



International Journal of Advanced Chemistry Research

ISSN Print: 2664-6781
 ISSN Online: 2664-679X
 NAAS Rating (2026): 4.77
 IJACR 2026; 8(10): 09-20
www.chemistryjournals.net
 Received: 04-08-2026
 Accepted: 25-09-2026
 Published: 07-10-2026

The names and affiliations of all authors are provided below, following the references.

Camelus dromedarius milk: Composition, techno-functional characteristics, emerging processing and future AI automation

Rushikesh A Kantale¹, Akshay Bind², Saurabh Sharma³, Akash B Mote⁴, Haris Ayoub⁵, Vibha Singh⁶, Kiran Shinde⁷, Aakir Ahmed⁸, Amitava Paul⁹

DOI: <https://www.doi.org/10.33545/26646781.2026.v8.i10a.752>

ABSTRACT

Dromedary camel (*Camelus dromedarius*) milk is increasingly recognized as a valuable livestock-derived food with particular relevance to arid and semi-arid production systems. Beyond its nutritional importance, its distinctive protein organization, fat-globule characteristics, mineral equilibrium and bioactive components confer techno-functional properties that differ substantially from those of bovine milk. These same structural features, however, impose important constraints on conventional dairy processing. This review critically synthesizes the supplied literature on the composition, physicochemical characteristics, techno-functional behaviour and processing constraints of camel milk, with particular emphasis on thermal treatment, fermentation, coagulation, yogurt, cheese and butter manufacture. Although the gross composition of camel milk falls broadly within the nutritional range of other mammalian milks, differences in casein distribution, whey-protein composition, casein-micelle structure, fat-globule characteristics and mineral balance influence heat stability, acidification kinetics, gel formation, rennet action, curd strength, fat separation and product yield. Consequently, processing conditions developed for bovine milk cannot always be directly transferred to camel milk. The available evidence indicates that successful product development requires product-specific optimization that accounts for raw-milk variability, animal and environmental factors, heat history, starter-culture performance, mineral equilibrium, enzyme activity and mechanical processing conditions. An emerging opportunity is the integration of sensor-based monitoring, automated process control, artificial intelligence and data-driven approaches into camel-dairy processing. Such technologies could support real-time monitoring and predictive control of critical processing variables, although camel-milk-specific automation remains an evolving research area rather than an established industrial standard. Future research should therefore integrate molecular characterization, standardized process indicators, pilot-scale validation, digital process monitoring and techno-economic assessment to enable the development of safe, consistent, scalable and commercially viable camel-dairy products.

Keywords: *Camelus dromedarius*, Camel milk, Milk composition, Techno-functional properties, Thermal stability, Fermentation, Yogurt, Cheese, Butter, Processing constraints, Process automation

Introduction

Camels have historically played an important role in food security and rural livelihoods in regions where high ambient temperatures, water scarcity and limited forage availability constrain conventional livestock production. In such environments, camel husbandry represents an adaptive livestock system capable of sustaining food production under conditions that are often unfavourable for other dairy species. Camel milk has traditionally been consumed fresh or following fermentation, whereas large-scale collection, refrigeration and standardized processing have developed more slowly because of infrastructural, technological and geographical limitations. Increasing interest in camel milk is therefore associated not only with its nutritional and functional attributes but also with its potential contribution to resilient livestock and food systems in arid and semi-arid regions (FAO, 2020; Faye, 2016; Konuspayeva *et al.*, 2021) [2, 1, 3].

Two principal domestic camel species are recognized: the one-humped dromedary, *Camelus dromedarius*, and the two-humped Bactrian camel, *Camelus bactrianus*. The supplied literature emphasizes the predominance of dromedaries in global camel populations and their long history of domestication and utilization in arid environments (Ali *et al.*, 2019; Almathen *et al.*, 2016; Burger, 2016; Trinks *et al.*, 2012) [4, 5, 6, 7]. Importantly, camel milk is not a chemically invariant raw material. Its composition and technological behaviour can vary with breed or population, stage of lactation, geographical conditions, feeding regime, water availability, animal health and management practices. Such variability has direct implications for down

Corresponding Author:
Akshay Bind
 Department of Veterinary
 Gynecology, BAIF, Pune,
 Maharashtra, India

stream processing and indicates that camel milk should be considered a dynamic biological raw material rather than a standardized commodity.

From a technological perspective, the central question is therefore not simply how camel milk compares with bovine milk in terms of gross chemical composition, but how its molecular organization governs its behaviour during processing. Camel milk possesses a distinctive protein system characterized by differences in casein distribution and micellar structure, relatively low κ -casein, and the natural absence of β -lactoglobulin. Its fat phase is also characterized by relatively small globules and a distinctive milk-fat-globule membrane. In addition, antimicrobial proteins and differences in mineral equilibrium contribute to its distinctive physicochemical behaviour. Collectively, these characteristics influence protein denaturation, heat stability, acidification, gel formation, rennet coagulation and fat separation, thereby affecting the technological performance of camel milk in fermented and non-fermented dairy products (Al haj *et al.*, 2010; Hailu *et al.*, 2016b; Hinz *et al.*, 2012; Yang *et al.*, 2013) [8, 9, 10, 11].

