International Journal of Multidisciplinary Research in Arts, Science & Commerce
(IJMRASC) ISSN Online: 2583-018X

Vol. 5(1), June 2025, pp. 01-18

THE FUTURE OF DAIRY: FERMENTATION-BASED MILK PRODUCTION, FUNCTIONAL PROPERTIES, AND NOVEL APPLICATIONS

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ABSTRACT

Fermentation-based milks are produced through fermentation of dairy proteins such as whey and casein and represent a transformative advancement in sustainable food technology. The article reviews the innovative products into whey protein-based, casein-based, and hybrid milks, highlighting their distinct functional and nutritional properties. The critical need for fermentation-based milks is underscored by their potential to address environmental concerns, meet shifting consumer preferences, and replicate the sensory and functional attributes of traditional dairy without reliance on animal farming. This review emphasizes the technological precision required to recreate authentic milk proteins. While fermentation-based milks offer significant advantages, including nutritional completeness, lactose-free composition, and reduced greenhouse gas emissions, and challenges such as production costs, allergenicity, and consumer perception persist.Fermentation-based milk products blend traditional fermentation methods with modern biotechnology, paving the way for a new era in dairy. They present a promising, eco-friendly alternative that can improve taste, nutrition, and overall functionality.

KEYWORDS *Precision fermentation, fermentation-based milk, whey protein, casein, sustainable dairy, functional foods, biotechnology, plant-based hybrid, dairy alternatives*

INTRODUCTION

Fermentation-based milks are an emerging class of dairy alternatives produced by fermentation of milk proteins, rather than by traditional animal farming. In this approach, microorganisms like yeasts, fungi, or bacteria are genetically modified with genes responsible for producing milk proteins, such as whey or casein. These engineered microbes are grown in fermentation tanks, where they produce dairy-identical proteins that are later collected and purified **(Bintsis&Papademas, 2022)**. The significance of fermentation-based milks lies in their potential to meet growing consumer demand for sustainable, ethical, and health-conscious foods. Traditional dairy farming is resource-intensive and contributes substantially to greenhouse gas emissions and environmental degradation **(Knychala*et al*., 2024).**

The exclusive production of milk proteins through fermentation substantially minimizes the environmental footprint. Life-cycle assessment studies report a 91–97% reduction in greenhouse gas emissions and a 96–99% decrease in water consumption compared to conventional whey protein production **(Chaves-López *et al*., 2020)**.Moreover, fermentation-based milks deliverthe taste, texture, and nutrition of real dairy while being free from lactose, cholesterol, and antibiotics **(Gervasi *et al*., 2021).**

ORIGIN AND HISTORY OF FERMENTATION-BASED MILKS

Fermented milk products have been part of human diets since millennium—10,000–15,000 years back to the dawn of animal domestication **(Bintsis&Papademas, 2022).** Early herding cultures discovered that raw milk would spontaneously ferment into tangy, preserved foods like yogurt and kefir from naturally occurring lactic acid bacteria **(Granato *et al*., 2010)**. These traditional fermented milks were produced by inoculating fresh milk with microbial cultures (often via a bit of a previous batch, a practice known as "back-slopping") and allowing fermentation to convert lactose into lactic acid, thus preserving the milk and imparting desirable flavors and health benefits **(Marco *et al*., 2017).**

Over centuries, every dairy-producing region developed its own fermented milk specialties—from yogurt in the Middle East and India, to kefir in Eastern Europe, to cultured buttermilk and cheeses worldwide. This long history established fermentation as a valuable tool to enhance the safety, shelf-life, and digestibility of milk, and even ancient sources lauded the functional and therapeutic properties of fermented milks **(Mugampoza*et al*., 2023).**

Industrial fermentation began to intersect with dairy science in the modern era. A landmark development was the introduction of fermentation-produced enzymes for cheese making: in the 1990s, scientists learned to produce chymosin (rennet) from genetically modified microbes, largely replacing calf stomach rennet in cheese production. This demonstrated that biotechnology could reliably produce dairy-associated biomolecules at scale **(Seth *et al.*, 2022).**

By the early 21st century, advances in genetic engineering and brewing technology set the stage for producing entire milk proteins via fermentation. Around 2014, a wave of startups and research projects emerged aiming to create "cow-free milk. These early efforts marked the birth of precision fermentation dairy**(Świąteckaet *al.*, 2020).**

Significant progress came in the late 2010s and early 2020s. By 2019–2020, the first prototype products made with fermentation-based milk proteins hit the market. Perfect Day, for instance, launched limited-edition ice creams made with its non-animal whey protein, demonstrating that consumers could not distinguish it from traditional dairy ice cream in flavor or texture**(Millward, 2023).**

TYPES OF FERMENTATION-BASED MILKS

Fermentation-based milks can be categorized by the primary protein component used as their base. The three main types are: whey protein-based milks, casein-based milks, and hybrid milks. Each type leverages different milk protein fractions (produced via fermentation) and thus has distinct properties and applications.

