum*	Homogenization of walnut milk (3 rounds upto 40 MPa, heat sterilization at 95 °C, 20 mins), cooling to 25 °C	Inoculation at 25 °C, fermentation at 37 °C for 11.36 hrs, refrigeration at 4 °C for 24 hrs	Improved antioxidant activity, higher protein and fat content compared to dairy yogurt, 92% reduction in bitter amino acid	[24]
4	Jackfruit seed milk and Coconut milk	Agar (1-2%), Strawberry crush (15-2%), Sugar (10 %)	*L. rhamnosus,L. acidophilus, B. longum, B. bifidum, S. thermophilus*	Jackfruit seeds soaked (4-5 hrs), blended (1:3 w/v), filtered, mixed with coconut milk, Pasteurized (80-90 °C) and cooled	Fermentation at 25-32 °C for 10-12 hrs	Yoghurt from underutilized ingredient, improved flavour and probiotic potential, reduced food waste	[25]
5	Peanut milk, Coconut milk and Oat milk	Corn starch (5%), Pectin *L.* (0.75%), Xanthan gum (0.15%), Sucrose (10%)	*L. bulgaricus, S. thermophilus*	Plant milks prepared by soaking, blending, filtering, Pasteurisation (72 °C, 20 min)	Fermentation at 41 °C for 18 hrs	Optimized formulation (7.13 ml peanut milk, 10 ml oat milk, 7.86 ml coconut milk) Low high viscosity	[26]
6	Peanut milk	Microbial transglutaminase (mTGase)	EPS (YoFlex) and non-EPS (YC350)	Roasted peanuts soaked in NaHCO3 (0.5% for 12 hrs), blended, filtered, pasteurized (90 °C, 3 min)	mTGase added, fermented at 42 °C for 4 hrs	Dense microstructure, high probiotic viability	[27]

Overall, plant-based yoghurts have probiotic and nutritional benefits, but they are barriers related to their texture, flavour and shelf life. Progress with hydrocolloids and improvements with starter cultures are promising, but require strong consideration before being readily accepted by consumers.

3.3 Plant-Based Cheese

Cheese is classified to be either ripened or unripened that is made through coagulating the milk or milk-derived products (cream or buttermilk) using rennet or other coagulants, with partial removal of whey. The ratio of whey proteins to casein must not exceed the ratio in milk [9]. Non-dairy cheese or Vegan cheese is unique substitute to dairy cheese. There are many studies being performed on various plant-based milks, probiotic cultures, and coagulants to develop plant-based cheeses which can mimic the nutritional profile, taste, and texture of dairy cheese.

Cheese was developed by fermenting almond milk with the probiotic *Lactobacillus casei* from Yakult. Almond milk was coagulated using magnesium chloride. A significant improvement to nutritional content of the cheese with the addition of beetroot extract was noted, increasing iron, folate, and vitamins. Overall a bright colored, soft cheese with viable probiotics was produced, although there was a slight decline in protein and carbohydrate due to microbial activity. The results highlight the potential for plant-based cheeses to be both functionally beneficial and fortified with key nutrients thus attracting consumers [28].

Cheese was also made using Bambara groundnut, an underutilized crop which is indigenous to the western parts of Africa. The cheese made from 100% Bambara milk had the highest fiber but the least amount of protein and fat. It was also dense and least accepted by consumers. Nevertheless, with the improvement and optimization of the product formulation, it can be a suitable option for mass production, especially in regions affected by protein-energy malnutrition, and where the availability of cow milk is relatively expensive [29].