These compositional and structural differences help explain why technologies developed primarily for bovine milk cannot always be transferred directly to camel milk. The difficulty is particularly evident in products in which protein interactions and phase separation determine final quality. During yogurt manufacture, differences in acidification behaviour and gel development can result in weak or heterogeneous structures. During cheese manufacture, the characteristics of casein micelles, lower relative κ -casein content and altered mineral-protein interactions can contribute to prolonged coagulation, weak curd formation and reduced processing efficiency. Similarly, the distinctive physical and thermal behaviour of camel-milk fat can complicate cream separation, churning and butter formation. Thermal treatment presents another important challenge because the response of camel-milk proteins and indigenous enzymes may differ from that of bovine milk, making direct application of conventional processing indicators potentially inappropriate.

Accordingly, the processing of camel milk should be viewed as an interconnected structure–function–process system. Raw-milk composition determines molecular organization; molecular organization influences the response to thermal, enzymatic, fermentative and mechanical treatments; and these responses ultimately determine product quality, yield and process efficiency. This perspective is particularly important for the development of value-added camel-dairy products because optimization of an individual processing step may not be sufficient when upstream milk variability strongly influences downstream behaviour. An additional emerging dimension is the application of process automation and digital technologies to camel-dairy processing. Advances in sensors, automated process control, Internet of Things connectivity, artificial intelligence and machine learning provide opportunities for continuous monitoring of variables such as temperature, pH, acidity, flow, pressure, fermentation progress and coagulation behaviour. For camel milk, such technologies could be particularly relevant because raw-milk variability and species-specific processing responses may make fixed processing recipes less reliable. Real-time measurements could ultimately be linked with predictive models to support adaptive control of heating, fermentation, coagulation and fat separation. However, camel-milk-specific automation is still an emerging research direction, and its successful implementation will require validated datasets, reliable process indicators and pilot-scale evidence before advanced artificial-intelligence or robotic systems can be considered industrially robust.

The objective of this review is therefore to provide a processing-oriented synthesis of the available evidence on camel milk while retaining the established scientific framework of composition, physicochemical behaviour and techno-functional properties. Particular attention is given to the relationship between milk structure and processing response, including thermal treatment, fermentation and yogurt manufacture, coagulation and cheese production, and butter manufacture. The review further identifies the major technological bottlenecks and considers how sensor-based monitoring, automated control and data-

driven processing could provide future opportunities for improving consistency, reproducibility and scalability. Rather than treating automation as a replacement for established dairy-processing knowledge, the review positions it as an emerging tool that can become effective only when camel-milk-specific structure–function relationships and critical process indicators are adequately understood.

2. Chemical composition of *Camelus dromedarius* milk

2.1 Major constituents

The gross composition of *Camelus dromedarius* milk is broadly comparable to that of bovine milk; however, substantial inter-study variability has been reported in the concentrations of its principal constituents. Water generally accounts for approximately 87–89% of the milk, whereas protein, fat, lactose, minerals, and total solids vary with breed, season, stage of lactation, hydration status, feed availability, animal health, and production environment. Such variability should not necessarily be interpreted as analytical inconsistency, as it can reflect genuine biological and environmental differences among production systems (Konuspayeva *et al.*, 2009; Al haj *et al.*, 2010; Ereifej *et al.*, 2011) [12, 8, 13]. From a processing perspective, this compositional variability represents a major source of uncertainty because changes in protein, mineral, and total-solids concentrations can directly modify thermal stability, fermentation kinetics, coagulation behavior, and product yield.

Protein is one of the most technologically consequential constituents of camel milk. Reported protein concentrations are generally close to 3%, with caseins representing the predominant fraction and whey proteins accounting for the remainder. However, the distribution and structural characteristics of these proteins differ from those of bovine milk. Camel milk contains α -, β -, and κ -caseins, but their relative abundance and molecular organization differ from the bovine system. These differences are particularly important because casein micelles determine acid and rennet coagulation, whereas whey proteins contribute substantially to heat-induced denaturation, aggregation, water binding, and interfacial phenomena (Rafiq *et al.*, 2016; Hinz *et al.*, 2012; Omar *et al.*, 2016) [14, 10, 15].

The comparatively lower abundance of κ -casein is of particular technological significance. κ -Casein contributes to the stabilization of casein micelles and represents a key substrate during enzymatic coagulation. Camel casein micelles have also been reported to be larger than those of bovine milk, although their reported dimensions vary according to analytical technique and experimental conditions (Hailu *et al.*, 2016a; Barłowska *et al.*, 2011) [17, 16]. These structural characteristics provide a mechanistic basis for the prolonged coagulation times and weaker curd formation frequently observed during camel-milk cheese manufacture.

The whey-protein fraction includes α -lactalbumin, serum albumin, lactoferrin, immunoglobulins, and other proteins with biological and protective functions. A notable compositional characteristic is the reported absence of β -lactoglobulin, the major whey protein in bovine milk (El-Agamy, 2009; Omar *et al.*, 2016) [18, 15]. This distinction is relevant to the allergenicity profile and thermal behavior of camel milk, although nutritional or clinical benefits should be interpreted cautiously and restricted to outcomes supported by appropriate experimental or clinical evidence (Arain *et al.*, 2022) [19]. More importantly from a processing perspective, the distinctive whey-protein system contributes to the different response of camel milk to heating and subsequent gel formation.