Whey Protein-Based Milks:

Whey Protein-Based Milks are milk alternatives formulated predominantly with whey proteins obtained through fermentation. In cow's milk, whey proteins (such as β-lactoglobulin and α-lactalbumin) make up about 20% of the total protein and are responsible for many functional attributes like water solubility and foaming. Fermentation allows production of these whey proteins without cows—for example, companies have engineered yeast (like *Trichoderma reesei* or *Pichia pastoris*) to secrete β-lactoglobulin, the major whey protein **(Knychalaet *al.*, 2024).**

Whey-based fermented milks typically require blending the fermented protein with water, fats, sugars, and micronutrients to emulate the composition of cow's milk. The resulting product is high in quality protein and often identical in amino acid profile and digestibility to conventional dairy whey. In fact, precision fermentation-derived β-lactoglobulin has the same PDCAAS (protein quality score) and functional properties as its bovine counterpart. A single fermented whey protein can thus provide a complete source of essential amino acids**(Tamang *et al.*, 2016).**

These whey-based milks excel in fluid applications - they dissolve well and impart a creamy mouthfeel and foaming ability for lattes or shakes **(Millward, 2023).** Such products deliver roughly the same protein content as cow's milk (≈3–4 g protein per 100 mL) along with added calcium and vitamins, but with zero lactose or cholesterol. Whey protein-based milks are particularly suited for drinking, blending into smoothies, or making cultured products like drinkable yogurts. However, on their own they lack the casein proteins needed to form firm curds, so they are less useful for solid cheeses—this is where casein-based emerged from.

Casein-Based Milks:

These fermented milks are built on casein proteins produced via fermentation. Caseins account for ~80% of protein in cow's milk and are the components that aggregate into curds (for cheese or yogurt). There are four major caseins (α_{s1}, α_{s2}, β, and κ-casein) which assemble into colloidal micelles in milk in the presence of calcium. Recreating caseins through fermentation is more complex than whey because one ideally needs multiple casein types and the proper post-translational modifications (like phosphorylation) to emulate their natural behavior**(Ziarno &Zaręba, 2022).**

Nonetheless, significant progress has been made. Multiple startups, including Remilk, New Culture, and Formo, have successfully engineered yeast and fungi to express bovine casein genes. The proteins produced are then blended to create a casein mixture that closely mimics the composition found in traditional milk.

Fermented casein, when combined with appropriate amounts of calcium and phosphate, can form casein micelles similar to those in real milk. This enables traditional dairy processes like curdling and cheese ripening**(Raveschot*et al.*, 2017).**

A prime example is New Culture's animal-free mozzarella cheese: they produce fermentation-derived β-casein (and likely κ-casein), blend it with plant-based fats and sugar, then add rennet and ferment it just like conventional cheese. The result is a mozzarella that has the same texture, melt, and stretch as dairy cheese **(Arora & Sharma, 2020).**

Casein-based fermentation milks are thus ideal for creating cheeses, fermented yogurt, and other gelled or solid dairy analogues. Nutritionally, casein is a slow-digesting, high-quality protein rich in amino acids and calcium-binding phosphopeptides. Fermented casein ingredients can be used in high-protein beverages and supplements as well.

