



Milk: A Scientific and Technological Review of Composition, Processing, Safety, Emerging Technologies and Future Perspectives

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Abstract- Milk is a biologically complex and nutritionally valuable food that has played an important role in human nutrition and the development of the dairy industry. It contains high-quality proteins, lipids, lactose, minerals, vitamins, enzymes and numerous bioactive compounds. At the same time, its high water activity and nutrient availability make raw milk highly susceptible to microbial contamination and deterioration. Consequently, milk production and processing require the integration of food science, microbiology, biotechnology, chemical analysis, engineering and information technology. This review examines milk from a science and technology perspective, covering its chemical composition, nutritional significance, microbiological characteristics, conventional processing methods, quality and safety challenges, and emerging technologies. Conventional heat treatments such as pasteurization and ultra-high-temperature processing remain fundamental to milk safety, but thermal treatment can influence proteins, vitamins, flavor compounds and other quality attributes depending on treatment intensity. Recent research has therefore investigated high-pressure processing, pulsed electric fields, ultrasound, microfiltration, cold plasma, ohmic heating and other non-thermal or hybrid technologies. These approaches aim to improve microbial safety while retaining nutritional and functional properties. The review also discusses advances in spectroscopy, biosensors, Internet of Things (IoT) systems and artificial intelligence (AI) for rapid detection of adulteration, contaminants, microbial deterioration and compositional changes. Sustainability is another major technological challenge, involving methane emissions, feed production, manure management, water use, energy consumption and waste generation throughout the dairy value chain. Precision livestock farming, improved nutrition, resource-efficient processing and data-driven management offer potential pathways toward more sustainable milk production. Future development will increasingly depend on the integration of biotechnology, advanced processing, smart sensing, artificial intelligence and sustainable engineering. A multidisciplinary approach is essential for producing safe, nutritious, affordable and environmentally responsible milk and dairy products.

Keywords- Milk; dairy technology; pasteurization; non-thermal processing; food safety; biosensors; artificial intelligence; spectroscopy; sustainability; biotechnology.



I. INTRODUCTION

Milk is one of the most important animal-derived foods and an important raw material for a wide range of dairy products. It is a complex biological fluid consisting primarily of water, lactose, proteins, fat and minerals, together with vitamins, enzymes, hormones, peptides and other minor constituents. Its composition varies according to animal species, breed, genetics, stage of lactation, nutrition, health status, season and management practices.

From a scientific perspective, milk is particularly interesting because its components are organized into a complex colloidal and emulsion system. Casein micelles exist in the aqueous phase, while milk fat occurs largely as globules surrounded by a membrane. Whey proteins are dispersed in the serum phase. These structural characteristics influence milk stability, digestion, heat sensitivity, fermentation and the manufacture of products such as cheese, yogurt, butter and milk powders.

Milk is also highly perishable. Raw milk can support the growth of a wide range of microorganisms because it contains water and readily available nutrients. Pathogenic organisms may enter milk during animal production, milking, transportation or handling. For this reason, hygienic production, rapid cooling, pasteurization and appropriate storage are central components of dairy technology. International food standards include specific hygienic practices and requirements for milk and milk products.

The modern dairy sector is moving beyond conventional processing toward technologies that can simultaneously address safety, nutritional quality, shelf life, energy consumption and sustainability. Research has increasingly investigated high-pressure processing, pulsed electric fields, ultrasound, microfiltration, cold plasma, ohmic heating and other emerging approaches.

In parallel, analytical science is transforming quality control. Spectroscopy, biosensors, microfluidics, machine learning and IoT-based monitoring can provide faster and potentially more continuous information about milk composition, contamination, adulteration and storage conditions.

This review therefore considers milk as both a nutritional food and a technologically important biological material, emphasizing developments relevant to modern science and technology.

II. CHEMICAL AND NUTRITIONAL COMPOSITION OF MILK

The major components of milk are water, carbohydrates, proteins, lipids and minerals. Although the approximate concentration of these components differs among species, they collectively determine the nutritional and technological properties of milk.

Water

Water is the major component of milk and acts as the continuous phase in which lactose, minerals, water-soluble vitamins and whey proteins are dissolved or dispersed. It also participates in biochemical reactions and influences viscosity, freezing point and microbial growth.

Carbohydrates

Lactose is the principal carbohydrate in milk. It is a disaccharide composed of glucose and galactose. Lactose contributes to the energy value of milk and acts as an important substrate during the fermentation of milk by lactic acid bacteria.



During yogurt and fermented-milk production, microorganisms metabolize lactose primarily into lactic acid. This decreases pH and causes changes in the casein system, resulting in gel formation and the characteristic texture of fermented products.