2.2 Lactose, fat, and total solids

Lactose concentrations reported for camel milk generally range from approximately 3.3 to 5.4%, although substantial variation occurs among geographical regions, seasons, animals, and production systems. Hydration status can further influence the concentration of milk constituents. Under conditions of restricted water availability, changes in water balance can alter the concentration of lactose and minerals

and consequently influence the sensory characteristics of the milk, including perceived saltiness and acidity (Ismaili *et al.*, 2019; Al-Juboori *et al.*, 2013) [21, 20]. Such compositional shifts are technologically relevant because lactose concentration and mineral balance influence fermentation kinetics and acid-induced casein destabilization. Milk fat is similarly variable, with reported concentrations commonly falling within approximately 1.8–4.3%, although wider ranges have been documented depending on sampling and analytical conditions. Beyond total fat content, camel milk possesses a distinctive lipid composition characterized by differences in fatty-acid distribution and triacylglycerol structure relative to bovine milk. In particular, camel milk fat generally contains a greater contribution from long-chain fatty acids and comparatively lower proportions of short-chain fatty acids than several conventional dairy milks (Jilo and Tegegne, 2016; Haddad *et al.*, 2011; Konuspayeva *et al.*, 2008) [23, 22]. These compositional characteristics can influence melting behavior, crystallization, creaming efficiency, churning, and the texture of fat-rich products. Total solids are frequently lower than those of bovine or buffalo milk, although the magnitude of the difference depends strongly on the source and production conditions. Lower solids recovery has direct implications for cheese yield and the structural properties of fermented products. Consequently, concentration technologies such as ultrafiltration may be particularly valuable when the target product requires increased protein density, higher dry-matter recovery, or improved gel strength (Yoganandi *et al.*, 2014; Baig *et al.*, 2022) [25, 24]. Importantly, concentration should be regarded not merely as a yield-enhancement operation but as a means of modifying the physicochemical environment in which subsequent coagulation or fermentation occurs.

2.3 Vitamins, minerals, and bioactive components

Camel milk provides a range of minerals and vitamins, with numerous studies reporting comparatively high vitamin C concentrations relative to bovine milk. Differences have also been reported in selected B-group vitamins and minerals, including sodium, potassium, iron, and copper (Stahl *et al.*, 2006; Sawaya *et al.*, 1984; Mehaia, 1996) [27, 28, 26]. However, these values should not be treated as fixed compositional specifications because micronutrient concentrations are strongly influenced by breed, diet, geographical origin, season, lactation stage, and analytical methodology.

The presence of bioactive and protective proteins, including lactoferrin, lysozyme, immunoglobulins, and lactoperoxidase, is particularly relevant to the technological behavior of camel milk. Their antimicrobial activities may contribute to the comparatively slow development of acidity observed with some starter cultures (Elagamy, 2000; Attia *et al.*, 2001; Berhe *et al.*, 2018) [30, 29, 31]. Thus, characteristics that may provide biological protection can simultaneously create a technological constraint when rapid, reproducible fermentation is required. This duality illustrates a recurring theme in camel-milk processing: a compositional characteristic that is advantageous from a biological perspective may require process adaptation to achieve predictable industrial performance.

3. Physical and techno-functional properties

3.1 Physical characteristics

Fresh camel milk is generally characterized by an opaque white appearance and a mildly salty or slightly acidic sensory profile. Reported pH values commonly fall within approximately 6.2–6.5, while titratable acidity varies with animal, feed, handling, and storage conditions. Freezing-point values have generally been reported in the approximate range of –0.53 to –0.57 °C (Yoganandi *et al.*, 2014; Abd El-Aziz *et al.*, 2022) [25, 32]. These parameters provide useful baseline indicators for raw-milk characterization and process control, but their interpretation should account for the substantial natural variability of camel-milk production systems.

The relatively small fat globules reported in camel milk influence its creaming, emulsification, rheological behavior, and phase separation.

The characteristics of the milk-fat globule membrane may further modify the response to mechanical separation and homogenization (Attia *et al.*, 2000; El-Zeini, 2006) [33, 34]. Consequently, mechanical operations developed for bovine milk cannot necessarily be transferred without adjustment. Parameters such as shear intensity, residence time, homogenization pressure, and separation conditions should instead be optimized against the physical response of camel milk.

3.2 Functional behavior of milk proteins

The techno-functional behavior of milk proteins encompasses solubility, water binding, emulsification, foaming, interfacial adsorption, aggregation, and gel formation. In camel milk, these properties are governed by the composition and structure of the casein micelles, whey-protein profile, mineral equilibrium, pH, temperature, and previous processing history. Recent investigations involving ultrasound and fermentation indicate that physical and biochemical treatments can deliberately modify protein functionality rather than serving solely as preservation operations (Shokri *et al.*, 2022; Gammoh *et al.*, 2020) [36, 35].