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As of 2024, precision-fermented casein was poised for commercial debut, with regulatory green lights and pilot-scale cheeses being tested in pizzerias**(Knychala*et al*., 2024, 2023)**

Hybrid Milks:

Hybrid fermentation-based milks refer to products that combine multiple protein sources or components to create a more complete milk analogue. In practice, this often means blending fermentation-derived whey and casein proteins—essentially reconstituting the full protein profile of cow's milk—or mixing fermentation-derived dairy proteins with plant-based ingredients to achieve desired properties **(Formo, 2021).**

One form of hybrid milk is a whey–casein blend produced by fermentation. By combining approximately 20% whey proteins and 80% caseins—replicating the natural ratio found in cow's milk—and incorporating plant-derived fats and carbohydrates, it's possible to create an "animal-free milk" that closely matches the composition of traditional dairy milk**(Layman*et al*., 2018).**

Another form of hybrid is incorporating plant-based elements alongside fermented proteins. For example, fermented dairy proteins can be combined with plant-derived fats (such as coconut or sunflower oil) and sugars to replicate milk's creaminess and slight sweetness. This is the approach used in the earlier-mentioned Bored Cow products: the base is fermentation-derived whey protein, but the fat comes from coconut cream and the carbohydrate from sugar, making a hybrid of microbial and plant ingredients **(Bernat *et al*., 2014).**

Hybrid milks leverage the strengths of each input—the authentic dairy proteins contribute emulsification, foam stability, and that unmistakable dairy flavor, while plant components can add fiber, vitamins, or cost-effective bulk**(Liu *et al*., 2024).**

NEED FOR FERMENTATION-BASED MILKS

Sustainability is a paramount motivator. Conventional dairy farming places heavy burdens on land, water, and the climate—it is responsible for significant GHG emissions, with livestock agriculture accounting for roughly half of agriculture's emissions **(Knychala*et al*., 2024).**

By cutting cows out of the loop, we can eliminate enteric methane emissions and manure management issues, and produce only the desired proteins rather than maintaining whole animals. Studies have quantified these benefits: fermentation-derived milk proteins can reduce greenhouse gas emissions by approximately 90% or more, and water and land use by over 95% compared to dairy farming. In a world facing climate change and resource constraints, such improvements are game-changing**(Bernat *et al.*, 2014).**

Producing milk via fermentation is also seen as a strategy for future food security—it decouples milk supply from animal herds, meaning production can be scaled in fermenters anywhere, insulating supply from droughts, diseases (like bovine mastitis outbreaks), or other farm vulnerabilities **(Knychala*et al.*, 2024).**

Fermentation-based milks align with vegan and cruelty-free values, since they require no animal farming and cause no direct harm to animals. These milks are naturally lactose-free and can thus provide the nutrition of milk without the digestive issues. Additionally, they contain no hormones or antibiotics, substances often present (in trace amounts) in industrial cow's milk **(Damin *et al.*, 2009).**

Nutritionally, fermentation-derived dairy proteins are complete proteins with high bioavailability, potentially superior to many plant-based milk alternatives that can be lower in protein or limiting in certain amino acids **(Mathai*et al.*, 2024)**. There is also scientific and culinary motivation: functional performance. Food scientists recognize that the proteins in milk (whey and casein) have unique functional properties—from foaming lattes to creating the stretch in melted cheese—that plant proteins struggle to replicate **(Layman*et al.*, 2024).**

OVERVIEW OF FERMENTATION-BASED MILKS SUBSTITUTE EXTRACTION PROCESS

The production of fermentation-based milk alternatives centers on extracting key milk proteins via microbial fermentation, then formulating them into a milk-like liquid. The process can be broadly divided into bioproduction of proteins and post-processing into milk substitutes.

Protein Fermentation (Bioproduction):

A crucial step is selecting the appropriate milk protein genes—such as those encoding β-lactoglobulin or α-lactalbumin for whey-based milks, and α-, β-, or κ-caseins for casein-based alternatives.These genes are inserted into a suitable microorganism, typically a GRAS (Generally Recognized as Safe) microbe such as baker's yeast *Saccharomyces cerevisiae*, *Kluyveromyces lactis*, *Pichia pastoris*, or filamentous fungi like *Trichoderma*. The microbes are engineered to efficiently express and, if possible, secrete the target protein **(Knychala*et al.*, 2024).**

Secretion is advantageous because the protein can be collected from the broth; yeast like *K. phaffii*is often used with signal peptides to secrete proteins into the culture medium. The fermentation is carried out in large stainless-steel bioreactors under controlled conditions (sterile environment, specific temperature, and pH, etc.). The microbes are fed a growth medium usually containing a sugar source (like glucose derived from corn or cane) and necessary nutrients. Over the course of days, the engineered microbes act as tiny "cell factories," converting the feedstock into the target milk proteins. Once fermentation is complete, the broth contains the produced protein **(Fonteles& Rodrigues, 2018).**

