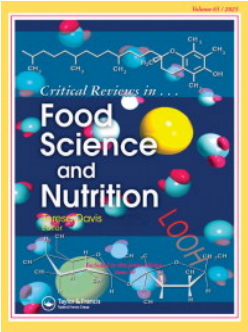

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: www.tandfonline.com/journals/bfsn20

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To cite this article: Elham Alehosseini, Paul L. H. McSweeney & Song Miao (2025) Recent updates on plant protein-based dairy cheese alternatives: outlook and challenges, Critical Reviews in Food Science and Nutrition, 65:30, 6846-6860, DOI: 10.1080/10408398.2025.2452356

To link to this article: https://doi.org/10.1080/10408398.2025.2452356

Published online: 17 Jan 2025.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
2025, VOL. 65, NO. 30, 6846–6860
https://doi.org/10.1080/10408398.2025.2452356

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REVIEW ARTICLE

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Recent updates on plant protein-based dairy cheese alternatives: outlook and challenges

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ABSTRACT
In response to population growth, ethical considerations, and the environmental impacts of animal proteins, researchers are intensifying efforts to find alternative protein sources that replicate the functionality and nutritional profile of animal proteins. In this regard, plant-based cheese alternatives are becoming increasingly common in the marketplace, as one of the emerging dairy-free products. However, the dairy industry faces challenges in developing dairy-free products alternatives that meet the demands of customers with specific lifestyles or diets, ensure sustainability, and retain traditional customers. These challenges include food neophobia, the need to mimic the physicochemical, sensory, functional, and nutritional properties of dairy products, the inefficient conversion factor of plant-based proteins into animal proteins, and high production expenses. Given the distinct nature of plant-based milks, understanding their differences from cow's milk is crucial for formulating alternatives with comparable properties. Designing dairy-free cheese analogs requires overcoming electrostatic repulsion energy barriers among plant proteins to induce gelation and curd formation. Innovative approaches have substantially enhanced the physicochemical and sensory properties of these alternatives. Researchers are exploring the application of microalgae as a plant protein source and investigating new microbial fermentation methods to increase protein content in dairy-free products.

KEYWORDS
Dairy-free cheese alternative; sustainable goals; mimicking the texture; market trends; 3D printed cheese analogue

Introduction

Dairy products are widely consumed due to their nutritional profiles and desirable flavors, which include high levels of fat, protein, vitamins, and calcium (McClements and Grossmann 2022; Mohd Shukri et al. 2022; Zhang et al. 2024). However, shifting dietary preferences, particularly in developed countries, have spurred demand for more sustainable food options (i.e., plant-based products) (Wouters et al. 2016). This shift is driven by health and ethical reasons (i.e., vegetarian diets), environmental sustainability, and concerns about greenhouse gas emissions from the dairy sector, which contribute to global warming (Alcorta et al. 2021; McClements 2023; Silva, Silva, and Ribeiro 2020, 2022). Additionally, the rising cost of dairy products has motivated food industry researchers to explore casein and fat replacers, which can design and develop dairy-free products with sensory and functional characteristics comparable to traditional dairy products (Kamath, Basak, and Gokhale 2022).

Plant-based cheese alternatives, in particular, offer significant opportunities for addressing consumer dietary needs and sustainability challenges (Monga, Dev, and Singhal 2022; Zhang et al. 2024). Around 75% of the global population suffers from lactose intolerance (lactose malabsorption), with prevalence rates ranging from 50% to 90% in regions like Africa, South America, and Asia, and 5% to 15% in North America and Europe, which means they should avoid consuming lactose-containing products and replace them with milk-free alternative products (e.g., vegetable milks) (Goh, Mohd Said, and Goh 2018; Oak and Jha 2019). In addition, milk proteins (i.e., casein and whey protein) can cause allergic reactions in some consumers, with cow's milk protein allergy affecting about 4% to 6% of children, a public health concern in developed countries, which may also drive the choice plant-based milk substitutes (Santalha et al. 2013; Silva, Silva, and Ribeiro 2020). Moreover, plant-based dairy alternatives, which do not contain hormones and antibiotics harmful to children's health, are increasingly popular among consumers, particularly in regions with limited cow's milk supply (Laila et al. 2021; Silva, Silva, and Ribeiro 2022). This growing interest in plant-based lifestyles is reflected in the increasing number of vegans in the United States (1% to 6% from 2014 to 2017) and the United Kingdom (a fourfold increase from 2014 to 2019), driving a surge in demand for dairy-free alternatives (Alcorta et al. 2021; McClements 2023; Silva, Silva, and Ribeiro 2020, 2022). As a result, the global plant-based food market has experienced remarkable

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growth, particularly in Western countries and emerging markets (e.g., Middle East and Asia-Pacific). In 2018, in the United Kingdom and the EU, about 16% and 9% of new products had a vegan claim, respectively (Capecchi 2019; Silva, Silva, and Ribeiro 2022). The global plant-based food market is expected to grow threefold, with a compound annual growth rate (CAGR) of 12.2% between 2023 and 2033 (FMI 2023). While the growing demand for plant-based cheese alternatives is well documented, understanding the specific challenges in replicating the complex textures and flavors of dairy cheese is crucial for advancing the development of these products.

Dairy-free alternatives (e.g., plant-based yogurt, plant-based cheese, plant-based butter, plant-based creamer, plant-based ice cream, etc.) can be designed using plant-based ingredients or directly from plant-based milks. In either case, the final product must closely mimic the functional characteristics of its conventional dairy counterpart (McClements and Grossmann 2022; Tachie, Nwachukwu, and Aryee 2023). The increasing production of plant-based milks has laid a strong foundation for the development and commercialization of diverse plant-based dairy products. However, due to the fundamental differences between plant-based milks and cow's milk, it is necessary to investigate these variations and develop methods for combining raw materials to replicate the functional properties of cow's milk. Evaluating the strengths and limitations of plant-based milks is crucial to validate their suitability for use in dairy-free alternatives. Innovative approaches, such as blending two or more raw materials, have shown promise in enhancing the nutritional and functional qualities of plant-based milks. Furthermore, leveraging locally abundant raw materials can help reduce production costs, particularly in developing countries, while fostering sustainability and supporting local economies. This strategy not only addresses affordability but also drives innovation in the growing plant-based sector (Mefleh, Pasqualone, Caponio, and Faccia 2022; Silva, Silva, and Ribeiro 2020, 2022).

Cheese is a nutrient-dense dairy product, providing calcium, zinc, phosphorus, magnesium, vitamins (A, B_2, B_6, and B_{12}), and protein (between 3% and 40%) (Ouyang et al. 2022; Silva, Silva, and Ribeiro 2022). However, traditional cheese production is energy-intensive, requiring 4.9–8.9 MJ/kg, highlighting the need for more sustainable alternatives. Plant-based cheese alternatives have gained significant interest due to their potential to mimic the physical, functional, and sensory attributes of traditional cheese while catering to evolving dietary preferences and sustainability goals (FDA 2012; Shahbandeh 2018; Xu, Flapper, and Kramer 2009). Unlike imitation cheeses, which may lack essential nutrients, plant-based cheese alternatives are formulated to maintain nutritional value. These products are created by coagulating plant-based milk proteins to remove carbohydrates and water, similar to traditional cheese-making methods (Balogun et al. 2019; Fox et al. 2017; Nakamura, Kitamura, and Kokawa 2016). Soy milk, with its curdling properties and unique nutritional profile, is a popular choice for plant-based cheese production. However, compared to cow's milk, the coagulation process of soy milk is typically slower and less efficient, which can present a challenge in cheese-making (Jeewanthi and Paik 2018; Silva, Silva, and Ribeiro 2022). Historical examples, such as fermented tofu, demonstrate the potential for plant-based cheese-like product to mimic the sensory attributes of traditional cheeses like Camembert or Roquefort (Grossmann and McClements 2021).

