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# Modernization of Traditional Milk Product Processing: Emerging Technologies and Industrial Applications

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## Abstract

Traditional milk products like khoa, paneer, ghee, dahi and shrikhand form the core value-added segment of the indigenous dairy sector, driving rural economies and food security. However, traditional artisanal methods are limited by high energy consumption, manual labor traps, quality inconsistencies and short ambient shelf lives. This comprehensive review synthesizes structural modernization pathways shifting the sector into the Dairy 4.0 paradigm. We critically analyze advanced processing technologies including pressure-driven membrane operations (Reverse Osmosis, Ultrafiltration), non-thermal physical barriers (High-Pressure Processing) and automated closed-loop systems (SCADA, PLC) alongside smart indicators and active packaging models. Sustainable solutions for waste utilization, such as whey valorization into protein powder and anaerobic biogas production, are detailed alongside machine learning algorithms for predictive texture grading. This paper maps out standard configurations to resolve commercial processing bottlenecks, establishing scalable manufacturing protocols that preserve traditional ethnic profiles while satisfying international quality and export compliance frameworks.

**Keywords:** Traditional dairy products, Dairy 4.0, Membrane processing, High-pressure processing, Smart packaging, Sustainability.

## 1. Introduction

Milk serves as a foundational component of global agricultural and nutritional sectors due to its highly balanced profile of essential amino acids, functional lipids, bioavailable minerals and water-soluble vitamins. In India, the world's leading milk producer, annual yields exceeded 239 million tonnes during 2023–24, representing approximately one-fourth of the global supply and significantly supporting rural household dynamics. Distinct from Western processing streams centered on standardized table butter and block cheeses, nearly half of the domestic milk volume is converted into traditional dairy products (e.g., khoa, paneer, ghee, shrikhand and rabri) via indigenous desiccation, concentration, coagulation and clarification procedures. These ethnic varieties act as excellent high-yield vehicles for economic returns, turning highly perishable raw milk components into premium consumer commodities. Despite their profound socio-economic impacts, traditional dairy operations face persistent structural constraints.

Artisanal methods typically deploy open-pan heating configurations and manual batch mixing with empirical end-point checks. This lack of rigorous standardization introduces wide variations in spatial texture, moisture content and chemical stability, which compromises large-scale distribution. Furthermore, nutrient-dense matrices with elevated initial water activities face extreme risks of post-pasteurization microbial contamination, leading to localized fermentation or surface mold defects. Short ambient shelf lives restrict commercial supply chains and stall entry into competitive international trade networks. Addressing these limitations mandates transitioning toward the Dairy 4.0 paradigm, integrating mechanized unit operations, digital process tracking and resource-efficient conservation loops to build a sustainable and globally compliant ethnic dairy industry.

## 2. Traditional Milk Products and Industrial Importance

Traditional dairy foods represent an optimized cultural framework designed to stabilize milk fractions through accessible processing techniques. Thermally desiccated products like khoa act as structural matrices for downstream confectionery configurations, whereas acid-coagulated varieties like paneer entrap casein and milk fat lattices into high-density protein blocks. Cultured products capitalize on controlled lactic acid bacterial pathways to create thick, digestible gel structures, while ghee clarification concentrates pure lipids, extending storage stability without refrigeration. Economically, these products provide value addition ranging from 2 to 10 times the margin of raw liquid milk, generating daily income for micro-entrepreneurs and cooperatives [1], [2].

The rising consumer demand for functional ethnic foods has driven organized dairy processors to invest heavily in industrialized manufacturing lines. However, to access international export pipelines, processors must strictly align with global food safety regulations, including FSSAI and Codex Alimentarius guidelines. This requirement introduces technical hurdles for traditional processing plants, requiring the elimination of open-pan volatile losses, manual contact loops and non-hermetic packaging lines. Bridging this gap requires integrating contemporary chemical engineering and automation into traditional manufacturing protocols.

## 3. Advances in Khoa Technology

Khoa is traditionally processed by boiling milk in open iron pans under atmospheric pressure, a method characterized by low thermal efficiency, prolonged exposure to heat and localized scorching. To standardize manufacturing, continuous Scraped Surface Heat Exchangers (SSHE) have been widely adopted. In an SSHE line, standardized milk moves inside a heated jacketed cylinder while rotating polytetrafluoroethylene (PTFE) blades continuously scrape the inner surface. This high scraping frequency increases convective heat transfer coefficients, avoids product browning variations and converts fluid inputs into uniform semi-solid masses continuously.

Pre-concentration via pressure-driven membrane loops further optimizes process efficiency. Integrating Reverse Osmosis (RO) or Ultrafiltration (UF) as a cold pre-treatment step isolates up to 25-30% total solids non-thermally. This minimizes downstream steam requirements by up to 50% and reduces thermal denaturation of delicate milk proteins [9], [2]. For premium applications, vacuum evaporation technology removes water under reduced pressure (45–60°C), minimizing Maillard browning and protecting volatile aroma compounds. Post-processing stability is achieved using gas-flush Modified Atmosphere Packaging (MAP) using 30-40% $CO_2$ and 60-70% $N_2$, extending the commercial shelf life of khoa from 3 days to over 25 days under cold storage.