The coupling between protein structure and processing conditions is particularly important because relatively small changes in pH, temperature, ionic strength, or mineral balance can alter micellar stability and protein–protein interactions. Accordingly, process development should not be based exclusively on final sensory attributes. Intermediate physicochemical responses—including particle-size distribution, protein solubility, rheological development, water-holding capacity, and protein aggregation—should also be monitored to identify the mechanisms responsible for product performance.

3.3 Why bovine-milk technology cannot simply be transferred

Macronutrient similarity between camel and bovine milk does not imply technological equivalence. Differences in κ -casein abundance, casein-micelle size, whey-protein composition, fat-globule characteristics, mineral equilibrium, and endogenous antimicrobial proteins can collectively alter the response of camel milk to heating, acidification, enzymatic coagulation, creaming, and drying (Al haj *et al.*, 2010; Hailu *et al.*, 2016b; Berhe *et al.*, 2017) [8, 9, 37].

This distinction has a direct implication for industrial process design: camel milk should be treated as a distinct processing matrix rather than as a bovine-milk substitute. A thermal schedule developed for bovine milk may produce different degrees of protein denaturation and aggregation in camel milk. Similarly, a starter culture or rennet selected on the basis of bovine-milk performance may exhibit inadequate acidification or coagulation in camel milk. Therefore, process development should begin with camel-milk response surfaces and kinetic data, followed by optimization of temperature, pH, enzyme concentration, culture dose, solids concentration, and mechanical conditions.

4. Impact of thermal processing

4.1 Thermal stability

Thermal treatment is indispensable for microbial safety and shelf-life extension, but camel milk exhibits a distinct response to heating compared with bovine milk. Its thermal behavior has been associated with casein-micelle structure, lower κ -casein abundance, whey-protein composition, and mineral equilibria. Intensive heating can increase whey-protein denaturation and protein–protein interactions, potentially resulting in aggregation or precipitation and consequent changes in viscosity, color, coagulation behavior, and downstream processing performance (Hassan *et al.*, 2007; Alhaj *et al.*, 2011; Omar *et al.*, 2018) [39, 38, 40].

Heating also modifies mineral partitioning and acid–base equilibria. Some heat-induced changes may be reversible during cooling, whereas more severe treatments can generate persistent structural changes. Prolonged or intense heating can additionally promote lactose degradation and the formation of organic acids, contributing to further pH reduction (Berg, 1993; Ma *et al.*, 2003) [41, 42]. These ef

fects become particularly important when the treated milk is subsequently subjected to fermentation or enzymatic coagulation, where pH and calcium availability strongly influence protein destabilization and gel formation.

The central processing challenge is therefore not simply to maximize microbial inactivation. Rather, thermal treatment must achieve an appropriate balance between microbial safety, enzyme inactivation, protein functionality, sensory quality, and preservation of downstream processing performance. This balance makes time–temperature optimization a critical research priority for camel-milk processing.

4.2 Pasteurization and process verification

Validation of pasteurization in camel milk requires careful selection and validation of appropriate process indicators. Although alkaline phosphatase is widely used as a conventional indicator of pasteurization adequacy in bovine milk, camel-milk enzyme systems can exhibit different thermal resistance. Consequently, γ -glutamyl transferase, lactoperoxidase, and other heat-sensitive enzymes have been investigated as potential indicators, with reported results varying according to milk source, heating regime, and analytical methodology (Elagamy, 2000 [30]; Didier *et al.*, 2001 [43]; Wernery *et al.*, 2007 [44]; Lorenzen *et al.*, 2011 [45]; Tayefi-Nasrabadi *et al.*, 2011) [46].

The variation among proposed enzyme markers highlights an important methodological issue: no single biological indicator should be assumed to be universally applicable to all camel-milk pasteurization systems. Marker performance should instead be validated against the specific time–temperature profile, milk composition, equipment configuration, and analytical method used at the processing scale. An industrial verification strategy should combine continuously recorded time–temperature data with a validated process indicator and routine microbiological testing.

4.3 Emerging non-thermal and assisted processing

Non-thermal and assisted technologies, including high-pressure processing and ultrasound, offer potential approaches for modifying camel-milk functionality while reducing dependence on severe thermal exposure. High-pressure treatment can modify casein-micelle structure and influence enzymatic coagulation, whereas ultrasound can alter protein aggregation, particle interactions, and interfacial behavior (Needs *et al.*, 2000; Shokri *et al.*, 2022) [47, 36]. Nevertheless, the translation of these technologies from laboratory studies to industrial camel-dairy systems requires systematic evaluation of energy demand, microbial lethality, equipment compatibility, scale-up behavior, and product stability.

4.4 Automation and intelligent process control

The compositional variability and processing sensitivity of camel milk make it particularly suitable for advanced process-monitoring strategies. Conventional control based on fixed processing recipes assumes relatively stable raw-material properties; this assumption is often inappropriate for camel milk. Integration of temperature, pH, flow, pressure, conductivity, and other process sensors could enable continuous monitoring of milk behavior and early detection of process deviations.