Many next generation of plant-based foods (e.g., dairy-free cheese alternatives), are categorized as ultra-processed according to the NOVA classification scheme (Monteiro 2009). These products often contain highly refined compounds such as starches, gums, protein concentrates, protein isolates, oils, colors, flavors, and vitamins, and their nutritional profiles depend on the types and amounts of these components (McClements 2023; Mefleh, Pasqualone, Caponio, and Faccia 2022). Despite advances in formulation techniques, the dairy industry faces considerable challenges in developing dairy-free cheese alternatives. These include meeting consumer expectations for vegan, allergen-friendly, and sustainable products without compromising safety, nutritional quality, or functionality. Key hurdles include replicating the complex flavors and textures of traditional cheese and making these products affordable for broader market adoption (Fox et al. 2017; Mattice and Marangoni 2020). While substituting animal proteins with plant-based proteins is critical to achieving sensory and functional parity, this remains a complex technical challenge (Short, Kinchla, and Nolden 2021). Although progress has been made in replicating the texture of traditional cheeses, further research is needed to enhance the taste and overall sensory attributes of these products (Nakamura, Kitamura, and Kokawa 2016; Silva, Silva, and Ribeiro 2022).

The development of plant-based cheese alternatives represents not only a response to dietary restrictions and preferences but also a transition toward more sustainable and energy-efficient food systems. This area of innovation holds significant potential to transform the food industry by creating products that cater to evolving consumer needs. Given the expanding market for plant-based products, this study explores the applications of plant protein in dairy-free cheese production, examining their current status of plant protein-based dairy cheese alternatives, challenges, and future outlook. By focusing on this growing sector, the study aims to contribute insights that will inform the development of novel plant-based cheese alternatives with unique properties, ultimately broadening consumer options and supporting sustainability goals.

Production methods of dairy-free cheese alternatives

Legumes, including common bean (*Phaseolus vulgaris*), lentil (*Lens culinaris* Medik.), lupin (*Lupinus albus* L.), fava bean (*Vicia faba* L.), pea (*Pisum sativum* L.), peanut (*Arachis hypogaea* L.), chickpea (*Cicer arietinum* L.), pigeon pea (*Cajanus cajan* L. Millsp.), black-eyed pea and cowpea (*Vigna unguiculata* ssp. *unguiculata*), as well as soybean (*Glycine max* L. Merr.), belong to the *Fabaceae* family (Mefleh, Pasqualone, Caponio, and Faccia 2022; Plamada et al. 2023). Due to their relatively low cost compared to nuts and high protein content compared to whole grain cereals and pseudo-cereals, legumes are considered suitable material for designing dairy-free cheese alternatives. Legumes are rich in lysine, carbohydrates, protein of high biological value, bioactive compounds, vitamins (e.g., niacin and thiamin), and minerals (e.g., iron and calcium), but are poor in sulfur-containing amino acids (i.e., cysteine, tryptophan, and methionine) (Gorissen et al. 2018; Mefleh, Pasqualone, Caponio, and Faccia 2022). Soy is known as a source of proteins, oils, fatty acids, amino acids, and vitamins, and is valued for its high antioxidant activity because of the presence of isoflavones and phytoestrogens (Plamada et al. 2023). Although soy proteins can be coagulated relatively easily, the process can be less efficient compared to that of cow's milk, leading to lower cheese yield when soy milk is used alone. Replacing part of the soy milk with another plant-based milk can further reduce the coagulability of the proteins, further decreasing the cheese yield (Balogun et al. 2019; Oyeyinka, Odukoya, and Adebayo 2019). In addition, it has been shown that cheeses formulated with soy milk have a higher moisture content, which can be attributed to the hydrophilic nature of soy proteins. Changes in moisture content in plant-based cheese alternatives can also be influenced by the coagulating strength of the coagulants used (Ayodeji et al. 2020; Rinaldoni et al. 2014).

Today, soy and nuts (such as cashews, peanuts, almonds, and macadamias) are the main plant-based derived proteins utilized in the preparation of dairy-free cheese alternatives (Tabanelli et al. 2018). However, it should be noted that nuts are usually more expensive than cereals and beans, and their content in final products is typically less than 5%, with protein contributions of less than 0.2 g (Mefleh, Pasqualone, Caponio, and Faccia 2022). The development of dairy-free cheese analogs involves overcoming the electrostatic repulsion energy barrier between plant protein molecules to induce gelation and curd formation (Grossmann and McClements 2021). Generally, to design dairy-free cheese alternatives with properties similar to dairy cheeses, two processing routes (i.e., tissue disruption route and fractionation route) can be applied, with their major difference attributed to the ingredients responsible for the sol-gel transition (Figure 1) (McClements and Grossmann 2022). In the fractionation route, sol-to-gel transition is created through isolated gelling ingredients from different plant materials. In other words, in this route, to form an oil-in-water emulsion, polysaccharides, proteins, and fats are mixed in a suitable proportion and finally a sol-to-gel transition occurs (Grossmann and McClements 2021). In contrast, the tissue-disruption route facilitates sol-to-gel transitions using components derived from primary raw materials. To form a curd, both routes utilize various techniques (e.g., pH changes, self-association, thermal treatment, enzyme crosslinking, and salt addition) and/or a combination of these methods (McClements and Grossmann 2022).

The amino acids composition of cereals differs from that of legumes; as a result, cereals proteins complement those of legumes. Therefore, a combination of both may balance the anabolic attributes of plant-based protein intake and is considered a suitable option for the production of dairy-free cheese alternatives (Kovačević, Bechtold, and Pham 2024; McClements 2023; Mefleh, Pasqualone, Caponio, and Faccia 2022). Dairy-free cheese alternatives can also be designed and produced without or with fermentation, a technique that improves sensory properties and increases micronutrient availability. In this regard, lactic acid bacteria (LAB) and yeasts are considered the main initiators (Boukid et al. 2023; Kovačević, Bechtold, and Pham 2024; Mefleh, Pasqualone, Caponio, and Faccia 2022). Compared to mono-culture, a mix of diverse strains is usually much more beneficial and efficient (Santos, Libeck, and Schwan 2014). In other words,

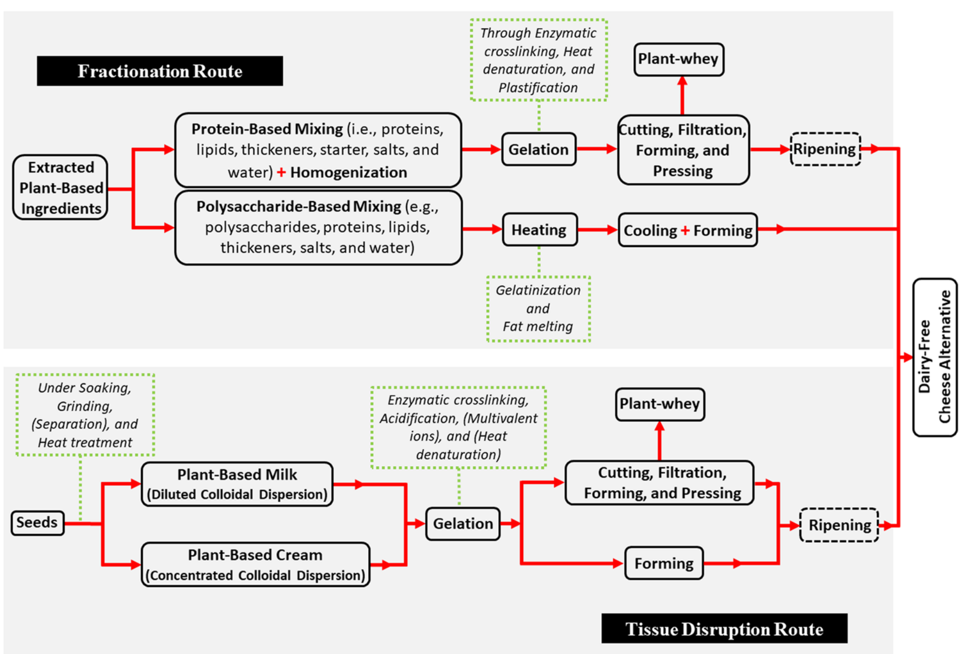

Figure 1. Flow process chart for dairy-free cheese alternatives from fractionation route and the tissue disruption route.