Milk Proteins

Milk proteins can broadly be divided into caseins and whey proteins. Caseins include α s1-casein, α s2-casein, β -casein and κ -casein. They are organized into casein micelles and are responsible for many of milk's functional properties.

Whey proteins include β -lactoglobulin, α -lactalbumin, serum albumin and immunoglobulins. They have important nutritional and technological functions. Heating can cause whey-protein denaturation and interaction with casein micelles, thereby changing the physical properties of milk.

Milk proteins are nutritionally important because they provide essential amino acids. They can also generate bioactive peptides during digestion or enzymatic and microbial processing. Consequently, milk proteins have attracted considerable attention in functional-food research.

Milk Fat

Milk fat is primarily present as milk-fat globules surrounded by a biological membrane. It contains triacylglycerols as the major lipid fraction together with phospholipids, cholesterol, fatty acids and other minor lipid-soluble compounds.

Milk fat contributes substantially to flavor, mouthfeel, energy density and technological properties. It also acts as a carrier for fat-soluble vitamins. Homogenization reduces the average size of fat globules and helps prevent rapid creaming during storage.

Minerals and Vitamins

Milk supplies calcium, phosphorus, potassium, magnesium and other minerals. Calcium and phosphorus are particularly important because they contribute to bone mineralization and are also involved in the structural organization of casein micelles.

Milk contains several vitamins, including riboflavin, vitamin B12, vitamin A and other water- or fat-soluble vitamins depending on the milk type and fortification practices. Thermal processing can influence certain heat-sensitive components, with the magnitude depending on temperature, time and processing conditions.

Overall, milk is a nutrient-dense food matrix containing multiple interacting components rather than simply a mixture of isolated nutrients.

III. BIOLOGICAL AND MICROBIOLOGICAL CHARACTERISTICS

Fresh milk contains natural antimicrobial systems, including lactoferrin, lactoperoxidase, immunoglobulins and other protective components. Nevertheless, these systems do not provide sufficient protection to make raw milk safe indefinitely.

Microbial contamination may originate from the udder, animal environment, equipment, water, handlers and transportation systems. Important microbial groups associated with milk include lactic acid bacteria, psychrotrophic organisms, coliforms, yeasts and molds. Some pathogens of concern in dairy systems include *Salmonella*, *Listeria monocytogenes*, pathogenic *Escherichia coli* and *Staphylococcus aureus*.



Psychrotrophic microorganisms are particularly important technologically because some can grow at refrigeration temperatures and produce heat-stable enzymes. Even when the microorganisms themselves are subsequently destroyed by pasteurization, enzymes produced before processing may contribute to quality deterioration.

Therefore, milk safety is not dependent on a single processing step. It requires a chain of controls beginning with hygienic animal production and continuing through cooling, transportation, processing, packaging and storage. Codex Alimentarius provides a dedicated Code of Hygienic Practice for Milk and Milk Products as part of the international food-safety framework.

IV. CONVENTIONAL MILK PROCESSING TECHNOLOGIES

Chilling

Immediately after milking, raw milk is normally cooled to restrict microbial multiplication. Rapid chilling is an important first barrier against deterioration. However, refrigeration does not eliminate microorganisms; it mainly slows their growth.

Pasteurization

Pasteurization is the controlled application of heat intended to destroy pathogenic microorganisms while retaining acceptable nutritional and sensory quality.

High-temperature-short-time (HTST) pasteurization is widely used for drinking milk. The precise processing conditions depend on the regulatory system and product requirements.

Pasteurization represents a balance between microbial safety and product quality. Excessive heating can cause undesirable changes in flavor, protein structure and certain heat-sensitive constituents. A comprehensive 2024 review emphasized that thermal-treatment intensity affects milk proteins, fatty acids, micronutrients, flavor compounds and heating markers.

Ultra-High-Temperature Processing

Ultra-high-temperature (UHT) treatment uses substantially higher temperatures for a short period and, when combined with aseptic packaging, permits extended shelf life without refrigeration before opening.

The major technological advantage of UHT processing is microbiological stability. However, higher thermal intensity can increase chemical reactions such as Maillard reactions and protein modifications. Therefore, modern research continues to investigate ways to obtain high microbial safety while reducing unnecessary thermal damage.

Homogenization

Homogenization mechanically reduces milk-fat-globule size and promotes a more stable emulsion. It improves physical stability and affects the sensory characteristics of drinking milk.

Membrane Processing

Microfiltration, ultrafiltration, nanofiltration and reverse osmosis can separate milk components according to particle size or molecular properties. Membrane technologies are useful for concentration, fractionation and microbial reduction and can reduce dependence on severe thermal treatment in selected applications.