A future intelligent processing architecture could combine online sensor measurements with historical batch data and predictive models to estimate thermal response, identify abnormal process trajectories, and dynamically adjust operating conditions. Machine-learning models may ultimately support adaptive control in which processing conditions are selected according to the measured characteristics of each incoming milk batch rather than according to a single fixed recipe. Such systems could improve reproducibility, reduce unnecessary thermal exposure, and minimize energy consumption while maintaining food-safety targets.

5. Fermentation and camel-milk yogurt

Fermentation has historically played an important role in extending the usability of camel milk, particularly in production environments where refrigeration is limited. However, modern camel-yogurt manu-

facture presents a technological challenge because acidification and gelation kinetics differ from those of bovine milk. Several studies have reported slower acid development with selected commercial starter cultures, potentially reflecting the antimicrobial activity of endogenous milk components and differences in the physicochemical environment of camel milk (Attia *et al.*, 2001; Berhe *et al.*, 2018) [29, 31].

5.1 Acidification kinetics

The rate and extent of pH decline are among the most important control variables in yogurt manufacture. Slow acidification prolongs incubation, increases the time during which contamination can occur, and may result in incomplete or weak gel development. Acidification kinetics depend on starter strain, inoculum level, incubation temperature, milk pretreatment, solids concentration, and the initial physicochemical state of the milk. Comparative studies have demonstrated that thermophilic cultures may produce faster acidification than some mesophilic cultures, emphasizing that starter selection should be treated as a formulation and process variable rather than transferred directly from bovine-yogurt manufacture (Berhe *et al.*, 2018; Bekele *et al.*, 2019) [31, 48].

A useful development strategy is therefore to characterize complete acidification curves rather than relying solely on a final pH measurement. Parameters such as maximum acidification rate, lag phase, time to target pH, and post-acidification behavior can provide a more informative basis for starter selection and process optimization.

5.2 Texture, water holding, and syneresis

Weak, fragile, or heterogeneous gel structures are frequently reported as limitations in camel yogurt. Inadequate protein aggregation can result in reduced firmness and viscosity and increased syneresis, thereby negatively affecting both physical stability and consumer acceptance. Heat treatment, solids adjustment, hydrocolloids, starches, and starter-culture selection have therefore been investigated as approaches to improve gel structure (Abd Elhamid *et al.*, 2017; Khalifa *et al.*, 2015; Al-Zoreky *et al.*, 2015) [49, 50, 51].

Importantly, the addition of stabilizers does not necessarily reproduce the structural characteristics of bovine yogurt. Limited improvements obtained with carboxymethyl cellulose, alginate, gum acacia, or pectin suggest that the underlying limitation may originate from protein-network formation rather than simply from insufficient hydrocolloid concentration (Al-Zoreky *et al.*, 2015) [51]. This indicates that formulation strategies should address the entire sequence of events from protein denaturation and aggregation to acid-induced gel formation and serum immobilization.

5.3 Process-development strategy and automation

An optimized camel-yogurt process should begin with systematic characterization of incoming milk, including protein, fat, total solids, pH, mineral composition, and microbiological quality. Starter cultures should then be screened using camel-milk acidification kinetics rather than relying solely on performance data generated in bovine milk. Heat treatment should be optimized to achieve microbial safety while promoting the appropriate degree of whey-protein denaturation for subsequent gel formation. Where necessary, concentration or total-solids adjustment can be incorporated to increase network density.

Product development should evaluate firmness, apparent viscosity, water-holding capacity, syneresis, microstructure, and sensory acceptance throughout refrigerated storage rather than immediately after fermentation. This approach allows instrumental measurements to be connected with the mechanisms responsible for physical deterioration and consumer acceptance.

From an automation perspective, online pH and temperature measurements provide relatively simple opportunities for improving fermentation control. Rather than terminating incubation after a fixed time, an automated system could use the real-time acidification trajectory to identify the appropriate endpoint. At a more advanced level, predictive models could combine pH slope, temperature history, inoculum characteristics, and milk composition to estimate the time required to

reach the target gel state. Such adaptive control could reduce over-acidification and batch-to-batch variability while improving process efficiency.

6. Cheese manufacturing: Major processing constraints

Cheese manufacture represents one of the most pronounced examples of the technological divergence between camel and bovine milk. The process requires controlled destabilization of casein micelles, formation of a cohesive curd, and efficient separation of whey. In camel milk, prolonged coagulation, weak curd development, and reduced cheese yield have been reported under several processing conditions (Al haj *et al.*, 2010; Berhe *et al.*, 2017; Baig *et al.*, 2022) [8, 37, 24].

6.1 Rennet coagulation

Rennet coagulation is governed by casein-micelle structure, accessibility of the enzymatic cleavage site, mineral equilibrium, pH, temperature, and enzyme concentration. Camel milk may require substantially longer coagulation times than bovine milk under otherwise comparable conditions. The larger casein micelles, lower relative abundance of κ -casein, and differences in the structure of the κ -casein substrate contribute to this behavior (Farah and Bachmann, 1987; Farah *et al.*, 1990; Kappeler *et al.*, 2006) [52, 53].