## 4. Advances in Paneer Technology

The mechanical constraint of conventional paneer production involves substantial solid losses specifically whey proteins and fine fat fractions in discharged whey streams, reducing final production yields to 18-20%. Incorporating ultrafiltration membranes into paneer lines effectively resolves this problem. UF filters retain both casein micelles and native whey proteins within a dense retentate matrix, boosting final product yields to 22-25% while decreasing the biochemical oxygen demand (BOD) of plant waste effluent streams. Automated continuous paneer lines replace manual cutting blocks with in-line computerized acid-injection systems and automated horizontal belt compressors, ensuring consistent block slicing behavior and uniform moisture levels [2], [9].

Preservation has also shifted from thermal pasteurization to non-thermal High-Pressure Processing (HPP). Packaged paneer blocks are subjected to hydrostatic pressure tracking from 400 to 600 MPa inside a multi-layered forged steel vessel for 5–10 minutes. This high pressure disrupts non-covalent bonds to selectively inactivate vegetative pathogens and surface yeasts without breaking down structural proteins or changing flavor compounds. HPP extends paneer shelf life to 45 days, providing an absolute clean-label preservation alternative that complies with modern clean-label regulatory directives.

**5. Advances in Ghee Technology**

Ghee processing has evolved from batch boiling kettles into high-capacity continuous clarification systems. In modern continuous lines, raw cream is melted, clarified and filtered in a continuous stream, minimizing heat loss and reducing fuel usage. Vacuum-assisted processing allows moisture to evaporate at lower temperatures under reduced pressure, which prevents lipid auto-oxidation loops and protects natural fat-soluble vitamins (A, D, E and K) from thermal degradation.

Ghee's high market value makes it a target for economic fraud, such as adulteration with cheap vegetable oils or animal fats. Advanced analytical technologies have replaced slow chemical metrics to ensure product authenticity. Fourier Transform Infrared (FTIR) Spectroscopy scans unique lipid absorption curves to flag foreign oils instantly. Gas Chromatography-Mass Spectrometry (GC-MS) detects foreign animal lipids by identifying irregularities in native sterol and fatty acid profiles. Simultaneously, consumer demand has driven the development of value-added functional ghee lines, including formulations fortified with natural antioxidants (e.g., curcumin extracts) or omega-3 fatty acids achieved through target dietary manipulation of cattle feed inputs [7].

**6. Emerging Cold Chain & Fermentation Technologies**

Fermented lines like dahi, lassi and shrikhand have been modernized by replacing wild starter cultures with defined, standardized bacterial strains (e.g., Streptococcus thermophilus and Lactobacillus bulgaricus). This ensures consistent daily acidification profiles. Probiotic and synbiotic dahi variants are increasingly formulated with microencapsulated strains of Lactobacillus acidophilus combined with prebiotic inulin fibers. This combination enhances cell survival during cold-chain distribution and supports gastrointestinal health. To monitor distribution safety, intelligent packaging frameworks utilize Time-Temperature Indicators (TTIs) that change color if the cold chain is broken, along with volatile gas-sensing labels to alert retailers to early microbial spoilage [6].

**7. Sustainability and Waste Valorization**

Modern sustainable dairy processing relies on strict resource recovery and waste minimization strategies. Paneer whey streams are processed using ultrafiltration and spray-drying systems to recover valuable solids and convert them into commercial Whey Protein Concentrate (WPC) powders. High-strength organic wastes are directed to anaerobic digesters to produce methane biogas, which is routed back to fuel plant boilers in a self-sustaining energy loop. Water conservation is maintained via automated multi-stage Cleaning-in-Place (CIP) installations that recover final rinse water to serve as the initial flush for subsequent cleaning cycles, reducing freshwater requirements [4].

**8. Future Prospects and Conclusion**

The transition to Dairy 4.0 will be accelerated by integrating real-time computer vision networks for automated color and structure grading, alongside cloud-connected Internet of Things (IoT) sensor arrays to track in-line pH and density changes. Predictive machine learning models will optimize processing parameters proactively, replacing old reactive testing loops. Key research gaps remain, particularly regarding the economic viability of non-thermal preservation systems for small-scale processors and the development of specialized bio-based packaging films tailored for ethnic products [8].

In conclusion, modernizing traditional dairy processing bridges the gap between indigenous knowledge and contemporary food engineering. Adopting membrane filtration, continuous thermal systems, non-thermal barriers and automated process tracking enable dairy plants to improve product yields, ensure absolute microbiological safety and extend commercial shelf lives. This technical transition provides the standardization and compliance required to expand the market footprint of ethnic dairy products from regional sectors into highly competitive global export spaces.

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