Table 3. Summary of research studies on plant-based cheese

Sl.No	Base Ingredients	Additional Ingredients	Processing Steps	Findings	Reference
1	Almond milk	Beetroot extract, *Lactobacillus casei*	Soaking (overnight), Almond milk extraction (1:3 ratio), heating at 95 °C, coagulation using 0.5% $MgCl_2$, fermentation at 37 °C for 24 hrs, beetroot extract addition (0.5 ml).	Decline in carbohydrates and protein, increase in iron, folate, vitamins A and C.	[28]
2	Bambara milk	Lemon juice	Soaking Bambara nuts (24 hrs), dehusking, wet grinding, triple filteration, coagulation with lemon juice (20 ml), pressing overnight.	Increased fiber and carbohydrate, lowest protein content for cheese with 100% Bambara milk, however the acceptability was low.	[29]
3	Coconut milk and. Soy milk	Lemon juice extract	Blending coconut and soy milk, coagulation with lemon juice extract, boiling to 80 °C for 10 mins, curd formation, separation, drying for 7 hrs.	Highest acceptability (color and aroma), yield and spreadability at 80:20 coconut-to-soy milk ratios. 60:40, and 70:30 coconut-to-soy milk were most preferred for texture, and taste, respectively.	[30]
4	Peanuts	$MgCl_2$, *Lactobacillus rhamnosus* NCDC 18	Soaking peanuts (6 hrs), Milk extraction, heating (95 °C for 5 mins), coagulation with $MgCl_2$ solution, inoculation of starter culture, fermentation at 37 °C for 24 hrs, seasoning (salt, black pepper).	Reduced pH, protein and carbohydrate content and increased acidity. Probiotic viability declined over 15 days storage in refrigerator.	[31]
5	Soy milk, Cashew nut milk	Alum (15g in 25ml water), salt, pepper and seasoning	Soaking cashew nut and soybean, milk extraction, coagulation with alum, curd formation, pressing, and boiling with seasonings.	Most preferred cheese obtained at 60:40 (%) soy-to-cashew milk blend, high protein content.	[32]
6	Soy milk	Lime water, Fermented maize extract	Soaking soybean, dehulling, wet milling, boiling (10 mins), coagulation (lime or fermented maize extract), frying (180 °C, 10 mins) and drying of curds (50 °C, 8 hrs).	Lime-fried-dried samples had lowest microbial load, superior stability, high sensory acceptability.	[33]

In another study, a spreadable vegan cheese was made using a blend of coconut and soy milk. The most desirable spreads (with the highest yield and spreadability) were made from an 80:20 coconut-soy blend. However, an increase in the soy content produced a firmer texture, and lower sensory scores. These findings emphasized that a minute change in ratios can have a vast impact on yield, flavor, and texture, and symbolized the need for precise formulation in product development [30].

A probiotic peanut cheese spread was developed from *Lactobacillus rhamnosus*. The most preferred peanut-to-water ratio was 1:6 which yielded 5.5% solids. The optimum concentration of magnesium chloride for maximum recovery of proteins and solids and total water retention was 0.5%. Fermenting the samples at an incubation temperature of 37°C for 24 hours showed a significant decrease in pH, protein, and carbohydrates levels confirming biological activity. However, the fat, ash, and antioxidants levels were not affected. When samples were refrigerated for 15 days, there was a significant decline in the viable probiotic concentrations suggesting that it's functionality reduced over time. Overall the product has potential as a dairy alternative [31].

Experiments with blends of cashew nut and soy milk were also attempted to test the acceptability of both these ingredients to develop vegan cheese. The blend 60% soy milk and 40% cashew milk was the most acceptable due to the higher protein level. Cashew milk helped reduce the beany flavor of soy, while improving nutritional value.The 100% cashew milk cheese had higher fat and energy content, but had lower yield and poor sensory characteristics compared to the 60:40 soy-cashew milk blend. Overall, the research suggests that soy-cashew nut blends can create an acceptable, nutrient-rich cheese alternative that potentially could help address protein-energy malnutrition associated with dairy in developing countries. However, Protein digestibility and storage stability were not evaluated and needs further research [32].

Soy-based cheese (beske) was also made with lime and fermented maize extract as coagulants. The curds were coagulated, fried and dried. The firmest curd with the lowest count of all tested microorganisms, and best sensory qualities, were the lime-fried-dried (LFD) samples. The samples made with fermented maize extract had more proteins and vitamins, while the lime water coagulant samples had more minerals. The LFD samples were more preferable with regards to commercial production as they had superior nutrient quality, storage stability, and sensory characteristics [33].

Thus, Plant-based cheeses have nutrient and probiotic possibilities however, they struggle with replicating the texture, and stability characteristics of dairy cheese. Indeed, innovations in coagulants and fermentation are necessary to improve sensory characteristics and shelf stability.