it has been reported that non-fermented dairy-free cheese alternatives usually have lower sensory scores than fermented samples (Nicolás Saraco and Blaxland 2020). Vegetable and fruit ingredients (such as apricot pulp, carrot paste, and pumpkin paste) can also be applied in the formulation of processed cheese analogues (Mohamed and Shalaby 2016; Mohamed, Shalaby, and Gafour 2016). Table 1 summarizes studies on the design and production of dairy-free cheese formulations, highlighting the routes, protein sources, other ingredients, and their impact on product characteristics. Notable trends include the predominant use of soy and pea proteins due to their availability and functionality, complemented by legumes or cereals to address amino acid balance. Challenges, such as achieving desirable texture, meltability, and coagulability, are often tackled using techniques like fermentation or blending raw materials.

Market trends and companies producing plant-based cheese alternatives

In recent years, the consumption of dairy-free alternatives has considerably increased, leading to a notable rise in the sales of these products. This growth reflects a broader global shift toward plant-based diets driven by health, ethical, and environmental considerations (Alcorta et al. 2021; Kovačević, Bechtold, and Pham 2024; Plamada et al. 2023; Tunick 2023). The global vegan cheese market, valued at approximately USD 2.43 billion in 2021, is expected to reach USD 7.10 billion by 2030, growing at a CAGR of 12.6% (GrandViewResearch 2023). This growth can reflect a shift toward more affordable, nutritionally flexible dairy-free cheese alternatives that can be tailored with added vitamins, minerals, and functional additives, meeting the diverse needs of health-conscious consumers (Kamath, Basak, and Gokhale 2022).

As markets outside Europe begin to mirror the growth seen in European countries, remarkable opportunities for innovation in plant-based cheese production will emerge. Currently, there are about 40 brands of plant-based cheeses in the global market (Silva, Silva, and Ribeiro 2022). These products are characterized by diverse formulations, with various companies incorporating a range of alternative proteins and fats to replicate the texture, flavor, and functionality of traditional dairy cheeses. Selected plant-based cheeses available in the market and their compositions are presented in Table 2.

Nicolás Saraco and Blaxland (2020) reported that the most common types of dairy-free cheeses are imitations of mild Cheddar (30%), Mozzarella (21%), and soft cheese (15%), respectively. Their study also showed that the commercial formulations of dairy-free imitation cheeses sold in the UK (regardless of water and starch) were based on coconut oil (74%), nut (10%), palm oil (5%), soya (3%), and sunflower oil (2%), respectively. These findings underscore the prevalence of coconut oil as the primary fat source due to its functional properties in texture and flavor mimicry.

It is important to note that soya and compounds derived from it, while commonly used in plant-based cheese production, are recognized allergens in the European Union. Consequently, manufacturers often opt to exclude these ingredients from their formulations to comply with regulatory requirements and cater to allergen-sensitive consumers (Union 2011). This regulatory consideration has encouraged the exploration of alternative protein sources such as peas, almonds, and cashews, which are now widely used in both commercial plant-based cheese production. The market's rapid growth is driven by innovations in ingredient functionality, including the use of starches, oils, and hydrocolloids to replicate the taste, texture, and melting properties of dairy-based cheeses. Companies are also leveraging advanced fermentation techniques and microbial cultures to develop cheeses with complex flavors and authentic textures, appealing to both mainstream and niche consumers.

Challenges

The growing consumer interest in dairy-free cheese alternatives, along with their potential benefits and rising demand, have driven increased entrepreneurial investment in this expanding industry. However, widespread consumer acceptance remains a challenge, requiring efforts to educate consumers on the advantages of these products, address concerns regarding quality and taste, as well as develop formulations that replicate the sensory characteristics of traditional dairy cheese (Tachie, Nwachukwu, and Aryee 2023). A major obstacle lies in achieving desirable texture and flavor, as the use of plant-based proteins often compromises sensory properties. This highlights the critical need for continued research and innovation to improve the texture, mouthfeel, and overall appeal of dairy-free cheese alternatives (Masotti et al. 2018; Zhang et al. 2024).

Plant proteins, when incorporated into cheese alternatives, can significantly alter their microstructure, rheology, and color, all of which affect consumer perception and acceptance (Omrani Khiabanian et al. 2020; Perreault et al. 2017). To address these issues, researchers are focusing on novel formulations and techniques that enhance the sensory attributes of dairy-free cheese alternatives. By improving texture and flavor, leveraging plant-based ingredients, and aligning with consumer expectations, the industry can bolster market support and attract further investment in this promising sector (Tachie, Nwachukwu, and Aryee 2023; Zhang et al. 2024).

Food neophobia

Educating consumers is crucial for promoting the acceptance of dairy-free cheese alternatives, particularly in overcoming "food neophobia"—the reluctance to try unfamiliar and novel food (Tuorila and Hartmann 2020). To cultivate healthy food habits, encourage acceptance of new products, and reduce food neophobia, it is very important to teach children and expose them to diverse foods early (Alcorta et al. 2021; Schyver and Smith 2005). Research shows that clear and informative labeling can significantly diminish

Table 1. Overview of the recent studies that investigated the design of dairy-free cheese alternatives.