Protein Extraction and Purification:

The milk protein is separated from the fermentation mixture. If the protein was secreted, the broth is first clarified to remove cells (e.g., by centrifugation or filtration). The produced protein can be concentrated and purified using methods similar to those used in traditional dairy or biotechnology. These include techniques like ultrafiltration, which uses membranes to separate proteins by size—allowing water and small molecules to pass while retaining larger proteins—or by adjusting pH or salt levels to precipitate the protein, which is then collected and dried**(Gänzle, 2015).**

The goal is to obtain a pure protein isolate or concentrate. If the protein was not secreted (less common in newer processes), cell disruption methods (high-pressure homogenization or enzymatic lysis) would be used first to release the protein from the cells, before purification. Throughout extraction, care is taken to preserve the protein's structure and functionality (e.g., maintaining proper temperature to avoid denaturation) **(Liu *et al*., 2024).**

At this stage, the protein is bioidentical to its dairy-derived counterpart in terms of amino acid sequence and structure, which has been confirmed through analytical techniques in various studies **(Mahomoodally*et al*., 2010).**

Formulating the Milk Substitute:

The purified fermentation-derived proteins are used to formulate the final "milk." To mimic whole milk, the proteins are rehydrated and mixed with additional components. In a basic whey-based milk formulation, the protein powder is blended with water, a source of fat (plant-derived fats like coconut oil, sunflower oil, This includes adding synthesized milkfat alternatives, a carbohydrate source—such as sugar, maltodextrin, or fiber—to provide sweetness and replicate the texture of lactose, along with essential micronutrients like calcium, potassium, vitamin B12, and vitamin D to align with the nutritional profile of cow's milk**(Chaves-López *et al*., 2020).**

Emulsifiers or stabilizers (such as lecithin or gellan gum) may be added in small amounts to help disperse the fat uniformly and give a stable milky texture. The mixture is then homogenized—much like cow's milk is—to create a stable emulsion of fat droplets coated by proteins **(Millward, 2023)**.The fermentation-derived whey proteins act as natural emulsifiers, similarly to how dairy whey and casein stabilize milk fat in bovine milk **(Layman*et al.*, 2024)**. In the case of hybrid milk, the process may include a step of re-forming casein micelles: adding calcium phosphate and letting the caseins self-assemble into micellar structures in the liquid, which is facilitated by the presence of κ-casein to stabilize the micelle surface**(Gervasi *et al.*, 2021).**The liquid is pasteurized or UHT-treated to eliminate microbes introduced post-fermentation, then packaged as a ready-to-drink milk alternative**(Granato *et al.*, 2010).**

MERITS AND DEMERITS OF FERMENTATION-BASED MILKS

Merits

Nutritional Quality:

Fermentation-derived milk proteins are nutritionally equivalent to those in cow's milk, offering complete proteins of high biological value. For example, recombinant β-lactoglobulin from fermentation has the same amino acid profile and protein quality scores (PDCAAS, DIAAS) as bovine β-lactoglobulin **(Layman*et al.*, 2018)**. In practice, products like animal-free milk deliver similar protein content to cow's milk (typically ~3 g/100 mL) and are often fortified with calcium and vitamins to match or exceed dairy's micronutrient levels Additionally, these milks are naturally lactose-free, which means they can provide the nutritional benefits of milk to the large population of lactose-intolerant individuals without causing digestive discomfort **(Marco *et al.,* 2017)**.They are also cholesterol-free and have negligible saturated animal fat (depending on the fat source used), potentially making them nutritious**(Mathai*et al.*, 2017).**

Functional and Sensory Performance:

A major advantage is that the fermented proteins have the same folding and properties, so they confer excellent functionality: foaming, emulsifying, gelation, and heat stability akin to conventional milk **(Liu *et al.*, 2024).**For instance, fermentation-derived whey protein has demonstrated emulsifying capacity and solubility indistinguishable from animal-derived whey. The mouthfeel of fermentation-based milk can be very creamy and rich, because the proteins can form the same kind of colloidal structures and light-scattering particles that give cow's milk its body and opacity **(Millward, 2023).**

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(IJMRASC) ISSN Online: 2583-018X

Vol. 5(1), June 2025, pp. 01-18

Health and Safety:

Fermentation-based milks remove certain health concerns associated with animal dairy. It is lactose free. There are also no residual hormones or antibiotics which might be present in cow's milk from dairy farm practices. The products are made in controlled stainless-steel tanks, reducing the risk of contaminants like pathogens that can sometimes be present in raw milk or result from on-farm contamination**(Knychala*et al*., 2024).**

Moreover, these milks can be made to be hypoallergenic by design—in theory, one could omit or modify the protein(s) that cause most milk allergies. While current products do contain β-lactoglobulin identical to the cow version (hence they would trigger dairy allergies) **(Mathai*et al*., 2017)**, future engineered versions might tweak epitopes or use only proteins like α-lactalbumin which are less allergenic.