3.4 Plant-Based Ice-cream

Ice Cream refers to a product obtained by freezing a pasteurized mix made from milk and/or milk products, with or without the inclusion of sweetener and other allowed ingredients. It can be frozen hard or frozen to a soft consistency [9]. The following section includes recent developments in vegan ice creams

Ingredients such as almond and hemp milk, are capable of producing ice creams with desirable textures and better stability with the right addition of stabilizers and emulsifiers. For instance, Almond milk combined with psyllium fiber and hemp milk mixed with pectin at various levels (0 – 10%) demonstrated desirable characteristics. In this case, sensory panels generally preferred the almond milk ice creams based on the perception of sweetness, while the pectin hemp milk ice creams had advantages in rheological stability, especially when the pectin level was more than 8%. The introduction of the fibers significantly enhanced viscosity, all notably at 6% psyllium fiber and 8% and 10% pectin leading to better melt resistance, better structure, and better air retention [34].

Alongside these, cashew milk and coconut cream are also being explored as promising bases for development of plant-based frozen desserts. A formulation of cashew milk, coconut cream, banana, sugar and butter was used, which showed that increasing coconut cream increased fat, protein, ash and fibre content levels. This formulation, with 54% cashew milk and 18% coconut cream, also had the slowest meltdown rate and maintained it's shape even after 180 min, which highlighted the critical role that coconut cream played in improving the thermal stability and lowering the drip-through [35].

In another approach, coconut milk was utilized as a base making a mulberry-flavored coconut ice cream. Various concentrations of mulberries were utilised for flavor enhancement, and the best results based on sensory evaluation were obtained with 10% mulberry crush and 2 ml of mulberry flavor as it provided a creamy mouthfeel and refreshing flavour. This study indicated the potential of mulberries, as flavor enhancers, that can be used to reduce the off-flavour of coconut milk [36].

The improvements in texture and stability in vegan ice creams have also been achieved using plant proteins derived from hemp, rice, almond, and walnut. Almond proteins, and hemp proteins in particular, affected the color and texture of the ice creams, while microbial transglutaminase (MTG) and guar gum improved thermal stability and overrun. Guar gum was the most effective textural modifier with significant effects on sensory quality and structure in hemp-based vegan ice creams whereas MTG provided structural attributes but reduced sensory quality. Among the formulations, Ice creams containing almond protein were most preferred for appearance and flavour [37].

Another unique innovation in plant-based ice cream was the utilisation of jackfruit seed milk. This led to a low-fat, creamy product with the addition of coconut milk and emulsifiers. With regard to sensory characteristics, ice-cream, without emulsifiers, was the most preferred for its flavor and overall acceptability. Thus, jackfruit seed milk serves as a promising ingredient to serve as an unique base to develop plant-based ice creams [38].

Ice creams made with barnyard millet, soy, and sesame seed extracts and coconut cream have also appeared as healthier and dairy-free product. These combinations were positively accepted for their taste and textural attributes suggesting millet ice creams offer a high protein, low-fat product with potential to compete with conventional dairy products in the market [17].