Route	Protein	Other ingredients	Key Findings	Reference
Material fractionation route	Pea protein	Tapioca starch, pea starch, pea fiber, potato fiber, glucose, sucrose, dextrose, inulin, xanthan, shea stearin, sunflower oil (or coconut fat and extra virgin olive oil), starter cultures (*Streptococcus thermophilus*, *Lactobacillus delbrueckii subsp. bulgaricus*, *Lactobacillus acidophilus*, *Lacticaseibacillus paracasei subsp. paracasei*, and *Bifidobacterium*), oregano, rosemary, lactic acid, salt, and water.	• Fermentation improves gel firmness and flavor profile in cheeses. • Adjunct cultures improve pea protein-based cheese flavor. • Higher olive oil content reduces gel firmness in cheese. • Pea protein emulsions produce stable cheese matrices.	(Masiá et al. 2023; Masiá et al. 2022; Mefleh, Pasqualone, Caponio, De Angelis, et al. 2022; Michel et al. 2022)
	Pea protein along with other plant protein	Soy protein isolate, rice protein, potato protein, corn starch, pea starch, wheat starch, potato starch, waxy starch, tapioca starch, sunflower oil, coconut oil, rapeseed oil, gelatin, sodium alginate, and water.	• Plant-based cheese formulation achieves high protein and low fat. • Starch-protein-oil interactions enhance viscoelasticity in plant cheeses. • Tapioca starch and soy protein enhance cheese quality.	(Fan et al. 2023)
	Fava protein	Waxy corn starch, modified potato starch, maltodextrin, cellulose nanofibril, coconut oil, lecithin, glycerin, sodium citrate, sodium bicarbonate, lactic acid, citric acid, and water.	• High-protein plant-based cheese improves texture, melt, and stretch. • Extrusion processing enhances fava protein functionality for cheese.	(Dobson and Marangoni 2023; Zeng 2021)
	Fava protein along with yellow peas	Rapeseed oil, xanthan gum, kappa- and iota-carrageenan, kappa-carrageenan, and water.	• Improved hardness compared to Gouda and vegan cheeses.	(Ferawati et al. 2021)
	Soy protein	Tapioca starch, palm oil (or canola oil and carnauba wax), agar, lemon juice, sugar, salt, sodium caseinate, glucono-δ-lactone, calcium chloride, magnesium chloride, and water.	Oleogels reduce saturated fat, improve textural properties in cheese. 3–6% oleogels maintain cheese meltability, enhance elasticity. Soy-based cheese analogs need higher dry matter content for texture.	(Moon et al. 2021; Sivakami 2021)
	Chickpea protein	Chickpea flour, shea butter, lactic acid, and water.	• Higher protein concentration improves texture, adhesiveness, and cohesiveness. • Chickpea-based cheese alternatives showed no melting under testing. • Storage increased hardness, lowered brightness in chickpea samples.	(Grasso et al. 2022)
	Zein protein	Corn starch, tapioca starch, maize starch, highland barley β-glucan (HBG), xanthan, coconut oil, high oleic sunflower oil, and water.	• Zein-based cheese with HBG mimics Cheddar cheese behavior. • Increased HBG enhances stretchability and reduces oil release. • Zein-based cheese offers low-fat and meltable options.	(Liu et al. 2023; Mattice and Marangoni 2020)
	Zein protein along with other plant protein	Chickpea protein concentrate, tapioca starch, shea butter, lecithin, lactic acid, calcium salts, salt, and water.	• Zein protein improves meltability, stretchability, and flow properties. • Chickpea protein increases adhesiveness, springiness, and cohesiveness. • Calcium fortification impacts meltability and enhances stretchability.	(Grasso et al. 2023; Grasso et al. 2024)
	Potato protein	Non-modified potato starch, root or tuber starch, sunflower oil, waxy, and water.	• Native potato protein improves stretch and body in cheese. • Reduced off-taste compared to conventional imitation cheeses. • Root/tuber starch enhances texture and melting characteristics.	(Bergsma 2017)
	Wheat germ	Modified potato starch, unrefined palm oil, Cheddar flavor powder, Bekaplus Q3B, lactic acid, white edible compressed shelled oats powder, emulsifying salts, and salt.	• Modified potato starch and palm oil yield acceptable imitation cheese. • Oats fortification improves texture, flavor, and nutritional benefits.	(Hussein and Shalaby 2018)
	Flaxseed oil cake	*Geotrichum candidum*, *Penicillium camemberti*, lactic acid bacteria, salt, and water.	• Starter cultures influence bioactivity and physicochemical characteristics.	(Łopusiewicz et al. 2020)

(*Continued*)

Table 1. Continued.

Route	Protein	Other ingredients	Key Findings	Reference
Tissue Disruption Route	Rice milk	Lactic acid bacteria, gelatin, agar, and xanthan gum.	• Gelatin-based rice cheese achieved high sensory acceptance. • Optimal texture achieved with 2.5% gelatin concentration.	(Nakamura, Kitamura, and Kokawa 2016)
	Soymilk	Soybean oil, sucrose, okara powder, microorganisms (i.e., *Lacticaseibacillus casei ssp.casei NCDC-0017, Lactobacillus delbrueckii subsp. bulgaricus*, and *Streptococcus thermophilus*), *Geotrichum candidum*, calcium chloride, salt, alum, lime, and steep water.	• Soy cheese made from probiotics shows high protein. • Probiotic soy cheese spreads exhibit antioxidant activity. • *Geotrichum candidum* enhances texture and reduces beany taste. • Lime as coagulant increases cheese yield and quality.	(Chikpah et al. 2015; Giri, Tripathi, and Kotwaliwale 2018; James et al. 2017; Li et al. 2020)
	Soy milk along with other plant-based milk	Almond milk, cashew milk, tiger nut milk, coconut milk, groundnut milk, coagulant whey (fermented water from maize slurry), salt, and pepper.	• 50:50 soy-coconut milk blend most nutritionally balanced. • Almond substitution improved protein, fat, and flavor balance. • 95% soymilk, 5% tiger-nut blend most sensory preferred. • Tiger-nut increased fat, reduced phytate, improved digestibility. • 10% groundnut milk reduced beany flavor in soypaneer. • Cashew inclusion enhances nutrition, combats malnutrition effectively.	(Adejuyitan, Olanipekun, and Moyinwin 2014; Arise et al. 2020; Ayodeji et al. 2020; Balogun et al. 2019; Khodke et al. 2014; Oyeyinka, Odukoya, and Adebayo 2019)
	Peanut milk	Probiotic microorganism (i.e., *Lacticaseibacillus rhamnosus*), and Magnesium chloride.	• Peanut cheese spread shows potential as dairy alternative. • Fermentation enhances product functionality using *Lactobacillus rhamnosus* strain.	(Sharma, Sharma, and Amin 2018)
	Cashew nut	Miso paste, rejuvelac, yeast flakes, *Lactobacillus acidophilus*, seaweed (*Chondrus crispus or Porphyra* sp.), vitamin B_{12}, herbs, and water.	• Seaweed improves cheese texture, flavor, and nutritional properties. • Cashew fermentation reduces allergens while retaining nutritional content. • Probiotic strains enhance product functionality and consumer acceptance.	(Campos 2022; Chen et al. 2020)
	Lentil milk	Salt, black pepper, and yeast (*Saccharomyces cerevisiae*).	• Cheese produced from lentil milk extracted from green gram demonstrated superior nutritional and sensory attributes. • Viscosity and syneresis increased over 15-day storage.	(Naeem et al. 2024)
	Lupine paste	Butter oil, emulsifying salts, and water.	• Lupine paste decreased the meltability, cohesiveness, and springiness. • 25% lupine substitution ensures optimal processed cheese quality.	(Awad, Salama, and Farahat 2014)

neophobia. By specifying a detailed ingredient list, such as protein source, emphasizing product quality, and highlighting environmental benefits, labels can effectively attract consumer attention and build trust (Alcorta et al. 2021; Pasqualone 2022).

Mimicking the physicochemical and sensory properties of the dairy product

Undoubtedly, designing and producing dairy-free products that closely mimic the flavor, texture, and sensory attributes of traditional dairy remains a significant challenge (Alcorta et al. 2021; Boukid 2021; McClements 2023; Nicolás Saraco and Blaxland 2020). Overcoming this hurdle requires addressing the functional and structural differences between animal-derived and alternative proteins. For instance, in dairy cheese, the cleavage of the Phe105-Met106 peptide bond in κ-casein by chymosin reduces the net negative charge and steric repulsion, facilitating casein micelle aggregation and contributing to the cheese structure. Moreover, caseins exhibit versatile structural properties, enabling interactions through hydrophobic associations, electrostatic interactions, or hydrogen bonding, which are pivotal in achieving desired texture and functionality (Diaz-Bustamante et al. 2023). Reproducing these molecular characteristics in plant-based alternatives is a primary obstacle in their development.

