CELL-CULTURED MILK AS AN ALTERNATIVE DAIRY SOURCE

(Opportunities and Challenges)

Tanya Tripathi[1], Anshika[2] and Deepshikha Thakur[3]

Amity Institute of Organic Agriculture

Amity University Noida, Uttar Pradesh - 201301

Corresponding author: *tanya.tripathi@s.amity.edu*

https://doie.org/10.10346/AE.2025436553

ABSTRACT

The global dairy industry is at a crossroads, facing growing scrutiny over its environmental footprint, ethical concerns regarding animal welfare, and increasing demand for healthier, more sustainable food alternatives. In this evolving landscape, cell-cultured milk—also known as lab-grown or animal-free milk—has emerged as a groundbreaking innovation within the field of alternative dairy. Unlike plant-based substitutes, cell-cultured milk is produced using precision fermentation and biotechnology to replicate the molecular structure of conventional dairy, including key proteins such as casein and whey. This technology offers the potential to deliver products that closely mimic the taste, texture, and nutritional profile of traditional milk, while significantly reducing greenhouse gas emissions, land use, and water consumption. This review paper explores the scientific principles underpinning cell-cultured milk production and provides a comprehensive analysis of its opportunities, including enhanced food safety, ethical production methods, and the ability to tailor nutritional content. It also delves into the major challenges that could hinder its mainstream adoption, such as scalability issues, high production costs, regulatory uncertainty, and consumer skepticism. Furthermore, the paper compares cell-cultured milk with conventional dairy and plant-based alternatives across nutritional, environmental, and economic parameters. As the technology rapidly advances, the review emphasizes the need for multidisciplinary collaboration across science, policy, and industry to address existing barriers and unlock the full potential of cell-cultured milk as a viable, sustainable alternative dairy source for the future.

Keywords: Cell-cultured milk; alternative dairy; precision fermentation; cellular agriculture; dairy innovation

INTRODUCTION

Milk and dairy products have been fundamental to human nutrition and culture for centuries, offering a valuable source of proteins, calcium, vitamins, and other vital nutrients. Nevertheless, the traditional dairy industry is facing growing criticism because of its environmental footprint, concerns over animal welfare, and challenges related to sustainability. Livestock farming, particularly cattle rearing, contributes significantly to greenhouse gas emissions, land degradation, and water usage, making the sector one of the major contributors to climate change. Additionally, issues such as antibiotic overuse, zoonotic disease risks, and ethical concerns surrounding animal exploitation have intensified the search for innovative and sustainable alternatives to traditional dairy production (Guardian 2024).

Cellular agriculture is an emerging process proposed for food production without animal involvement. Although milk production through cellular agriculture is in the initial phase and presents many technical challenges, its production is promising and has attracted key players in the dairy sector. This review highlighted two types of lab-grown milk production: production using mammary cells and precision fermentation using specific microbial hosts. There are still few scientific articles that address milk production through cellular agriculture. Studies have focused on obtaining milk proteins that can be combined with other constituents, such as water, oils, and carbohydrates, to create products that simulate milk's nutritional and functional properties. Patent applications from dairy industries and startups describing methods for obtaining lab-grown milk include genetic manipulation, selection of microorganisms, culture medium for growth of microorganisms or mammary cells, growth factors, and engineering of bioreactors used in milk production and/or constituents. Challenges related to optimal nutritional profile, costs and regulatory issues must be addressed in the coming years (Guzmán et.al., 2023).

Cellular agriculture is an emerging sustainable production method that enables the creation of products like meat, milk components, and egg proteins through cell culture systems. Currently, several companies are exploring the use of fermentation-based and animal cell culture technologies to develop cell-cultured milk components. However, high research, development, and production costs pose significant barriers. As a result, this section discusses the technical advancements and economic feasibility in the field of cell culture-based dairy (Kwon et al., 2024). In light of these challenges, the global food technology industry has seen a rapid rise in the development of alternative dairy products. Although plant-based milk options—such as almond, soy, oat, and rice milk—have become popular among consumers seeking healthier and more sustainable choices, they often fail to fully replicate the taste, texture, and nutritional value of traditional cow's milk. This has led to increasing interest in advanced solutions that can closely mimic real dairy without involving animals (Sethi et al., 2016).