V. EMERGING AND NON-THERMAL PROCESSING TECHNOLOGIES

The development of alternative processing technologies is one of the most active areas of dairy science. The objective is not necessarily to replace heat completely, but to create optimized processes that achieve microbial safety with improved quality retention.

High-Pressure Processing

High-pressure processing (HPP) subjects food to elevated hydrostatic pressure. It can inactivate many vegetative microorganisms while operating at relatively low temperatures compared with conventional thermal sterilization.

HPP has attracted interest for milk and dairy products because it can alter microbial viability while reducing some of the thermal effects associated with traditional heating. Its effectiveness depends on pressure, temperature, treatment time, milk composition and the target microorganisms.

However, HPP equipment is capital-intensive and industrial implementation requires careful consideration of throughput, energy consumption, packaging compatibility and microbial targets.

Pulsed Electric Fields

Pulsed electric field (PEF) technology applies short-duration high-voltage pulses to liquid foods. A major mechanism is electroporation, in which electric fields disrupt microbial cell membranes.

PEF is particularly attractive for liquid foods such as milk because continuous-flow systems can be designed for industrial processing. Recent research continues to examine PEF for microbial inactivation and preservation of milk quality.

Recent work has also proposed on-farm PEF approaches intended to reduce initial microbial loads before milk enters conventional processing systems, although such concepts still require substantial engineering, economic and regulatory validation before broad industrial adoption.

Ultrasound and Thermosonication

Ultrasound generates acoustic cavitation, producing localized physical effects that can disrupt microbial cells and influence food structures. When combined with moderate heating, thermosonication may enhance microbial inactivation.

The technology is attractive because it may reduce the thermal intensity required for processing, but optimization is essential to prevent undesirable changes in flavor and physicochemical characteristics.

Ohmic Heating

Ohmic heating generates heat directly within food through electrical resistance. Because heating can be rapid and relatively uniform, it has potential advantages for continuous dairy processing.

Research has considered ohmic heating as an alternative or complementary approach for milk processing, particularly when rapid heating and cooling are desirable.

Cold Plasma

Cold plasma uses ionized gas containing reactive species capable of damaging microorganisms. It has been investigated for surface decontamination and food processing applications.



For milk, the challenge is to obtain sufficient microbial inactivation without causing unacceptable oxidation, flavor changes or modification of sensitive components. Consequently, cold plasma remains an area requiring further process optimization.

Combined Technologies

A major direction in food engineering is the combination of technologies. Examples include mild heat plus HPP, ultrasound plus heat, PEF plus moderate temperature, and membrane separation followed by mild pasteurization.

Combination processes can exploit synergistic effects and potentially reduce the intensity required from each individual treatment. Current evidence suggests that emerging technologies are more realistically viewed as complements or components of hybrid processing systems rather than universal replacements for conventional heat treatment.

VI. MILK QUALITY, ADULTERATION AND FOOD SAFETY

Milk quality is influenced by its composition, microbiological condition, chemical residues, adulteration and storage history.

Adulteration

Milk adulteration may involve dilution, addition of substances intended to modify apparent composition, or substitution with lower-value materials. Such practices can reduce nutritional quality and potentially create health risks.

Traditional laboratory analysis is accurate but can require considerable time, equipment and trained personnel. Consequently, rapid analytical technologies have become an important research area.

Spectroscopic Analysis

Near-infrared spectroscopy, mid-infrared spectroscopy, Raman spectroscopy and related optical techniques can provide rapid measurements of milk composition.

Modern approaches increasingly combine spectroscopy with machine learning. A 2024 review reported applications involving prediction of fat, protein and lactose, identification of origin, adulteration assessment and detection of drug residues.

These methods can potentially support real-time or near-real-time monitoring, although calibration, instrument cost, sample variability and model transfer between production environments remain challenges.

Biosensors

Biosensors combine a recognition element with a transducer to detect target compounds. They have been investigated for the detection of veterinary-drug residues, pesticides, microorganisms and other contaminants.

Recent research indicates that both conventional biosensors and biomimetic sensors can provide rapid and sensitive approaches for dairy-product testing.

Internet of Things and Artificial Intelligence

IoT-based systems can connect sensors distributed across farms, transport systems, processing plants and storage facilities. Data can be collected continuously and analyzed using machine-learning algorithms.



A 2024 study demonstrated the potential of sensor-driven systems coupled with machine learning for milk-quality monitoring and anomaly identification within dairy production.