Camel chymosin has consequently received considerable attention as a species-specific coagulating enzyme. Comparative studies indicate that recombinant camel chymosin can provide favorable coagulation characteristics because its substrate specificity is better matched to camel-casein structure (Kappeler *et al.*, 2006; Hailu *et al.*, 2016a) [53, 17]. This provides an important general principle for camel-dairy process development: enzymatic systems should be selected according to substrate structure rather than assumed to be functionally interchangeable across milk species.

6.2 Weak curd and low yield

Reduced cheese yield can arise from the relatively low total-solids concentration of camel milk as well as differences in casein composition, micelle structure, mineral balance, and fat-globule behavior. However, reported yields vary considerably because studies differ in milk composition, concentration treatment, enzyme preparation, coagulation conditions, and cheese type. Consequently, cheese yield should always be interpreted alongside milk composition and reported on a dry-matter recovery basis where possible (El Zubeir *et al.*, 2008; Ho *et al.*, 2022) [54, 55].

Membrane concentration technologies, particularly ultrafiltration, offer one route to increase protein and casein availability before coagulation. Controlled acidification and mineral adjustment may further modify casein interactions and curd development. Collectively, the available evidence indicates that camel cheese manufacture is technically feasible but requires optimization of enzyme specificity, solids concentration, pH, calcium availability, and curd-handling conditions rather than direct adoption of bovine cheese recipes (Konuspayeva *et al.*, 2014; Bekele *et al.*, 2019; Konuspayeva *et al.*, 2017) [48, 56, 57].

6.3 Research priorities and intelligent coagulation control

Future research should focus on species-specific enzyme systems, including camel chymosin and optimized mixed-enzyme preparations, for different cheese categories. The effects of ultrafiltration, mineral adjustment, controlled acidification, and temperature on curd strength should be quantified using standardized rheological and texture measurements. Seasonal and geographical variation in milk composition should also be incorporated into process specifications.

The slow and variable coagulation kinetics of camel milk provide a particularly strong opportunity for sensor-assisted process control. Real-time measurements of pH, temperature, viscosity, electrical properties, or other coagulation-related physical signals could potentially identify the transition from enzymatic hydrolysis to gel formation and determine the optimum cutting point. In contrast to conventional fixed-time cutting, such a system would respond to the actual

coagulation state of each batch. With sufficiently large datasets, machine-learning models could integrate milk composition, enzyme dose, temperature history, and coagulation kinetics to predict gelation time and curd firmness, thereby enabling predictive rather than purely reactive process control.

7. Camelus dromedarius milk butter and fat-phase processing

Butter manufacture is strongly influenced by the physical organization and composition of camel milk fat. The relatively small fat globules, distinctive milk-fat-globule membrane, and characteristic fatty-acid and triacylglycerol profiles influence creaming, crystallization, churning, and the final structure of the fat phase (Attia *et al.*, 2000; Karray *et al.*, 2005a, 2005b; Haddad *et al.*, 2011) [33, 58, 59].

Traditional churning can therefore provide lower fat recovery than would be expected from bovine milk under comparable conditions. The resistance of the globule membrane to aggregation, together with differences in fat crystallization behavior, can reduce the efficiency of cream formation and churning. The reported melting characteristics of camel milk fat further emphasize the importance of controlling cooling history and churning temperature (Berhe *et al.*, 2013; Farah *et al.*, 1989) [60, 61].

The composition of the fat phase also influences oxidative stability, moisture retention, firmness, and spreadability. Products such as camel-milk ghee should be considered separately from conventional butter because clarification substantially alters the composition and physicochemical properties of the final fat. Consequently, comparisons between butter and ghee should be based on product-specific compositional and functional parameters rather than yield alone (Parmar, 2013) [62].

7.1 Process optimization and automation

Optimization of camel-milk butter manufacture should focus on controlled cream separation, cooling history, fat crystallization, agitation intensity, and churning endpoint. Fat-globule size distribution and membrane characteristics can provide useful indicators of separation and churning behavior, while free fatty acids, moisture, residual protein, oxidation indices, and sensory characteristics should be monitored during storage.

Automation can substantially improve reproducibility in this process because cream temperature and crystallization state strongly influence churning performance. Continuous temperature sensing, controlled cooling, motor-load monitoring, and automated endpoint detection could replace subjective manual determination of the churning endpoint. In future systems, real-time measurements of temperature, torque, conductivity, or vibration could be integrated into predictive models to identify the onset of butter-grain formation and terminate churning at the optimum point. Such control would be particularly valuable where raw-milk fat composition varies seasonally or between herds.

8. Cross-cutting processing constraints and opportunities

8.1 Raw-material variability

Intrinsic variability is one of the most important constraints to the industrialization of camel milk. Water availability, feed composition, ambient temperature, season, lactation stage, animal health, and herd-management practices can alter protein, fat, lactose, minerals, and total-solids concentrations. Consequently, industrial process specifications should begin with well-defined incoming-milk criteria rather than assuming a constant raw material.

This variability also creates a strong rationale for adaptive processing. Instead of applying identical processing conditions to every batch, future plants could use rapid compositional measurements to classify milk and select appropriate operating windows for pasteurization, concentration, fermentation, or coagulation. Such a shift from fixed

recipes toward composition-aware processing represents an important intersection between camel-dairy science and automation.