Dairy-free cheeses must fundamentally have suitable and acceptable flavor, taste, and texture to be appealing to consumers; otherwise, they are unlikely to purchase them. Although this issue may be less important for vegetarians and vegans, it is crucial for the broader consumer base, which comprises about 90% of the population (McClements 2023; Nicolás Saraco and Blaxland 2020). For example, taste,

Table 2. Selected plant-based cheese alternatives on the market and their combinations.

Route	Product/Type	Ingredients	Company name
Material fractionation route	Cheddar style/ Semi-hard	Pea protein, potato protein, tapioca starch, pea starch, corn starch, modified potato starch, modified food starch, fava bean flour, potato flour, potato cashew nut, maize starch, modified maize starch, xanthan gum, carrageenan, guar gum, chicory root fiber, oat fiber, margarine, coconut cream, shea, coconut oil, canola oil, safflower oil, tricalcium phosphate, vegan enzyme, yeast extract, vegan lactic acid, calcium citrate, Tricalcium citrate, sodium lactate, citric acid, sugar, salt, vegan natural flavors, vitamins (B_2, B_{12}, and D_2), iodine, colors (beta carotene and annatto), and water.	Daiya, Vitalite, Emborg, Gusta, Green Rebel, Bute island food, Oddly good, Bedda, Nurishh, etc.
	Parmesan style/Hard	Soy protein, rice protein, modified potato starch, potato and rice starch, rice flour, bamboo fiber, organic chickpea miso (organic whole chickpeas, organic handmade rice Koji, Koji spores, water, and sea salt), organic palm fruit oil, expeller-pressed canola oil, coconut oil, olive extract, lecithin, glycerin, carrageenan, maltodextrin, calcium phosphate, sodium phosphate, tricalcium phosphate, lactic acid, citric acid, yeast extract, natural flavors, annatto, beta carotene, vitamin B_{12}, sea salt, and water.	Follow your heart, Go veggie foods, Whole foods, Violife, etc.
	Mozzarella style/Soft or semi-soft	Organic soy protein, potato protein, pea protein, organic soymilk powder, potato starch, corn starch, modified corn and potato starches, modified food starch, tapioca starch, fava bean flour, oat flour, konjac flour, tapioca flour, wheat, oat fiber, cellulose, agar agar, carrageenan, xanthan, guar gum, inulin (chicory root extract), organic expeller-pressed soybean oil (or coconut oil, canola oil, and sunflower oil), shea, olive extract, vegan lactic acid, sorbic acid, sodium lactate, calcium citrate, citric acid, tricalcium phosphate, sea salt, dextrose, natural flavors, yeast extract, beta carotene, vitamins (B_{12} and D_2), iodine, and water.	Follow your heart, Vitalite, Nurishh, Oddly good, Gusta, Good plant food, Daiya, OATzarella, Moocho, Violife, etc.
	Farmstead style/ Semi-hard	Miyoko's cultured vegan milk (oat milk, organic garbanzo beans, navy beans, and cultures), faba bean protein, organic tapioca starch, potato starch, organic locust bean gum, organic coconut oil, sea salt, calcium sulfate, organic yeast extract, organic cultured dextrose, natural flavors, Konjac, organic annatto, and water.	Miyoko's creamery, etc.
	Gouda style/Semi-hard	Maize starch, potato starch, modified maize starch, modified potato and corn starch, oat fiber, coconut oil, olive extract, guar gum, carrageenan, yeast extract, lactic acid, sodium lactate, sea salt, natural flavorings, coloring (e.g., beta carotene), vitamin B_{12}, and water.	Bute Island foods, Green Vie, Follow your heart, etc.
	Cream cheese style/ Semi-hard, and ripened flavor	Potato protein, soy protein, pea protein, chickpea protein, almond protein, cashew nut, potato and corn starch, modified potato and corn starch, pea starch, oat bran, fermented chao tofu, tapioca flour, sugarcane fiber, coconut cream, coconut oil, palm oil, sunflower oil, expeller-pressed high-oleic safflower oil, olive extract, lecithin, powdered cellulose, maltodextrin, dextrose, glucono-δ-lactone, locust bean gum, guar gum, xanthan, sodium ascorbate, sodium citrate, lactic acid, citric acid, tricalcium phosphate, calcium phosphate, vegan culture, yeast extract, natural flavor, beta carotene, coloring food (apple and carrot concentrate), nisin, enzyme, sea salt, sugar, vitamin B_{12}, and water.	Field roast, Violife, Simply V, Philadelphia, Tofutti, Trader Joe's, Daiya, Go veggie foods, Follow your heart, Vevan, etc.
	White Cheese	Modified potato starch, coconut oil, calcium lactate, sorbic acid, natural flavorings, beta carotene, iron, salt, vitamin (D_2, B_6, and B_{12}), and water.	Dairygold, etc.
Tissue disruption route	Cream cheese style	Cashew nuts, sunflower seeds, almond milk, cashew milk, bamboo fiber, coconut cream, truffle oil, xanthan, guar gum, mushroom extract, lactic acid, citric acid, tricalcium citrate, lemon juice, cultures, sea salt, sugar, natural flavors, enzyme, preservation, and water.	Kite Hill, Miyoko's creamery, Darë, Treeline cheese, Lauds, Spero foods, Nurishh, Monty's, etc.
	Ricotta style/Semi-soft	Cashews, almond milk, sea salt, tartaric acid, enzymes, cultures, water.	Kite Hill, Savor, etc.
	Mozzarella style/Soft	Soy milk, cashew milk, tapioca starch, κ-carrageenan, agar, organic refined coconut oil, sea salt, vegan lactic acid, garlic, spice, mushroom extract, cultures, organic Konjac, sundried tomato, and Kalamata olives.	Cheeze & Thank You, Miyoko's creamery, etc.
	Gouda cheese	Cashews, coconut oil, quinoa rejuvelac, chickpea miso, natural hickory smoke, Worcestershire sauce, fermented oregano extract, ascorbic acid, natural flavors, cultures, nutritional yeast, tocopherols, sea salt, and water.	Plant perks, Nuts for cheese, etc.
	Cheddar cheese spread/Firm or semi firm	Sunflower seeds, cashews, chickpea miso, coconut oil, ascorbic acid, pork wine, probiotic cultures, nutritional yeast, sriracha (jalapeno peppers, water, sugar, distilled vinegar, garlic powder, xanthan gum), natural flavors, sea salt, Himalayan salt, tocopherols, and water.	Spero, Plant perks, Vtopian, etc.
	Aged cheese	Cashews, coconut oil, water kefir, miso paste, chickpea miso, agar agar, xanthan, nutritional yeast, mustard powder, onion powder, sea salt, Himalayan pink salt, sorbic acid, citric acid, silicas, magnesium stearate, cultures, and water.	Lauds, Vtopian, etc.
	Fermented tofu	Soya beans, calcium sulfate, magnesium chloride, *Streptococcus thermophilus*, salt, and water.	Food Data Central, etc.
	Feta style	Whole soybean, cashews, organic refined coconut oil, rice bran oil, olive oil, vegan lactic acid, white wine vinegar, natural flavors, culture, sea salt, and water.	Cheeze & Thank You, Savor, etc.
	Chipotle cheese spread	Sunflower seeds, coconut oil, liquid smoke, salt, onion powder, chipotle peppers, probiotic cultures, and water.	Spero, etc.
	Ashed walnut cheese	Cashews, tasmanian walnuts, coconut oil, kefir, miso paste, nutritional yeast, onion powder, mustard powder, tasmanian sea salt, activated charcoal, citric acid, sorbic acid, and water.	Lauds, etc.
	White cheese/Firm	Cashews, soy yogurt, coconut oil, sauerkraut, onion, agar agar, tapioca flour, nutritional yeast, chives, dill, lemon juice, chickpea miso, Himalayan sea salt, extra virgin olive oil, xanthan gum, and water.	Vtopian, etc.
	Blue cheese style/Soft-ripened	Cashews, tofu, tapioca flour, coconut oil, vegan probiotics, bacterial culture, nutritional yeast, natural sweetener, salt, and water.	The Frauxmagerie, RIND, etc.