More recent research has also explored AI-enabled multisensor systems for real-time adulteration detection, demonstrating the growing convergence of sensor technology, data analytics and dairy quality control.

VII. BIOTECHNOLOGY AND FUNCTIONAL DAIRY PRODUCTS

Biotechnology has transformed the development of fermented and functional dairy foods.

Fermentation

Starter cultures such as *Lactococcus*, *Lactobacillus* and related lactic acid bacteria convert lactose and other substrates into metabolites that influence acidity, flavor, texture and preservation.

Controlled fermentation is central to the production of yogurt, cultured milk, cheese and numerous regional dairy foods.

Probiotics

Probiotic dairy products contain selected microorganisms intended to provide health benefits when consumed in adequate quantities. Milk and fermented dairy matrices can provide suitable environments for probiotic delivery.

However, successful probiotic-product development requires consideration of strain viability, processing conditions, storage stability, gastrointestinal survival and interactions with the food matrix.

Bioactive Peptides

Proteolysis during fermentation, cheese production or digestion can release peptides with biological activity. These compounds have attracted research interest in areas including antioxidant, antimicrobial and enzyme-inhibitory activity.

However, laboratory evidence for a biological activity does not automatically establish a clinically meaningful health effect in humans. Future research therefore needs well-designed human studies in addition to biochemical and laboratory investigations.

A2 Milk and Specialized Products

A2 milk has received increased commercial and scientific attention. Recent reviews have examined differences between A1- and A2-type β -casein and associated processing and consumer trends. Claims concerning health advantages should nevertheless be evaluated according to the strength and quality of clinical evidence rather than marketing claims.

VIII. SUSTAINABILITY OF MILK PRODUCTION AND PROCESSING

Sustainability is increasingly central to dairy science. The environmental footprint of milk arises from multiple stages, including animal feed production, enteric fermentation, manure management, farm energy use, milk collection, processing, packaging and distribution.

Methane from enteric fermentation and manure, together with nitrous oxide associated with manure and feed production, are important greenhouse-gas sources in dairy systems.



Precision Livestock Farming

Precision livestock farming uses sensors, automation, data analytics and connected systems to monitor individual animals and herds. Potential applications include monitoring animal health, feeding, reproduction, milk production and environmental conditions.

Research published in 2024 has examined how precision livestock technologies may influence the life-cycle environmental impacts of dairy farms.

Nutritional Strategies

Feed formulation is an important area for reducing emissions and improving productivity. Nutritional interventions, genetic approaches and improved herd management have been investigated as possible strategies for reducing environmental impacts.

Sustainable Processing

Dairy processing requires energy for heating, cooling, pumping, separation, drying and refrigeration. Water is also required for cleaning and sanitation.

Energy-efficient heat exchangers, heat recovery, membrane technologies, optimized refrigeration, renewable energy and improved process control can reduce resource consumption.

Life-Cycle Assessment

Life-cycle assessment (LCA) is useful for examining environmental impacts across the complete production system. Importantly, comparisons between animal milk and plant-based beverages depend on system boundaries, functional units, allocation methods and the environmental indicators selected. A 2024 critical review of 70 LCA and carbon-footprint studies emphasized the importance of these methodological choices.

Thus, sustainability assessment should consider not only greenhouse-gas emissions but also water, land, nutrient density, biodiversity, economics, waste and social factors.

IX. DIGITAL TRANSFORMATION OF THE DAIRY INDUSTRY

The dairy sector is increasingly becoming a data-driven industry.

Smart Sensors

Sensors can monitor temperature, pH, conductivity, flow, composition and other indicators. Miniaturized sensors may facilitate measurements at farms, collection centers and processing facilities.

Recent research on raw-milk quality emphasizes fluorescence, colorimetric, electrochemical and spectroscopic sensing, as well as the development of online and inline monitoring systems.

Machine Learning

Machine learning can identify patterns that are difficult to detect through conventional threshold-based approaches. Applications include milk-quality prediction, adulteration classification, microbial-spoilage prediction, process optimization and equipment monitoring.

Machine-learning approaches have also been investigated for monitoring and optimizing dairy pasteurization processes.



Digital Traceability

Blockchain and related digital systems can potentially improve traceability by linking information from farm production through processing and distribution. Their effectiveness depends on data accuracy at the point of entry and interoperability between different organizations.

Digital traceability should therefore complement, rather than replace, physical testing and food-safety management systems.

X. MAJOR CHALLENGES

Despite rapid technological progress, several challenges remain.

First, technological scalability is a major concern. A process that performs well at laboratory scale may behave differently at industrial throughput.