Environmental and Ethical Benefits:

The environmental merit of fermentation-based milks is a key advantage from a sustainability perspective. Production of these milks can reduce GHG emissions by over 90%, land use by 90+%, and water use massively relative to dairy farming. This makes them a climate-friendly choice for eco-conscious consumers. Ethically, no cows are involved, which addresses concerns about animal welfare and intensive farming conditions **(Knychala*et al*., 2024).**

Innovation and Customization:

Fermentation-based milks offer flexibility. Producers can create tailor-made milk—for example, adjusting the protein ratio for a specific application (more casein for a cheese-heavy milk, or more whey for a workout recovery drink), or enriching the milk with additional functional proteins. Furthermore, the supply chain for fermentation-based milk might eventually be more efficient: powders of protein can be shipped and mixed with local water, potentially reducing refrigeration and transport of liquid milk over long distances**(Liu et al., 2024).**

Demerits

Cost and Scale Challenges:

Fermentation-based milks are still an emerging product and generally more expensive to produce than high-volume conventional milk. While the cost has come down rapidly, large fermenters and sophisticated downstream processing are required, involving high capital expenditure. The fermentation process also requires inputs (sugars, energy) that have a cost and environmental impact; if not powered by renewable energy, the GHG savings can be partially offset by industrial energy use **(Knychala*et al*., 2024).**

Regulatory and Labelling Issues:

Fermentation-derived milk components are novel in the sense of regulation. While they are compositionally the same as traditional ingredients, they often fall under "novel food" regulations and require approvals to ensure safety and proper labelling. So far, precision fermentation proteins like β-lactoglobulin have been granted GRAS status, confirming safety **(Layman*et al*., 2018).**

Allergenicity:

A notable drawback is that, biologically identical proteins will trigger identical allergies. People with a milk protein allergy (distinct from lactose intolerance) cannot safely consume these products, even though they are vegan, because the immune system recognizes the protein**(Laureys & De Vuyst., 2014).**

Functional Gaps and Need for Blending:

While fermentation-based milks have excellent functionality, using only a single protein isolate (like only β-lactoglobulin) doesn't fully replicate the complexity of whole milk. Milk's performance comes from a medley of whey proteins, caseins, minerals, etc. A fermented whey-only product may have some limitations **(Marco *et al*., 2017).**

BLENDING OF FERMENTATION-BASED MILKEXTRACTSFROM DIFFERENT SOURCES

Blending constitutes a critical innovation strategy in the development of fermentation-based milk alternatives. By combining fermentation-derived milk extracts (primarily proteins) from multiple sources or with other ingredients, developers optimize nutrition, sensory profiles, and functional performance. Two primary contexts define this blending strategy: (1) the combination of different fermentation-derived proteins, such as whey and casein, and (2) the integration of fermentation-derived proteins with plant-based matrices or additives to harness synergistic effects **(Mathai*et al*., 2017).**

Blending Whey and Casein Proteins

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Using a single type of protein isolate does not mimic whole milk's performance. The natural solution is to blend whey proteins and caseins produced via fermentation to reassemble the complete dairy protein spectrum**.**By combining these proteins in the correct ratio, the resulting mix behaves much like the real milk from a cow. Caseins provide structure and the ability to gel or curdle (crucial for cheese and yogurt), while whey proteins provide solubility, foaming, and nutritional boost **(Chaves-López et al., 2020).**For instance, a blend might include fermentation-derived β-casein and κ-casein (for curd formation and micelle structure) together with β-lactoglobulin and α-lactalbumin (for emulsification and protein fortification) **(Liu *et al*., 2024).**The technique for blending could involve mixing thepurified protein powders in water and adding calcium salts—under the right conditions, the caseins will form micellar aggregates coated by κ-casein, just as in raw milk **(Gervasi *et al*., 2021)**.