(*Continued*)

Table 2. Continued.

Route	Product/Type	Ingredients	Company name
Tissue disruption route	Garlic and herb soft spreadable cheese	Almond milk, dehydrated onions, dehydrated garlic, rice starch, potato starch, mushroom extract, enzyme, tartaric acid, cultures, salt, sugar, and spices.	Kite Hill, etc.
	Classic cheese style/ Soft-ripened	Cashew nuts, hickory smoked sea salt, lactic acid, *Lactobacillus acidophilus*, and water.	Treeline cheese, etc.
	Muenster style/ Semi-soft	Hemp milk, tapioca, κ-carrageenan, coconut oil, nutritional yeast, cultured, organic apple cider vinegar, organic smoked paprika, organic onion powder, organic mustard, sugar, and sea salt.	Catalyst creamery, etc.
	Brie style/Soft-ripened	Cashews, coconut milk, quinoa rejuvelac, chickpea miso, coconut oil, xanthan, agar agar, nutritional yeast, fermented organic oregano extract, cultures, sea salt, Himalayan pink salt, and water.	Nuts for cheese, Vtopian, etc.
	Camembert style/ Soft-ripened or semi firm	Cashews, soy yogurt, tapioca flour, extra virgin olive oil, gluconolactone oil, sauerkraut, vegan fermentation & edible mold cultures, nutritional yeast, xanthan, agar agar, lactic acid, balsamic vinegar, coconut sugar, Himalayan pink salt, salt, and water.	Happy Cheeze, Vtopian, etc.
	Farmstead cheese style	Cashew milk, organic chickpea miso, nutritional yeast, cultures, natural flavors, and sea salt.	Miyoko's creamery, etc.
	Plant-based goat cheese	Sunflower seeds, water, coconut oil, natural flavors, salt, and probiotic cultures.	Spero, etc.
	Monterey Jack style/Semi-hard	Cashew milk, potato starch, modified food starch, coconut oil, yeast extract, cultures, natural flavor, peppers, annatto, and sea salt.	Parmela creamery, etc.

such as the beany flavor of soy, is a major factor in the acceptance of soy-based products (e.g., soy milk) (Schyver and Smith 2005). Additionally, while consumers view plant-based dairy alternatives as more sustainable, factors like organic certification and packaging significantly influence their purchasing decisions (Schiano et al. 2020). The use of additives, such as flavors and colors, is often criticized, which has led to a focus on developing natural flavors, pigments, and preservatives from natural sources (e.g., essential oils, proteins, or peptides with antioxidant or antimicrobial properties), for plant-based formulations (Bensid et al. 2022; McClements 2023).

Since salt plays a key role in flavor formation and helps prevent excessive acidity, off-flavors, and bitterness, designing low-salt products presents a challenge. To address this, food technologists are working to optimize formulations of cheese analogs by incorporating salt replacers, bitter blockers, and flavor enhancers to reduce sodium levels (Kamath, Basak, and Gokhale 2022; Khetra, Kanawjia, and Puri 2016).

Mimicking the functional and nutritional properties of the dairy product

One of the most significant challenges in the dairy-free cheeses industry is designing and developing safe products with high functional and nutritional qualities that can meet all consumer expectations (Boukid 2021; Gharibzahedi and Smith 2021). Another key challenge is mimicking the meltability of dairy cheeses. It should be noted that in order to improve the meltability of commercial dairy-free cheese alternatives, it is suggested that the amount of thermoreversible gel-forming ingredients (e.g., κ-carrageenan) and non-thermoreversible gel-forming ingredients (e.g., native starch) should be increased and reduced, respectively. Furthermore, using affordable, plant-based thermoreversible gel-forming proteins can enhance nutritional quality (Nicolás Saraco and Blaxland 2020).

Since proteins are essential for the formation of body tissue and the regulation of enzymes, hormones, and antibodies, their consumption is necessary for maintaining health and proper body function (Alina et al. 2019). Therefore, another controversial issue in the production and consumption of dairy-free products is the quality of plant proteins, particularly in terms of amino acid composition and digestibility (bioavailability) in the small intestine. Plant-based proteins typically have lower bioavailability compared to animal proteins (Day, Cakebread, and Loveday 2022). Moreover, many plant proteins lack one or more essential amino acids, and their digestible indispensable amino acid score (DIAAS) are often below 100. For example, the DIAAS values of potato, soy, canola, lupin, pea, rapeseed, oat, fava bean, wheat, hemp, rice, and corn are 125, 103, 85, 83, 83, 79, 68, 64, 56, 56, 56, and 43, respectively (Herreman et al. 2020). In general, the concentration of essential amino acids such as lysine, methionine, threonine, and tryptophan are lower in plant-based proteins (Chardigny and Walrand 2016). However, a well-planned and balanced plant-based diet can help overcome these nutritional challenges (García-Maldonado, Gallego-Narbón, and Vaquero 2019). To overcome the challenge of the potential lack of essential amino acids in alternative products, mixing proteins from different sources (e.g., legumes and cereals) or enriching these products with specific amino acids has been suggested (Day, Cakebread, and Loveday 2022; Kouw et al. 2021). Moreover, to improve the digestibility of plant-based proteins, different strategies can be employed, such as using protein concentrates and isolates, selecting plant species with more digestible proteins naturally or through genetic engineering, applying food processing methods that alter the structure and aggregation state of proteins, and removing anti-nutritional factors (ANFs) (Bryant 2022; Gorissen et al. 2018). ANFs (e.g., tannins, phytates, and saponins) can impair protein absorption and disrupt digestion and nutrient absorption in the gastrointestinal tract (Alcorta et al. 2021; Arbab Sakandar et al. 2023; Kong, Li, and Liu 2022). Pre-processing techniques such as soaking, sprouting, roasting, fermentation, and milling can reduce anti-nutrient levels, improve color and mouthfeel, as well as enhance digestibility (Alcorta et al. 2021; Samtiya, Aluko, and Dhewa 2020). Also, genetic mutations in legumes can decrease the ratio of anti-nutrients to mineral acids, while fermentation is particularly effective for reducing heat-resistant anti-nutrients (e.g., phytates) (Hummel et al. 2020; Tangyu et al. 2019). Legumes proteins face specific challenges due to their heat resistance and ANFs, which hinder digestibility and contribute to undesirable beany flavors caused by lipoxygenase activity on unsaturated fatty acids (Mefleh, Pasqualone, Caponio, and Faccia 2022). Advanced processing methods, such as extrusion and high hydrostatic pressure, can significantly improve the digestibility and functionality of legume protein (Gharibzahedi and Smith 2021; Pasqualone et al. 2020). However, ANFs and the anti-nutritional proteinaceous compounds present in legumes contribute to reduced nutrient digestibility, allergic reactions, and gastrointestinal distresses in some people (Mefleh, Pasqualone, Caponio, and Faccia 2022; Samtiya, Aluko, and Dhewa 2020). Various strategies have been proposed to address these issues, including the use of traditional and/or economic treatments before grinding or cooking (for example, it has been proved that roasting at 180 to 200 °C for 15 to 20 min can reduce the ANFs and the beany flavor) (Khattab and Arntfield 2009), cornell hot grinding method to inactivate lipoxygenase (this method can be combined with a two-phase ultra-high temperature processing) (Sethi, Tyagi, and Anurag 2016), micronisation or infrared heating of seed (Arntfield et al. 2001; Khattab and Arntfield 2009), vacuum at high temperature to remove sulfur compounds, short chain fatty acids, and sterols (Sethi, Tyagi, and Anurag 2016), steam flashing to strip volatiles (Mefleh, Pasqualone, Caponio, and Faccia 2022), innovative non-thermal processing techniques (e.g., pulsed electric field (PEF), high and ultra-high pressure homogenization (HPH and UHPH), high hydrostatic pressure (HHP), radio frequency, and ultrasonication) (Jiang et al. 2021; Munekata et al. 2020; Vanga et al. 2021), deodorization of milk to remove the off-flavor (Villarino et al. 2016), enzymatic treatment or fermentation of seeds or slurry combined or not with high temperature pretreatment (Coda et al. 2015), protein concentrates, protein isolates, and defatted flour (Sethi, Tyagi, and Anurag 2016), natural or synthetic food additives to mask flavor (e.g., flavors and gums) (Sethi, Tyagi, and Anurag 2016), and breeding varieties devoid of lipoxygenase (e.g., the modern sweet lupin) (Mefleh, Pasqualone, Caponio, and Faccia 2022).