Table 4. Summary of research studies on plant-based ice-creams

Sl.No	Milk Base	Additional Ingredients	Processing Steps	Findings	Reference
1	Almond milk and Hemp milk	Psyllium, pectin, sweeteners (Agave syrup – 5% and Vanillin – 1%)	Soaking almond (overnight)and hemp seeds (12 hrs), milk extraction (1:10), Pasteurisation (82 °C, 30 secs) homogenization, freezing (4 °C)	Increased viscosity and texture stability with fiber, especially at 6% psyllium and 8% pectin. Almond milk ice-cream received higher sensory acceptance than hemp milk ice-cream	[34]
2	Cashew milk and Coconut cream	Banana (8%), sugar (5%), butter (4%), stabilizers (0.5%)	Soaking cashew (overnight), blending, milk extraction (1:3 cashew-to-water) Dehusking coconut, blending, milk extraction (1:3 coconut-to-water) Heating of combined mix (90 °C, 1 min)	53.6% cashew milk, 18% coconut cream had the slowest meltdown and better thermal stability	[35]
3	Coconut milk cream	Mulberry crush (0-10%), mulberry flavouring agent (2-3 ml), sugar, coconut milk powder	Pasteurisation, mixing all the ingredients, freezing	10% mulberry crush, 2 ml mulberry flavor exhibited superior sensory appeal	[36]
4	Hemp drink and Coconut cream	Plant protein concentrates (hemp, almond, rice and walnut), guar gum, MTG	Addition and homogenization of all the ingredients, Pasteurisation (75 °C, 30 mins), Cooling and ageing (4 °C, 24 hrs)	Almond protein concentrate was most desirable for taste, texture and colour, Guar gum was the better texture modifier than MTG	[37]
5	Jackfruit seed milk and Coconut milk	Jackfruit juice (50 ml), sugar (20g), xanthan gum, lecithin, surface perfectant	Homogenization and freezing at -18°C	Low fat, creamy ice-cream was developed with acceptable sensory attributes	[38]
6	Barnyard millet milk, Soy milk, Sesame milk and Coconut cream	Icing sugar, honey, cocoa powder	Churning in ice-cream maker, set in refrigerator for 4 hrs	Barnyard millet milk along with soy milk coconut cream had highest sensory acceptability and nutritional value (High protein, low fat)	[17]

Plant-based ice creams are emerging as innovative, nutritious, and sustainable alternatives to conventional dairy ice-creams. With diverse bases like almond, coconut, jackfruit seed, and millets, these formulations offer improved texture, taste, and stability through strategic use of plant proteins, fibers, and emulsifiers. As consumer demand for dairy-free options grows, these ice creams present a promising future in delivering health, functionality, and environmental benefits without compromising indulgence.

3.5 Other Emerging Innovations

Besides cheese, curd, and ice cream, there has also been research & development on various vegan alternatives to dairy products. A probiotic kefir using oat, soy, and coconut milk was developed using a traditional kefir microbiota starter. The kefirs maintained microbial viability displaying high values of beneficial bacteria, including *Lactobacillus*, *Lactococcus*, and *Bifidobacterium spp*., however they incurred higher whey separation and were void of yeasts post fermentation. Antimicrobial testing indicated *E. coli O157:H7* was resistant to oat and soy kefirs, while *S. Typhimurium* was resistant to coconut kefir. The study concluded that additional work on evaluating microbial viability under gastrointestinal conditions, antioxidant capacity, and sensory analysis is needed to improve the commercial viability and consumer acceptance of plant-based kefirs [39].

A non-dairy, soy-based, cocoa-flavored, vegan cream cheese was formulated using coconut milk, lime juice, sucralose, and vegetable oil. With the aim of improving shelf stability, the product was vacuum-packed, and showed good acceptability for all the sensory attributes. It contained 13% protein and 32.9% fat [40]. Similarly, another kind of plant-based cream cheese was developed by blending soy cheese with soy, almond and coconut yogurts, seasoning it with herbs and spices. Of all variations evaluated, the soy yogurt cheese spread had the highest degree of consumer acceptance compared to the coconut yogurt spread and the almond yogurt spread. Sensory evaluations found favorable overall spreadability and high preference with strong market potential [41].

Paneer is a product derived from milk, with or without added milk solids, through precipitation by permitted acidulants and heating [9]. Research is being conducted to develop vegan versions of paneer products. Plant-based paneer was developed from hemp milk, which was coagulated using 0.2% citric acid. 2% spice blend was added to improve the flavour before pressing the coagulated solids. The paneer had 11.08% protein, and 12.63% fat. Significant antioxidant activity, microbial safety, and sensory scores comparable to dairy paneer were observed, suggesting plant-based paneer is a functional food option for individuals avoiding dairy [42].

In another study, paneer was prepared using peanut milk where citric acid, vinegar, and tamarind juice were used as coagulants. Peanut milk with 2% tamarind juice was rated highest overall in sensory attributes, and significant increases ($p<0.05$) were observed in fat, energy and carbohydrate levels compared to the control (citric acid), showing that tamarind juice is a suitable natural coagulant [43].