The purpose of blending fermentation-derived proteins is to achieve complementary functionality. Whey and casein in combination can replicate milk's emulsifying and water-binding capacity. Dairy's superior functionalities arise from the diverse protein components and structures working together**(Laureys and De Vuyst., 2014).**

NutritionalImpact:

Blending casein and whey mimics the digestion profile of milk—whey is fast-digesting and casein is slow-digesting—providing both immediate and sustained amino acid availability. This combined effect is considered optimal for muscle protein synthesis and satiety, making blended fermentation-based milks ideal for athletic and general health applications**(Marco *et al*., 2017)**

Blending with Plant-Based Ingredients:

According to **(Mugampoza*et al*., 2023)**it is sensory and nutritional balancing: plant-based milks (like oat, almond, or pea milk) often lack sufficient protein or have a thin body, but they may have desirable flavors or micronutrients. By adding a fraction of fermented dairy protein, the hybrid beverage can achieve a creamier texture, higher protein content, and closer resemblance to dairy, while retaining the plant milk's characteristics**(Seth *et al*., 2022).**

Blending also helps with cost management: fermentation proteins are expensive, so using them as part of a mixture with cheaper plant ingredients can make a product more affordable while still delivering key functional benefits. A small addition of fermented whey protein to a soy or pea base, for instance, can dramatically improve mouthfeel and foam stability **(Layman*et al*., 2018).**

Advanced Techniques:

The techniques for blending fermentation-based extracts with plant bases often involve creating stable mixtures at the molecular level. One novel method reported by food scientists is co-encapsulation: for instance, encapsulating a casein protein together with a plant protein (like pea protein) into one stable protein particle **(Tamang *et al.*, 2016).**Another approach is sequential blending: first emulsify the fermentation-derived proteins with fats, then blend that emulsion into a plant milk base to create stable, creamy textures without excessive stabilizers **(Ziarno and Zaręba., 2022).**

Purpose of Blending:

Blending different sources is fundamentally about achieving an optimal balance of properties that no single source can provide. Fermentation-derived proteins contribute authenticity and functionality; plant sources contribute fiber, flavors, and cost efficiency **(Raveschot*et al.* 2017).**

The end goal is to make fermentation-based milks that are indistinguishable from cow's milk in every use-case—whether drinking fresh, steaming, fermenting into yogurt, or making cheese**(Arora and Sharma., 2020)**.Importantly, blending leverages the notion that fermentation-based milks and plant-based milks are not competitors but allies in creating the next generation of dairy alternatives **(Bernat *et al.*, 2014).**

NOVEL PRODUCT DEVELOPMENT FROM FERMENTATION-BASED MILKS

The advent of fermentation-based milk ingredients has unlocked an exciting array of novel products. Food scientists and startups are no longer limited to traditional dairy or purely plant-based formulations—they can create entirely new categories or improved versions of familiar dairy foods by using fermented milk proteins.

Probiotic-Enhanced Milks and Yogurts:

One promising area is the development of probiotic dairy beverages that are fully vegan. Fermentation-based milks can serve as the growth medium for beneficial bacteria (just like cow's milk does in yogurt or kefir) without involving animals.Beyond yogurt drinks, one could envision kefir-like beverages or probiotic shakes using fermented milk bases **(Damin *et al.*, 2009).**

Since the protein base is real dairy protein, it can ferment and acidify similarly to milk—lactic acid bacteria can metabolize added sugars (like cane sugar) to produce lactic acid, thickening the product and yielding that familiar tartness. Additionally, novel probiotics beyond the traditional yogurt strains could be incorporated since the fermentation base can be formulated without any inhibitory factors **(Mathai*et al.*, 2022).**

Functional Dairy Beverages:

Fermentation-based milks allow creation of highly functional dairy analog beverages tailored to specific dietary needs. One example is sports and recovery drinks. Traditional whey protein shakes are popular among athletes; now, companies can offer an "animal-free" whey shake that provides the same muscle-building benefits**(Millward, 2023)**.