Another challenge facing plant-based products is the possible lack of certain nutrients such as vitamins (D and B_{12}), calcium, and iron (Alcorta et al. 2021). To address these deficiencies, it is essential to enrich products with these micronutrients and amino acids (McClements 2023; Pasqualone 2022). Encapsulation technologies can also be utilized to improve the stability and bioavailability of fat-soluble vitamins (such as A, D, E, and K) and hydrophobic bioactive agents (e.g., nutraceuticals) (McClements 2021; Tan and McClements 2021a, 2021b).

Studies indicate that the absorption of non-heme iron from plant sources is reduced compared to heme iron from animal sources due to its binding to inhibitors (Blanco-Rojo and Vaquero 2019; García-Maldonado, Gallego-Narbón, and Vaquero 2019). Moreover, designing plant-based products to address nutritional deficiencies for people with allergies can be particularly challenging (Tachie, Nwachukwu, and Aryee 2023). Some plant sources such as tree nuts, peanuts, soy, buckwheat, lupine, sesame seeds, and mustard, are known to cause allergic reactions (Hertzler et al. 2020). To mitigate this, alternative legumes, cereals, and nuts can be used, but precautionary allergen labeling is also recommended (Protudjer and Mikkelsen 2020; Tachie, Nwachukwu, and Aryee 2023).

Other challenges associated with legume-based products include susceptibility to favism, aflatoxin intoxication, and high alkaloid content in fava beans, peanuts, and lupins, extended processing time, and strong beany flavor (Acquah et al. 2021; Semba et al. 2021). Additionally, coconut oil-based dairy-free cheese alternatives usually contain a mixture of starches (such as native and modified corn or potato starch). However, modified starch is considered undesirable by some people (Mefleh, Pasqualone, Caponio, and Faccia 2022; Saraco 2019).

Plant-based proteins conversion factor

It has been reported that the conversion of plant-based proteins into animal proteins is inefficient. To generate 1 kg of plant-based milk that can be consumed by human and also achieve the same amount of protein in 1 L of cow's milk, 7 kg of plant protein and 13% more soy milk are needed, respectively (Coluccia et al. 2022; Diaz-Bustamante et al. 2023; Jeske, Zannini, and Arendt 2018).

Environmental impact some plant-based milks and palm oil

In general, the production of milk substitutes has less environmental impact compared to dairy milk (Ritchie, Reay, and Higgins 2018). However, some plant-based milks, such as almond milk, can have a significant impact due to the use of zinc fertilizer and the high water requirements for irrigation (Grant and Hicks 2018). Additionally, since not all palm oils are produced based on the Roundtable on Sustainable Palm Oil certification standard, the environmental effects of palm oil should be carefully considered in the production of dairy-free cheese alternatives (Saswattecha et al. 2015).

The price of plant-based dairy products

Some consumers of plant-based dairy products have expressed concerns about their high cost, limited availability in the supermarkets, and the high salt and sugar content in some of these products (Aydar, Tutuncu, and Ozcelik 2020; Laila et al. 2021). For example, dairy-free cheese alternatives, which often have lower nutritional value than dairy cheese, are typically more expensive (Glover et al. 2024; Southey 2022b). It seems that optimizing and improving the formulation of novel dairy-free cheese alternatives can reduce the price. Additionally, scaling up production may contribute to cost reduction.

Future outlook

Increasing demand for sustainable products and reducing the greenhouse gas emissions

Due to population growth, crises and losses of food and waste, climate change, as well as competition for natural resources, the current agricultural and food systems urgently require a transition to more sustainable products and food production systems (Alcorta et al. 2021). This transition aims to align with the 2015 Sustainable Development Goals (SDGs) set by the United Nations (UN 2015). Plant-based diets are generally more environmentally sustainable than animal-based diets, as they require fewer natural resources and result in less environment degradation (Melina, Craig, and Levin 2016). However, the sustainability of plant-based products is influenced by the degree of processing; less processed foods typically have a smaller environmental footprint due to lower energy consumption (Pasqualone 2022).

Studies have revealed that the production of milk by cows is a significant contributor to the greenhouse gas emissions associated with cheese production. Approximately 82% of the total CO_2-eq emissions arise from the milk production stage, while the subsequent processes of converting milk into dairy cheese and retailing have comparatively lower impacts on the emission of greenhouse gases (Bava et al. 2018; Finnegan et al. 2018; Tarighaleslami et al. 2020; Üçtuğ 2019). Depending on the type of cheese, about 4 to 10 L of cow's milk are required to produce 1 kg of cheese. Consequently, the greenhouse gas emissions related to raw milk production for fresh and semi-hard cheeses have been estimated at around 1.62 and 8.3 kg CO_2-eq per kg of cheese, respectively (Clune, Crossin, and Verghese 2017; Finnegan et al. 2018).

According to results, the materials used in the production of plant-based cheeses generally emit fewer greenhouse gases (i.e., pea milk (0.39), coconut and almond milk (0.42), cassava starch (0.59), sunflower oil (0.8), soy milk (0.88), tofu (0.98), tree nuts (1.42), as well as palm oil (1.4–2.0) in kg CO_2-eq per kg or L) (Braun et al. 2016; Henderson and Unnasch 2017; McClements and Grossmann 2022; Usubharatana and Phungrassami 2015). However, it should be noted that the ingredients used in plant-based cheeses differ in nutritional value from those dairy cheeses, making it challenging to exactly calculate their environmental impacts based on nutritional equivalent. On the other hand, since the amount of plant-based milk required to produce 1 kg of dairy-free cheese alternatives has not been reported so far, it is not possible to make an accurate assessment of their environmental sustainability (McClements and Grossmann 2022).

If it is assumed that the conversion ratio of plant-based milk to dairy-free cheese alternatives is similar to cow's milk to cheese, plant-based cheeses could significantly reduce greenhouse gas emission. For example, nut-based cheeses, produce through tissue disruption route and without whey separation, can use 1 kg of plant-based milk to yield 1 kg of cheese (Clune, Crossin, and Verghese 2017; McClements and Grossmann 2022). According to the evidence, legumes cultivation for dairy-free products has a lower environmental impact, but the extent of greenhouse gas emissions depends on the agro-ecosystem management (Clune, Crossin, and Verghese 2017; Stagnari et al. 2017). The hydroponic cultivation, an emerging technology that enables crops to grow directly in nutrient-rich water, offers an efficient and innovative method for producing plants used in dairy-free products (Alcorta et al. 2021).