This review aims to present a comprehensive analysis of cell-cultured milk as a novel alternative dairy source, highlighting both its opportunities and challenges. By exploring the scientific principles behind its production, its potential impacts on sustainability and public health, and the obstacles it faces in achieving mainstream acceptance, this paper seeks to provide critical insights into the future of dairy and the evolving landscape of food innovation (Kwon et al.,2024).

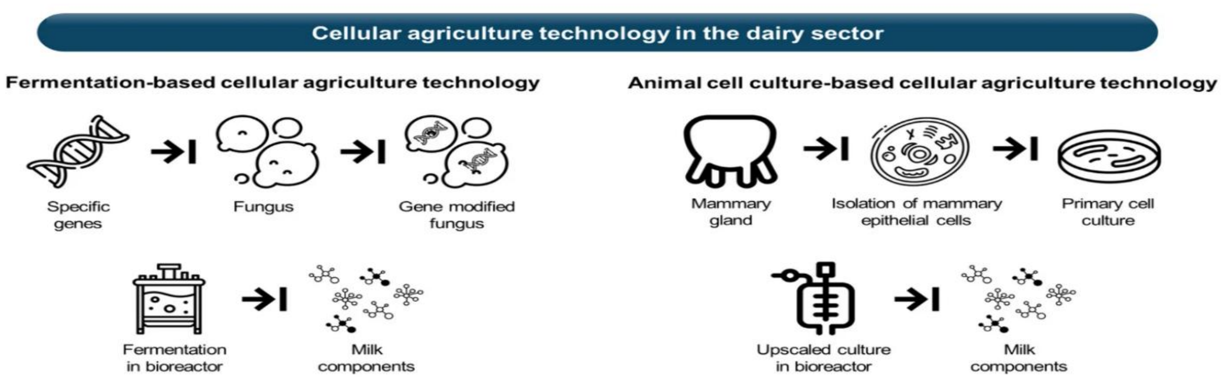

Figure 1: Cell-Cultured Technology in the Dairy Industry

Source: *Journal of Animal Science and Biotechnology, Current Status and Challenges for Cell-Cultured Milk Technology, 2024*

UNDERSTANDING THE CELL-CULTURED MILK

Cell-cultured milk is not derived from cows or any other farmed animals. Instead, it is produced through biotechnological processes in controlled laboratory environments. The key goal is to manufacture dairy proteins—particularly casein and whey, which are responsible for the structural and functional properties of milk—without involving animals in the process. The production of these proteins is made possible by inserting the DNA sequences responsible for milk protein synthesis into microorganisms (such as yeast, fungi, or bacteria). These genetically modified microbes are then cultivated in bioreactors, where they ferment sugars and produce milk proteins in a process analogous to brewing beer. "This biotechnology involves a fermentation process that involves injecting specific genes into microorganisms like bacteria or yeast to create cultured cells under a controlled environment. The cultured cells are grown to produce proteins and fats that mimic traditional animal milk without the traditional methods," explained Wendy Johnson, the director of safety and corporate compliance for Nelson-Jameson, one of the leading distributors in the food and beverage processing industry (Willow et al., 2023).

Gene Identification and Insertion

Scientists identify and isolate the genes responsible for producing casein and whey proteins in cows. Genetic engineering methods are employed to incorporate these genes into microbial hosts. In dairy cattle, several traits influence production efficiency, including calving traits, milk production traits, and longevity traits (Weller et al., 2013). Of these, milk production traits are the most economically significant in dairy breeding, comprising milk yield, fat yield, protein yield, as well as fat and protein percentages (Spellman et al., 1999). Since the introduction and application of genomic selection (GS) in China in 2012, the genetic improvement of Chinese Holstein cows has advanced considerably.