Beyond paneer, innovation in vegan confectionery products has advanced. A vegan milk chocolate has been developed with oat milk, soy protein isolate (SPI), and strawberry extract encapsulated (ESE). The overall composition of 50% OM, 50% SPI and 10% ESE, exhibited desirable textural characteristics and high antioxidant activity. The sensory scores indicated overall high acceptability, therefore showing promise as a functional dairy-free option for health conscious consumers [44].

Furthermore, A probiotic vegan shrikhand was also produced from soymilk and coconut milk, jaggery, and mixed fruit pulp (papaya and mango), and then the shrikhand was cultured with different *Lactobacillus* strains along with traditional curd cultures. The optimized formulation containing 80% coconut milk, 20% soymilk, and 15% fruit pulp, had the highest sensory scores and improved desirable nutritional attributes, associated high fat, protein, fiber, and mineral content, such as magnesium, iron and zinc [45].

Thus, the emerging vegan dairy alternatives like kefir and paneer currently add cultural and nutritional relevance but are not well-established products. The continuous innovation of these products will require deeper assessment on standardization, shelf-life, and sensory attributes.

4. Challenges in the Development of Plant-Based Dairy Alternatives

Developing plant-based versions of dairy products presents numerous challenges with regard to nutritional adequacy, texture compatibility, flavor enhancement, and shelf-stability of the product. Although plant-based formulations are increasingly gaining popularity for ethical and health reasons–overcoming technical challenges is essential for successful commercialization. This section address overall challenges experienced during product development and discusses the existing documented approaches that may help mitigate these challenges.

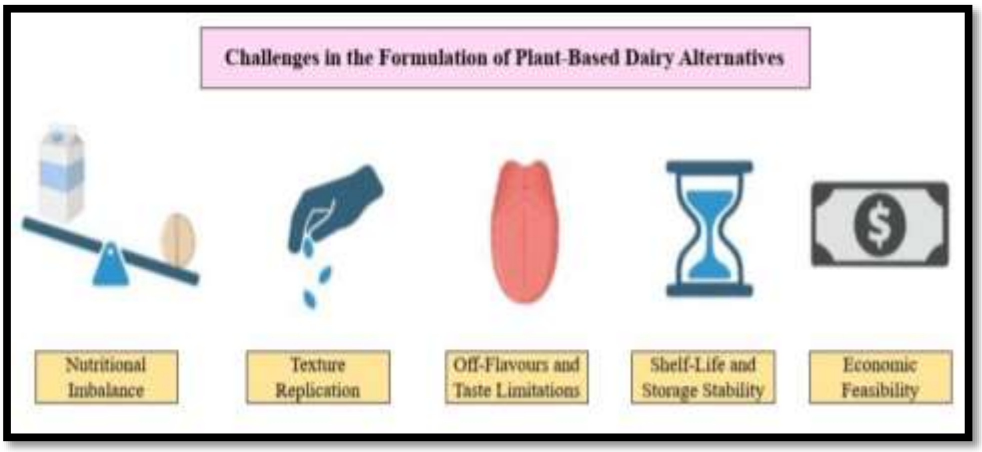

Figure.3. Key challenges in the development of Plant-Based Dairy Alternatives

4.1 Nutritional Imbalance

One primary challenge to developing plant-based dairy substitutes relates to nutritional imbalances compared to bovine milk, which typically has high-quality protein, calcium, vitamins (such as B12 and D). The vast majority of plant-based dairy alternatives may not include key nutrients. For instance, millet based curd contains many essential minerals such as iron and magnesium but deficient in essential macronutrients (e.g., protein, fat) and calcium compared to dairy curds [18]. Peanut-based cheeses were also reported to have the lower level of protein compared to dairy curds [31].

To overcome this issue, ingredient blending has been an effective approach. For example, a study where plant-based yogurt was developed by combining peanut, oat, and coconut milk resulted in a nutritionally balanced product with adequate protein and fat levels [26]. Moreover, the use of functional additives like honey [23], which enhances antioxidant levels and beetroot extract [28], which contribute both micronutrients and antioxidants can thus improve the overall nutritional quality of non-dairy products.