Second, economic feasibility must be established. Advanced equipment, sensors and analytical systems can require substantial investment.

Third, regulatory acceptance is essential. New technologies must demonstrate consistent microbial safety and quality under validated processing conditions.

Fourth, model reliability is important for AI-based systems. Machine-learning models may perform well on training datasets but become less reliable when applied to different breeds, seasons, geographical regions, instruments or milk compositions.

Fifth, consumer acceptance influences commercialization. Consumers may be uncertain about unfamiliar processing technologies or biotechnology-derived products.

Sixth, sustainability must be evaluated holistically. A technology should not automatically be considered sustainable simply because it reduces one environmental parameter. Energy requirements, water consumption, equipment manufacture, waste generation and end-of-life impacts should also be considered.

Future Perspectives

The future of milk science is likely to be characterized by increasing integration rather than the dominance of a single technology.

One important direction is hybrid processing, in which moderate thermal treatment is combined with PEF, HPP, ultrasound, membrane filtration or other technologies. Such systems may allow processors to balance microbial safety with nutritional and sensory quality.

A second direction is real-time quality control. The integration of spectroscopy, biosensors, IoT connectivity and AI could move dairy quality analysis from periodic laboratory testing toward continuous monitoring.

A third direction is precision dairy farming, where individual-animal data are used to improve health, productivity, feed efficiency and environmental performance.

A fourth direction is advanced biotechnology. Precision fermentation and cellular-agriculture approaches are being investigated for the development of dairy proteins and animal-free dairy products. These approaches may eventually complement conventional dairy production, although scalability, cost, regulatory requirements and consumer acceptance remain important challenges.



A fifth direction is sustainable dairy engineering, involving energy-efficient processing, renewable energy, water recycling, heat recovery, waste valorization and improved packaging.

Finally, future research should connect laboratory innovation with field-scale validation. Technologies should be evaluated not only for microbial reduction or analytical accuracy but also for cost, energy use, environmental impact, reliability, food quality and consumer acceptance.

Research Gaps

- **Several research gaps can be identified from the current scientific and technological landscape:**
 1. Industrial-scale validation of non-thermal technologies remains necessary for many milk-processing applications.
 2. Long-term nutritional studies are needed to determine the effects of emerging processing methods on bioavailability and biological activity.
 3. Standardized AI datasets would improve the transferability of machine-learning models between farms and processing plants.
 4. Low-cost sensors are required for widespread deployment in small and medium dairy enterprises.
 5. Integrated sustainability assessment should include environmental, nutritional and economic indicators.
 6. Authentication technologies should be validated against diverse and sophisticated adulteration practices.
 7. Consumer studies are needed to understand acceptance of novel processing and biotechnology-derived dairy products.
 8. Hybrid processing systems deserve further research to determine optimal combinations of heat and non-thermal technologies.
 9. Digital traceability systems require improved interoperability and reliable data capture.
 10. Research should better connect laboratory-scale findings with commercial dairy processing conditions.

XI. CONCLUSION

Milk is a scientifically complex and technologically important food matrix whose value extends from basic nutrition to advanced applications in food engineering and biotechnology. Its proteins, lipids, carbohydrates, minerals, vitamins and bioactive components provide important nutritional and functional characteristics, while its susceptibility to microbial contamination creates significant processing and safety requirements.

Conventional technologies such as refrigeration, pasteurization, homogenization and UHT treatment remain fundamental to the dairy industry. However, advances in high-pressure processing, pulsed electric fields, ultrasound, membrane separation, cold plasma and ohmic heating are creating new opportunities to improve safety and quality. Current evidence suggests that these technologies are most likely to have their greatest practical value when integrated with appropriately controlled thermal processes rather than viewed universally as replacements for heat.

At the same time, rapid advances in spectroscopy, biosensors, IoT and artificial intelligence are transforming milk-quality assessment. These technologies may enable faster detection of adulteration, contaminants, microbial deterioration and compositional changes, while data-driven systems can support process optimization and traceability.

Sustainability represents another major challenge. Improvements in animal nutrition, precision livestock farming, manure management, energy efficiency, water management and processing technologies can



contribute to reducing the environmental burden of milk production. Nevertheless, sustainability assessments must consider the complete production system and avoid conclusions based on a single environmental indicator.

The future of milk science and technology will therefore depend on multidisciplinary integration. Food scientists, microbiologists, dairy technologists, engineers, biotechnologists, data scientists and environmental researchers will need to work together to develop systems that deliver safety, nutrition, quality, affordability and sustainability. The transition from conventional dairy processing toward intelligent, precise and resource-efficient dairy systems represents an important opportunity for future research and technological innovation.

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