Production Process

The typical production of cell-cultured milk involves several stages. Here is the schematic diagram of the production process of the cell-cultured milk:

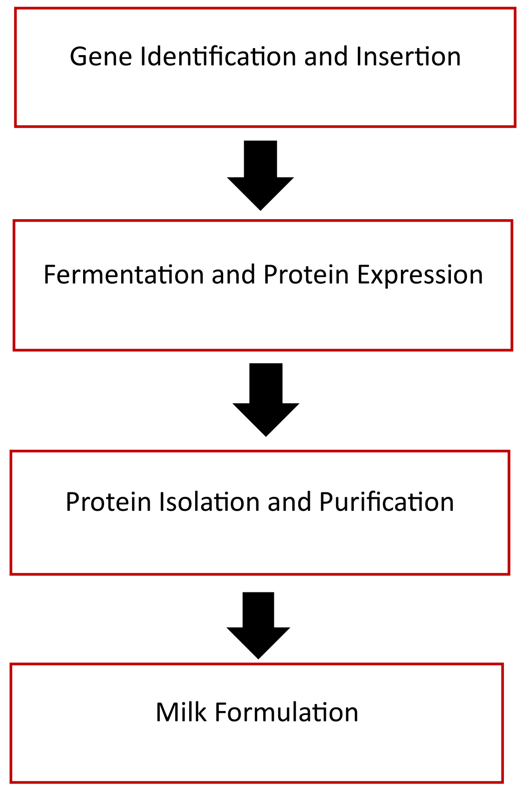

Figure 2: Production Process of Cell-Cultured Milk

Studies suggest that incorporating functional genes with strong genetic effects on target traits into single-nucleotide polymorphism (SNP) marker datasets can significantly increase the accuracy of genomic estimated breeding value (GEBV) predictions (Zhang et al., 2014; Zhang et al., 2015; de Las Heras-Saldana et al., 2020).

Fermentation and Protein Expression

The modified microbes are cultivated in fermentation tanks, where they consume a feedstock (commonly sugar) and begin producing the milk proteins as they grow. Milk protein expression by microorganisms has made great progress. The three production hosts most frequently utilized are E. coli, Saccharomyces cerevisiae, and K. phaffii. Examples such as caseins and two types of whey proteins (α-lactalbumin and β-lactoglobulin) illustrate the advancements made in the bioproduction of milk proteins (Li et al., 2023).

Protein Isolation and Purification

The expressed proteins are separated from the microbial cells and purified to remove impurities or allergens, resulting in food-grade ingredients. Proteins can be sourced from a diverse range of samples. For diagnostic applications, they are typically extracted from a patient's cells or tissues, while for experimental laboratory use, proteins may be derived from microorganisms or from cell lines originating from insects, vertebrates, or plants. To ensure reliable analytical results, proteins must be purified to achieve a high signal-to-noise ratio. Various methods exist for isolating target proteins from complex mixtures, with chromatography being the most common approach for preparation-grade purification. Protein purification can involve one or more of the following chromatographic techniques, used individually or in combination: hydrophobic interaction chromatography, size exclusion chromatography, ion exchange chromatography, and affinity chromatography (Buettner et al., 2023).

Milk Formulation

Cellular agriculture based on animal cell and tissue culture utilizes tissue engineering to create functional tissues from a small number of cells or cell lines derived from living animals. Milk components like casein, whey protein, and tri-glycerides are mainly produced and secreted by the epithelial cells (ECs) of the mammary gland [34, 35]. Therefore, the initial step in the in vitro production of cell-cultured milk components involves obtaining these ECs. Companies such as BIOMILQ and Wilk extract ECs from the milk-producing parenchymal tissue of the mammary gland. The purified proteins are blended with plant-based fats (like coconut oil or sunflower oil), carbohydrates (like glucose or lactose), vitamins, and minerals to form a liquid product that closely resembles cow's milk in taste, appearance, and nutrition (Ishikawa et al., 2024).