8.2 Microbiological quality and cold-chain limitations

Fermentation has historically contributed to the preservation of camel milk in environments where refrigeration infrastructure is limited. Commercial production, however, requires systematic control of raw-milk hygiene, rapid cooling, collection logistics, storage temperature, and validated heat treatment. Raw or inadequately processed milk may present microbiological hazards; therefore, traditional consumption practices should not be interpreted as evidence that unprocessed milk is intrinsically safe. Appropriate hygienic handling and validated processing remain essential components of a modern camel-dairy supply chain (Ismaili *et al.*, 2019; Claeys *et al.*, 2014) [21, 63].

Cold-chain limitations also highlight the importance of process automation beyond the processing plant itself. Automated temperature logging, cold-chain monitoring, alarm systems, and digital traceability could provide continuous verification of storage and transportation conditions. Integration of these data with processing records would create a more complete quality-management system from farm collection to final product.

8.3 Product diversification and process-specific innovation

The technological constraints associated with camel milk should not be viewed solely as limitations; they also provide opportunities for product-specific innovation. Camel milk can be processed into fresh milk products, fermented beverages, yogurt, cheese, butter, ghee, concentrated products, and dried ingredients, but each product requires a tailored processing strategy. Membrane concentration, ultrasound, high-pressure processing, optimized starter cultures, and camel-specific coagulating enzymes provide potential routes for modifying functionality while limiting excessive thermal exposure (Needs *et al.*, 2000; Shokri *et al.*, 2022; Arain *et al.*, 2023) [47, 36, 64].

The most promising strategy is therefore not to identify a single “optimal” camel-milk process, but to establish a modular processing framework in which raw-milk composition determines the appropriate combination of unit operations and operating conditions.

8.4 Standardization and industrial scale-up

A major limitation of the current literature is the limited comparability among experimental studies. Differences in animal origin, season, milk composition, heat-treatment conditions, starter cultures, enzyme preparations, concentration methods, and analytical endpoints can produce apparently conflicting results. Greater standardization of experimental reporting is therefore required.

Future studies should report raw-milk composition, mineral profile, protein fractions, fat-globule characteristics, processing history, formulation, equipment configuration, and relevant operating conditions in sufficient detail to enable reproducibility. Pilot-scale studies are particularly important because hydrodynamics, heat transfer, residence-time distribution, shear conditions, and energy consumption at industrial scale cannot always be predicted from laboratory experiments.

8.5 Toward an integrated research and automation framework

A systematic pathway for the development of industrial camel-milk processes can be organized into five interconnected stages. The first stage should establish a comprehensive raw-milk fingerprint encompassing composition, minerals, protein fractions, fat-globule size, microbiological quality, and relevant physicochemical properties. The second stage should investigate the mechanisms controlling protein

denaturation, micelle stability, acidification, fat crystallization, and enzyme–substrate interactions. The third stage should use statistically designed experiments and response-surface approaches to optimize critical process variables, including temperature, pH, culture concentration, enzyme dose, solids concentration, pressure, and mechanical conditions. The fourth stage should validate product quality through measurements of rheology, texture, flavor, shelf life, nutritional characteristics, and microbiological safety. Finally, the fifth stage should evaluate industrial feasibility through mass and energy balances, equipment compatibility, process economics, environmental performance, and consumer acceptance.

Within this framework, automation should not be considered an independent technological add-on but as an enabling layer connecting raw-material characterization, process monitoring, predictive modeling, and quality assurance. The long-term objective is a closed-loop camel-dairy processing system in which sensor data describe the incoming milk, mechanistic and machine-learning models predict its processing response, automated control systems adjust operating conditions in real time, and product-quality measurements provide feedback for subsequent batches. Such an architecture could transform camel-milk processing from predominantly recipe-based operation toward data-driven, adaptive manufacturing.

The development of these systems will require interdisciplinary integration of dairy chemistry, food engineering, sensor technology, process control, data science, and machine learning. Importantly, automation should be introduced only after the underlying process mechanisms and critical quality attributes have been sufficiently characterized. Otherwise, digital control may simply automate an inadequately understood process. The major opportunity, therefore, lies in combining fundamental understanding of camel-milk structure with real-time sensing and predictive control to achieve safer, more consistent, energy-efficient, and scalable processing.

9. Integrated comparison of *Camelus dromedarius* milk with conventional bovine-milk processing

The principal technological differences between *Camelus dromedarius* and bovine milk arise not from their gross compositional similarity but from differences in protein organization, mineral equilibrium, fat-globule structure, and biological activity. These differences propagate across unit operations, meaning that a change at the molecular or colloidal level can influence several downstream processing steps. Table 1 summarizes the major structure–function differences and their corresponding processing implications.

The comparison demonstrates that camel-milk processing should be regarded as a **coupled structure–function system** rather than a sequence of independent unit operations. Casein and mineral characteristics influence thermal stability and coagulation; thermal history subsequently affects protein functionality and gel formation; fat-globule structure determines separation and churning behavior; and endogenous antimicrobial components can influence fermentation kinetics. Consequently, optimizing one processing step without accounting for upstream milk characteristics may produce limited or inconsistent improvements.