Such protein supplements can be mixed into water or plant milk to make a potent post-workout beverage. Furthermore, fortified milks can be enhanced with functional additives like omega-3 oils, vitamins, or prebiotics. This transforms milk into a platform for delivering additional health benefits.Some startups are exploring adding collagen or gelatin (also fermentation-derived) into dairy beverages for enhanced joint or skin health properties **(Liu *et al.*, 2024).**

Fermented Milk Snacks and Desserts

The solid and semi-solid dairy alternative category is also evolving with fermentation-based milks. Cheeses are a prime target—not just standard cheese like mozzarella, but also snackable formats**(Pimentel *et al.*, 2021).**

Since fermentation-derived casein can undergo normal cheese aging, snack products like cheese cubes, crisps, or spreads become feasible.Yogurt-based snacks are emerging too—freeze-dried animal-free yogurt bites could deliver probiotics and protein in a shelf-stable, candy-like format**(Millward, 2023).**

Future novel concepts include panna cotta or puddings made from fermentation-derived casein and gelatinanalogs—potentially enhanced with functional ingredients like melatonin to create a sleep-aid dessert **(Marco *et al.*, 2022).**

Infant Formula and Baby Foods

Precision fermentation is enabling new infant nutrition products by producing human milk proteins like α-lactalbumin and lactoferrin. This could dramatically improve infant formula, bringing it closer to the composition of human breast milk, and supporting better immunity and gut development in infants.Startups like TurtleTree are working on scaling the production of human lactoferrin via precision fermentation **(Lönnerdal*et al*., 2018).**

Culinary Ingredients

Fermentation-based milks are spawning new culinary ingredients. For example, chefs can use animal-free cream bases, fermentation-derived butter analogs, and vegan cheese curds to create innovative dishes. Dressings like Caesar could now use precision fermentation-derived parmesan for authentic flavor without anchovies or egg **(Mahomoodally*et al*., 2010).**

CONCLUSION

Fermentation-based milks represent a paradigm shift in how we can produce and enjoy dairy-equivalent products. By leveraging the tools of biotechnology, we are now able to brew milk proteins with precision and drastically lower environmental impact, ushering in a new era of sustainable dairy.

This comprehensive review has highlighted the origin of fermented milk products from ancient traditions to modern precision fermentation techniques, and delved into the specific categories of whey protein-based, casein-based, and hybrid milks. Each type offers unique advantages: whey-based milks provide high-quality protein and versatility in beverages; casein-based milks enable the creation of authentic cheeses and fermented foods; and hybrid milks combine components to achieve an all-purpose analogue to cow's milk.

Scientifically, the rationale for these innovations is compelling—they promise to meet nutritional needs in a way that aligns with pressing environmental and ethical considerations. Commercially, there is growing momentum as companies refine extraction processes for fermentative milk protein production and overcome initial challenges in cost and scale.

The merits of fermentation-based milks are substantial: nutritionally complete proteins, absence of lactose and cholesterol, identical functionality to dairy (allowing for one-to-one substitution in recipes), and a dramatically smaller carbon and resource footprint. These milks can truly claim to offer everything consumers love about conventional milk—the creamy taste, the froth in a cappuccino, the protein punch—but "nothing they don't".

At the same time, we have candidly examined the demerits and areas needing further work: ensuring cost-effectiveness, educating consumers to dispel misconceptions about lab-grown foods, addressing allergenicity, and enriching these products to fully match the complexity of cow's milk.

Notably, blending strategies and hybrid formulations are already mitigating some shortcomings by marrying the best of different worlds—fermented dairy proteins with plant bases, and multiple proteins together to achieve broad functionality.Perhaps most exciting is the wave of innovation these fermentation-based milks have unleashed. We are witnessing the development of dairy foods that were once thought impossible without cows—from vegan cheeses that stretch and melt, to probiotic yogurts and rich ice creams that are indistinguishable from their dairy counterparts.

The technology has opened the door for creative product development, some of which we are only beginning to explore. In the coming years, as research continues and production capacity expands, fermentation-based milks are expected to move from novelty to a mainstay in the global diet.They offer a viable path to decouple dairy production from animal agriculture, making the food system more resilient and sustainable. In future perspectives, large fermentation facilities might co-exist with traditional dairies, supplying ingredients for a variety of foods.

In conclusion, fermentation-based milks, especially those centered on whey proteins, caseins, and their combinations, have demonstrated immense potential to transform the dairy landscape. As research and development forge ahead, fermentation-based milks are poised to become a cornerstone of a more sustainable and inventive food future—one where we can enjoy all the richness of dairy, with the power of fermentation doing the work of the cow.

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