Industry Pioneers

Several biotechnology companies are at the forefront of developing and commercializing cell-cultured milk:

- **Perfect Day** (USA): One of the pioneers in precision fermentation-based dairy proteins, already offering animal-free whey protein used in ice cream, cream cheese, and protein powders (Perfect Day, 2025).
- **Turtle Tree** (Singapore/USA): Focuses on cell-based production of lactoferrin and human milk components (Turtle Tree, 2021).
- **Senara:** This startup is based in Germany and is developing cell-cultured milk with the goal of becoming a mainstream option in supermarkets. They are actively collaborating with universities and food technology companies.

OPPORTUNITIES IN CELL-CULTURED MILK

The emergence of cell-cultured milk presents a wide range of opportunities across environmental, ethical, nutritional, economic, and technological dimensions. As a novel approach within alternative dairy, it has the potential to revolutionize how dairy products are produced, consumed, and perceived globally. Cellular agriculture is an eco-friendly production technology that generates products like meat components, milk components, and egg proteins through cell culture systems. Several companies are actively working to produce cell-cultured milk components using both fermentation-based methods and animal cell culture technologies. Nonetheless, the high costs associated with research, development, and production continue to pose significant challenges (Ishikawa et al., 2024). Below are the key opportunity areas:

Environmental Sustainability

One of the most compelling drivers of cell-cultured milk is its potential to significantly reduce the environmental impact associated with traditional dairy farming. Compared to conventional dairy:

- It emits fewer greenhouse gases (notably methane from cows).
- Requires less land and water, preserving ecosystems and biodiversity.
- Generates less manure and agricultural runoff, reducing pollution.

Early life cycle assessments suggest that precision fermentation-based dairy could cut carbon emissions by up to 90% and water usage by up to 95% when compared to industrial dairy operations (Perfect Day, 2021).

Ethical and Animal Welfare Benefits

Cell-cultured milk is animal-free, meaning:

- It eliminates the need for animal husbandry, factory farming, and related ethical concerns.
- Reduces the exploitation and suffering of dairy cows, including issues like forced impregnation and early calf separation.
- Offers a compassionate solution aligned with vegan and animal rights values.

For consumers seeking cruelty-free options, cell-cultured milk offers a genuine dairy experience without ethical compromise (Green Queen, 2023).

Food Safety and Hygiene

Because it is produced in a controlled lab environment, cell-cultured milk:

- Reduces the risk of pathogen contamination (e.g., *E. coli, listeria*).
- Offers traceability and consistency in quality.
- Avoids the use of antibiotics, mitigating the risk of antibiotic resistance—an emerging global health crisis.

This has important implications for public health and global food security.

Furthermore, this technology enables the development of new categories of dairy products that aren't possible with conventional milk, fueling food innovation in the culinary and health sectors (Ishikawa et al., 2024).

Table 1: Comparison of Traditional Dairy, Plant-Based and Cell-Cultured Milk

Aspect	Traditional Dairy Milk	Plant-Based Milk	Cell-Cultured Milk
Source	Cows (animal-derived)	Plants (soy, almond, oat, etc.)	Microbial fermentation of milk protiens
Protein Type	Contains lactose	Usually lactose-free	Can be made lactose-free (can
Cholestorol & Saturated Fat	Present	Generally low	Nutritionally equiv-alent to dairy, milk
Taste & Texture	Complete protein, high in calcium, vitamin, vituns	Very similar	Very similar to real dairy milk
Environmental Impact	High GHG emissions, water, and land use	No anmils involved	No animals involved
Animal Welfare	Involves animal farming	No animals invol-	No animals involved
Food Safety	Risk of pathogens	Generally safe	Emerging market acceptance depends on'
Consumer Acceptance	Widely accepted	Widely available	High potential to replicate dairy
Use in Dairy Products	Suitable for infrastructure	Scalable depending on crop –sill developing	High potential to replicate dairy funtionity

that must be addressed before it can achieve mainstream adoption and market success. These challenges span across technological, economic, regulatory, and social domains. The mammary gland functions as a complex bioreactor, consisting of alveolar structures made up of multiple cell types. One of the major technical challenges in producing cell-cultured milk is replicating the architecture of the milk-secreting mammary gland and reconstructing it in an in vitro setting. The production of cell-cultured milk involves intricate processes, including cellular structural interactions and the regulation of hormones responsible for milk synthesis (Ishikawa et al., 2024).