It should also be noted that educating consumers about the environmental benefits of plant-based cheeses is critical to promoting sustainable dietary changes. By raising awareness of these advantages, consumer demand for such products could increase, potentially reducing production costs and enhancing affordability (Garcia-Oliveira et al. 2022; Jeske, Zannini, and Arendt 2018).

Innovation in the design of dairy-free cheese alternatives

The future of plant-based cheese alternatives looks promising, with ongoing advancements in food science technology and the growing availability of diverse plant protein sources. The incorporation of plant-based proteins into dairy-free alternatives is expected to continue evolving, further enhancing the development of more sustainable, nutritious, and consumer-friendly products (Kamath, Basak, and Gokhale 2022; Yashini et al. 2021). Innovation in the design and production of dairy-free cheese alternatives has significantly improved their sensory and functional properties. For example, vegan Mozzarella and Parmesan can be produced using cashews with Rejuvelac (a fermented drink made from sprouted wheat berries) and walnuts with nutritional yeast, respectively (Usher 2018). Cassava and arrowroot are also used to produce commercial vegan cheese with good meltability and stretchability (Alcorta et al. 2021). Recently, a protein isolate from cross-bred pea with 65–72% protein and improved functional properties (i.e., enhanced solubility, emulsification, and gelation) has been produced by an Israeli company, which appears to be suitable for use in the design of plant-based products (Southey 2022a). Similarly, Motif Food Works, in collaboration with the University of Guelph, improved the springiness of plant-based (corn-based) cheese using prolamin technology as an innovative method (Cumbers 2021). Combining amino acids from different plant protein sources also optimizes the nutritional and sensory profiles of dairy-free cheese alternatives (Alcorta et al. 2021).

Emerging ingredients, such as microalgae, and protein-enriching microbial fermentation methods are being explored to increase the protein content of dairy-free products (Alcorta et al. 2021; Tangyu et al. 2019). Interesting techniques such as ferritin content enrichment, bio-fortification, phytic acid reduction, ascorbic acid addition, and microencapsulation of iron to increase bioavailable iron in dairy-free products have attracted the attention of the food industry (Blanco-Rojo and Vaquero 2019; Shubham et al. 2020). In vegetarian diets, choosing products rich in bioavailable calcium is essential. Calcium enhancers and inhibitors (e.g., phytates and oxalates) should be considered when fortifying dairy-free cheeses, and fermentation can enhance calcium bioavailability (Alcorta et al. 2021; Melina, Craig, and Levin 2016). Since excess vitamin B_{12}, being a water-soluble vitamin, is excreted through urine, the design and development of dairy-free products containing higher amounts of active forms of B_{12} can help prevent vitamin B_{12} deficiency and reduce the need for frequent supplementation (Rizzo et al. 2016). Furthermore, the application of natural vitamin-producing microorganisms in the formulation of plant-based products has been proposed as a more natural, safer, and environmentally friendly solution (Tangyu et al. 2019).

The formulation of ultra-processed plant-based foods allows for designing products with tailored nutritional profiles and gastrointestinal behavior (McClements 2023). However, it seems that more studies are still needed to understand the relationships between compounds in dairy-free cheese alternatives and their physicochemical, nutritional, sensory, and functional properties. Diversifying legume-based cheese formulations is a cost-effective step toward sustainable food systems, as legume proteins offer significant potential in novel food development (Mefleh, Pasqualone, Caponio, and Faccia 2022). Recent trends in sustainable food systems have drawn the attention of researchers to 3-D food printing as a novel and innovative technique for producing food with desired nutrition, shape, taste, and color (Kamath, Basak, and Gokhale 2022). For example, a reduced-fat, highly porous 3D-printed cheese analogue was produced in presence of different proportions of acetylated microcrystalline cellulose, used as a micro-biosurfactant, using extrusion printers. The results showed that the manufactured product exhibited higher creaminess, a fattier aftertaste, and improved stability against freezing (Shahbazi, Jäger, and Ettelaie 2021).

Plant-based diets have also shown benefits in preventing and treating conditions such as obesity, Type 2 diabetes, and high blood pressure. They lower energy density, increase satiety, and reduce inflammation (Kahleova, Levin, and Barnard 2017; McMacken and Shah 2017; Melina, Craig, and Levin 2016; Yeh and Glick-Bauer 2016). However, more research is needed to assess the role of dairy-free cheese alternatives in disease prevention across different genders and populations.

Generally, dairy-free cheese alternatives are more expensive than dairy cheese (i.e., cow's cheeses). This is partly because innovative products are produced on a small scale, and demand is limited to specific group, such as vegans. As a result, the price of dairy-free cheese alternatives made from legume protein does not necessarily align with the price of the ingredients that are typically not more expensive than dairy cheeses (Mefleh, Pasqualone, Caponio, and Faccia 2022; Saraco 2019). In this regard, we strongly believe that by changing people's perspectives, plant-based products can be considered a food option for all consumers who are concerned about their health and seeking natural, functional, and novel products without synthetic ingredients. As demand increases and production scales up, the final price is likely to decrease.

Conclusions

Today, the market for plant-based products is expanding due to consumer demand for nutritious, palatable, affordable, safe, sustainable, and environmentally friendly options. In this regard, dairy-free cheese alternative made from legumes and nuts proteins, as well as enriched with vitamins and calcium, can attract the attention of consumers. However, nuts tend to be more expensive than cereals and beans. Generally, two processing routes (i.e., tissue disruption route and fractionation route) can be applied to design dairy-free cheese alternatives. Considering the world's population, if other countries follow the growth pattern of dairy-free cheese consumption seen European countries, there will be significant opportunities for innovation in plant-based cheese production. It is predicted that the global vegan cheese market will reach a value to USD 7.10 billion by 2030, which presents promising prospects for factories producing innovative dairy-free products. One of the biggest challenges in the dairy-free cheeses industry today is the design and development of safe products with high functional and nutritional characteristics that meet consumer expectations. To improve the meltability of commercial dairy-free cheese alternatives, increasing thermoreversible gel-forming ingredients while reducing non-thermoreversible ones has been suggested. Furthermore, to address potential deficiencies in essential amino acids, mixing proteins from different sources (e.g., legumes and cereals) or enriching products with amino acids is recommended. In addition, hydroponic cultivation—an emerging technology that allows crops to grow in nutrient-rich water—presents an efficient and interesting method for producing dairy-free products. Innovation in dairy-free cheese design has significantly enhanced the sensory properties of these products. Techniques such as ferritin enrichment, bio-fortification, phytic acid reduction, ascorbic acid addition, and iron microencapsulation to increase bioavailable iron are gaining attention of the food industry. Equally important to product innovation is the need for consumer education, as it plays a crucial role in fostering acceptance and encouraging the adoption of dairy-free cheese alternatives. Educating consumers about the nutritional benefits and environmental sustainability of these products will help drive market growth and support the industry's long-term success.

Author contributions

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Disclosure statement

The authors declare that they have no conflict of interest.

Funding

This project has received funding from the European Union's Horizon 2022 research and innovation programme under the Marie Sklodowska-Curie (MSCA-Postdoctoral Fellowships 2022) grant agreement No. 101105558—NovelPBC—HORIZON-MSCA-2022-PF-01.

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