Additionally, plant-based milk that has high nutritional profile, for example, chickpea milk or soy milk, if used in appropriate proportions within products, may provide more nutritious vegan alternatives to dairy products. Using these various approaches, the nutritional quality of PBDA's can be improved.

4.2 Texture Replication

The ability to mimic the desired texture in plant-based dairy alternatives still remain a significant challenge as casein and milk fats are absent. Without these components, textural defects such as syneresis in vegan yogurts, and spreadability issues in vegan cheeses may arise. To overcome textural defects, researchers have tested a variety of functional ingredients.

One of the most effective methods is to use hydrocolloids—especially stabilizers like, tapioca starch [22], pectin, xanthan gum, and corn starch [26]—which have all been able to considerably enhance the texture and reduce syneresis in plant-based yogurt. Another processing strategy is the use of the enzyme microbial transglutaminase (mTGase), which promotes protein cross-linking [46]. There has been work done with peanut milk yogurt and the addition of mTGase has been effective in terms of obtaining a denser microstructure and creamier product [27]. These technological advances can be considered in order to enhance the overall quality and acceptance of plant based dairy alternatives.

4.3 Off-Flavours and Taste Limitations

Overcoming undesirable off flavours presents another significant hurdle in the formulation of plant-based dairy alternatives, as many plant-based ingredients have undesirable or overpowering aromas. The intent is not to diminish the undesirable characteristics of these plant-based products, but to develop innovative flavour masking and fermentation methods.

Pre-treatments such as using sodium bicarbonate, and fermenting peanut milk with green chili to obtain peanut curd masked the beany flavour very well and improved the antioxidant activity, resulting in improved taste and nutritional properties [20]. Mixing natural flavour enhancers such as strawberry crush in jackfruit seed yogurt [25] and using mulberry with coconut milk ice cream [36], provided better sensory attributes and improved flavour balance. Hence, combining natural flavouring methods with pre-treatment techniques is a viable approach to the development of nutritious plant-based dairy alternatives that are appealing to consumers.

4.4. Shelf-Life and Storage Stability

The plant-based dairy alternatives with live cultures or high moisture content, such as yogurt and cheese, are more susceptible to microbial spoilage and loss of nutrients. For instance, peanut yogurt had limited shelf life of only 14 days [27]. Natural preservatives and fermentation using green chili provide higher probiotic levels and offer antimicrobial effects [18]. Lime-fried-dried soy cheese showed improved shelf stability due to reduced moisture, acidity, and heat treatment that inhibited microbial growth as well as sensory acceptability [33]. Novel packaging technologies like vacuum sealing, help enhance the shelf-life of soy-based cream cheese [40].

Therefore, relevant methods specific to the product can be used to improve shelf stability of plant-based dairy alternatives, which can benefit commercial production and distribution.

4.5. Economic Feasibility and Ingredient Accessibility

Developing plant-based dairy substitutes presents major hurdles in terms of economic viability and ingredient accessibility as premium components such almonds or cashew nut typically increase costs, hence restricting affordability and scalability particularly in underdeveloped regions.

To overcome these barriers, the use of indigenous crops such as barnyard millet, foxtail millet [18], jackfruit seed [25] has proven to be a cost-effective and locally available solution, showing promising results in various formulations. Additionally, optimizing ingredient blends by mixing higher-cost milks with more affordable bases like coconut milk, peanut milk and oat milk as demonstrated in a study of development of plant-based yogurt [26], helps maintain product quality while keeping production costs under control, making these alternatives more accessible to a wider consumer base.

These are some of the hurdles faced in the development of vegan dairy alternatives. Through continuous research and development, these problems can be addressed, therefore enabling more suitable, nutritious, and sustainable choices.

5. CONCLUSION

Thus, plant-based dairy alternatives are rapidly progressing and thereby providing nutritious and sustainable options for people who avoid animal-based products. The challenges of replicating the exact texture and taste of dairy products exist, but with improvements in ingredient formulation and fermentation processes, better quality products are being developed. As the proportion of the consumer demand for vegan and lactose-free options continues to grow, more research is needed to effectively optimize formulations, address sensory challenges, facilitate large scale production of plant-based dairy alternatives.

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