High Production Costs

One of the most significant barriers to commercial viability is the high cost of production. Producing milk proteins via precision fermentation currently requires expensive bioreactor infrastructure, genetic engineering tools, and nutrient-rich feedstock for microbial growth.

- While companies like Perfect Day have made progress in lowering costs, their products remain more expensive than traditional milk and many plant-based options.
- Achieving economies of scale through industrial optimization and improved fermentation efficiency is essential for affordability (Southey et al., 2022).

Consumer Acceptance and Perception

Even with scientific advancements, public skepticism remains a hurdle:

- Consumers may view lab-grown products as “unnatural” or “synthetic.”
- Misinformation and lack of awareness can fuel resistance or fear, especially regarding GMOs or “bioengineered” foods.
- Cultural preferences, traditions, and emotional attachment to conventional dairy can influence market reception.

Building trust will require transparent communication, educational campaigns, and positive brand messaging around sustainability and safety (NIZO, 2021).

Market Competition and Positioning

Cell-cultured milk must compete with both:

- **Traditional dairy:** which remains cheaper and deeply rooted in the global food system.
- **Plant-based alternatives:** which are already widely available, affordable, and accepted by consumers.

Positioning cell-cultured milk as a premium, sustainable, and ethical alternative—while proving its value—will be essential for long-term success (Ishikawa et al., 2024).

CONSUMER PERCEPTION AND MARKET TRENDS

Consumer perception plays a crucial role in the success of cell-cultured milk.

- ***Awareness Gap**:* Many consumers are unaware of the technology or confuse it with synthetic or unsafe methods.
- ***Acceptance Factors**:*
  - ➢ Trust in science and food safety
  - ➢ Belief in ethical and environmental benefits
  - ➢ Positive branding and transparent communication
- ***Label Sensitivity**:* Words like "lab-grown" or "bioengineered" may deter buyers; terms like “animal-free dairy” or “sustainable milk” are more acceptable.

- **Market Trends**:
  - Younger, environmentally conscious consumers are more open to trying new food tech.
  - Growing demand for climate-friendly and ethical alternatives is pushing food companies to innovate (Kwon et al., 2024).

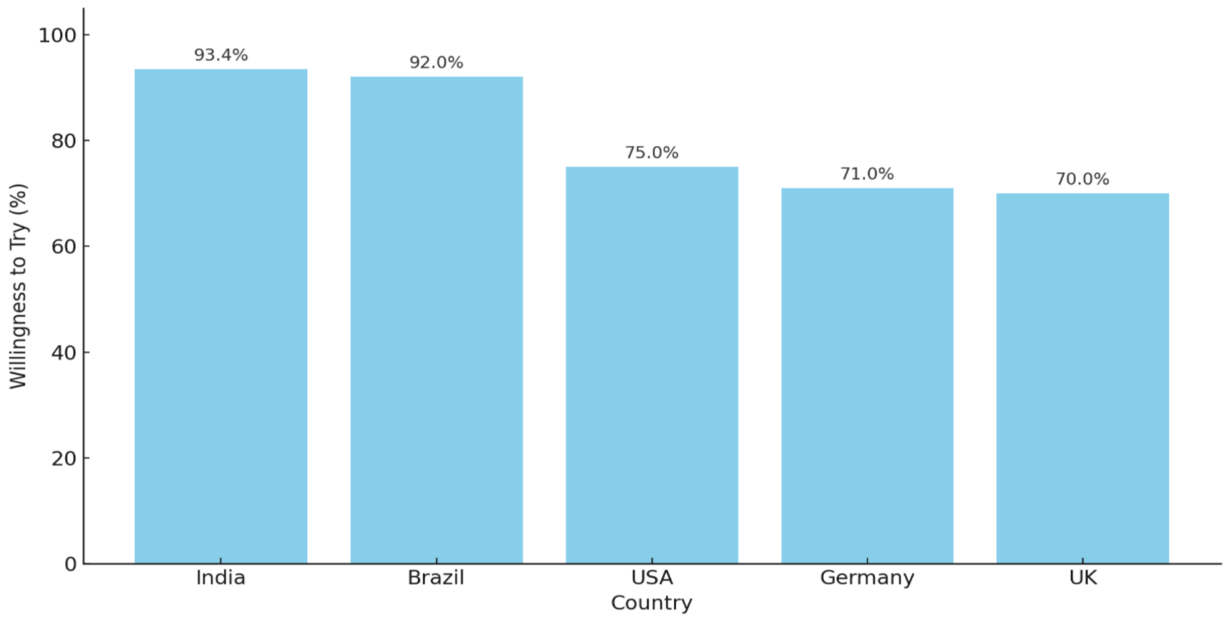

Figure 3: Consumer Willingness to Try Cell-Cultured Dairy Products by Country

CONCLUSION

Cell-cultured milk represents a transformative innovation in the search for sustainable, ethical, and nutritionally equivalent alternatives to conventional dairy. By leveraging precision fermentation to produce real milk proteins without the use of animals, this emerging technology addresses some of the most pressing challenges associated with traditional dairy production, including greenhouse gas emissions, animal welfare concerns, and resource consumption. Cellular agriculture presents numerous opportunities for the sustainable production of agricultural goods. The initial products and those currently in development primarily target Western markets. Both plant and animal cell and tissue cultures serve as key production systems. Notably, cellular agriculture utilizing plant cell and tissue cultures has already led to the commercialization of various products (Eibl et al., 2021).

Despite its immense potential, cell-cultured milk faces significant hurdles that must be overcome for widespread adoption. High production costs, regulatory ambiguity, scalability issues, and consumer skepticism remain central challenges. However, ongoing scientific advancements, increased investment, and growing public awareness are steadily paving the way toward commercialization and acceptance.

As global demand for dairy alternatives continues to rise, cell-cultured milk has the potential not only to complement but also to redefine the future of dairy. With interdisciplinary collaboration among researchers, regulators, industry stakeholders, and consumers, cell-cultured milk could become a key pillar of a more resilient, inclusive, and environmentally conscious food system (George et al., 2023).

REFERENCES

Cornall, J. (2021, June 7). TurtleTree set to commercialize human lactoferrin as its first major product. Dairy Reporter. https://www.dairyreporter.com/Article/2021/06/07/TurtleTree-set-to commercialize-human-lactoferrin-as-first-major-product/https:/

Di Cagno, R., De Angelis, M., & Gobbetti, M. (2017). Fermented foods and beverages: An overview. Frontiers in Microbiology, 8, Article 1234. https://doi.org/10.3389/fmicb.2017.01234

Eibl, R., Senn, Y., Gubser, G., Jossen, V., van den Bos, C., & Eibl, D. (2021). Cellular agriculture: Opportunities and challenges. Annual Review of Food Science and Technology, 12, 51–73. https://doi.org/10.1146/annurev-food-063020-123940

Floris, R. (2021, November 22). Precision fermentation – making the case for animal protein without the animal. NIZO. https://www.nizo.com/blog/precision fermentation-making-the-case-for-animal-protein-without-the-animal/

George, A. S. (2023). The promises and challenges of cell-based dairy: Assessing the viability of lab-grown milk as a sustainable alternative. PUIRJ, 5(2), 218–230.https://doi.org/10.5281/zenodo.8372867

Holmes, B. (2022, December 22). Getting lab-grown meat — and milk — to the table. Knowable Magazine. https://knowablemagazine.org/content/article/food-environment/2022/lab-grown-meat-and-milk

Huang, M., Lv, J., Liang, H., & Yu, H. (2024). Current status and challenges for cell-cultured milk technology: A systematic review. ResearchGate. https://www.researchgate.net/publication381279505_Current_status_and_challenges_for_cellcultured_milk_technology_a_systematic_review

Kothuri, V., & Kwon, H. C. (2023). The promises and challenges of cell-based dairy: Assessing the viability of lab-grown milk as a sustainable alternative. ResearchGate.https://www.researchgate.net/publication/374134102_The_Promises_and_Challenges_of_Cell-Based_Dairy_Assessing_the_Viability_of_LabGrown_Milk_as_a_Sustainable_Alternative

Kwon, H. C., Jung, H. S., Kothuri, V., & Han, S. G. (2024). Current status and challenges for cell-cultured milk technology: A systematic review. Journal of Animal Science and Biotechnology, 15, Article 81. https://doi.org/10.1186/s40104-024-01039-y

Labiotech.eu. (n.d.). Lab-grown dairy: The future of milk without cows. Retrieved May 27, 2025, from https://www.labiotech.eu/in-depth/lab-grown-dairy/

Liu, Y., Wang, X., & Zhang, L. (2024). Milk without animals – A dairy science perspective. Trends in Food Science & Technology, 137, 123–132. https://doi.org/10.1016/j.tifs.2024.01.005 ScienceDirect

Liu, Y., Zhang, Y., & Zhang, X. (2024). Figure 1 from Journal of Animal Science and Biotechnology, 15, Article 39. https://jasbsci.biomedcentral.com/articles/10.1186/s40104-024-01039-y/figures/1

López-García, M., González-Molina, E., & Gutiérrez-López, M. D. (2022). Nutrients, 14(3), Article 456. https://doi.org/10.3390/nu14030456 PMC article: https://pmc.ncbi.nlm.nih.gov/articles/PMC9846039/

Miller, J. A., & Smith, R. T. (2025). Can lab-grown milk be a novel trend in the dairy industry? Critical Reviews in Food Science and Nutrition, 65(4), 567–580. https://doi.org/10.1080/10408398.2025.2471013Taylor & Francis Online

Mridul, A. (2023, September 18). Animal-free milk: What precision fermentation dairy LCAs tell us. Green Queen. https://www.greenqueen.com.hk/environment-sustainable-precision-fermentation-life-cycle-assessment-lca-scientific-research/

Perfect Day. (2021, April 18). The life cycle of our non-animal protein. https://perfectday.com/blog/life-cycle-assessment-of-perfect-day-protein/Perfect Day. (n.d.). Non-animal whey protein made through fermentation - ProFerm™. https://perfectday.com/animal-free-milk-protein/Senara. (n.d.). Home Senara. https://www.senara.bio/

Smith, K. A., & Johnson, L. M. (2021). Dairy 3.0: Cellular agriculture and the future of milk. New Biotechnology, 61, 1–5. https://doi.org/10.1080/15528014.2021.1888411Taylor & Francis Online

Southey, F. (2022, October 6). Precision fermentation dairy: Consumers 'cautiously open' but industry must 'rise to meet consumer expectations'. Food Navigator. https://www.foodnavigator.com/Article/2022/10/06/Precision-fermentation-dairy-Consumers-cautiously-open-but-industry-must-rise-to-meet-consumer-expectations/

Tamang, J. P., & Tamang, B. (2023). Fermented foods and beverages: A review. Food Research International. https://doi.org/10.1016/j.foodres.2023.112456

Zhang, Y., & Chen, H. (2022). Cell-cultivated food production and processing: A review. Food and Bioprocess Technology, 15(3), 456–470.https://doi.org/10.1002/fbe2.12009 Wiley Online Library

Zhou, Y., Liu, X., Wang, J., & Chen, G. (2025). Advances and challenges in the development of cell-cultured milk: A comprehensive review. Critical Reviews in Food Science and Nutrition. https://doi.org/10.1080/10408398.2025.2471013

*****