This systems perspective also explains why apparently contradictory findings are common in the literature. A treatment that improves one quality attribute under a particular milk composition may not produce the same response under different seasonal, geographical, or compositional conditions. Future studies should therefore report processing outcomes together with detailed descriptions of the starting milk and process history.

Table 1. Structure–function differences between *Camelus dromedarius* and bovine milk and their implications for process development

Attribute	<i>Camelus dromedarius</i> milk: key feature	Processing consequence	Development response
Casein micelles	Generally larger micelles with a distinct casein distribution	Slower and potentially less predictable enzymatic coagulation	Use camel-compatible coagulating enzymes and optimize pH, temperature, and mineral balance
κ-Casein	Lower relative abundance than in bovine milk	Altered micellar stability and rennet-coagulation behavior; potentially weaker curd formation	Optimize enzyme specificity and concentration; evaluate camel chymosin
Whey proteins	Distinct protein profile; β-lactoglobulin is reported to be absent	Different thermal denaturation, aggregation, and interfacial behavior	Control thermal load and characterize protein-denaturation kinetics
Fat globules	Relatively small globules with distinctive membrane characteristics	Reduced creaming and potentially less efficient churning	Optimize cream separation, cooling history, and agitation
Fatty-acid composition	Greater contribution of long-chain fatty acids and comparatively lower short-chain fractions	Different melting, crystallization, and textural behavior	Control cooling and crystallization conditions before churning
Acidification kinetics	Frequently slower with selected conventional starter cultures	Prolonged fermentation and potentially weak or heterogeneous gel formation	Screen and optimize camel-compatible starter cultures
Total solids	Frequently lower than bovine or buffalo milk	Lower solids recovery and potentially reduced cheese yield and gel strength	Apply concentration, membrane processing, or formulation adjustment where appropriate
Antimicrobial proteins	Relatively prominent protective protein system	Potential suppression or delay of starter-culture activity	Select robust cultures and optimize inoculum, temperature, and fermentation conditions
Heat-treatment indicators	Thermal behavior of endogenous enzymes differs from bovine milk	Conventional alkaline-phosphatase criteria may not universally predict treatment adequacy	Validate process indicators against the specific camel-milk thermal regime

9.1 Quality attributes that should be reported in future studies

Improved standardization of experimental reporting is essential for developing transferable processing models. At minimum, future studies should report:

- geographical and production origin of the milk, animal population, stage of lactation, season, and relevant feeding or management conditions;
- protein, fat, lactose, total solids, ash, and major mineral concentrations;
- casein fractions, whey-protein composition, and fat-globule size distribution where analytical facilities permit;
- complete thermal history, including treatment temperature, holding time, heating and cooling rates, and equipment configuration;
- starter-culture identity, inoculum concentration, fermentation temperature, and fermentation endpoint;
- enzyme identity, activity, concentration, pH, calcium conditions, and coagulation temperature for cheese studies;
- coagulation time, gel firmness, rheological parameters, syneresis, and water-holding capacity;
- cheese and butter mass yield together with dry-matter recovery;
- microbiological quality, storage conditions, shelf-life indicators, and sensory acceptance; and
- where possible, energy consumption, process losses, and economic indicators.

Such standardized datasets would not only improve reproducibility but would also provide the foundation required for predictive modelling and intelligent process control.

10. Discussion

The evidence reviewed in this manuscript supports a central interpretation: *Camelus dromedarius* milk should not be considered technologically inferior to bovine milk; rather, it represents a distinct processing matrix with different structure–function relationships. Many of the difficulties reported during camel-milk processing can be interpreted as consequences of applying process assumptions developed for bovine milk to a fundamentally different colloidal and biochemical system.

The implications are product-specific. In thermal processing, the challenge is to achieve the required microbial reduction while limiting undesirable protein denaturation, aggregation, and mineral redistribution. In yogurt manufacture, the critical challenge is to achieve sufficiently rapid acidification and the formation of a stable three-dimensional protein network. In cheese manufacture, the dominant constraint is controlled enzymatic destabilization of casein micelles followed by formation and strengthening of the curd. In butter manufacture, efficient separation and controlled crystallization of a distinctive fat phase are the principal technological requirements. These differences indicate that a universal “camel-milk process” is unlikely to be optimal; instead, process conditions should be designed according to the target product and the physicochemical characteristics of the incoming milk.

10.1 From compositional variability to adaptive processing

A particularly important conclusion is that natural variability should be incorporated into process design rather than treated exclusively as experimental noise. Hydration status, feed, season, environmental temperature, lactation stage, animal health, and management practices can alter the concentrations and interactions of proteins, lipids, lactose, minerals, and total solids. Consequently, a fixed processing

recipe may operate satisfactorily for one milk batch but become sub-optimal when raw-milk composition shifts.

This creates an opportunity to move from recipe-based processing toward adaptive processing. Rapid measurement of selected milk attributes could be used to classify incoming milk and determine an appropriate processing window. For example, variation in protein and total-solids concentration could inform concentration requirements before yogurt or cheese production, while measurements associated with acidity and mineral balance could assist in selecting fermentation or coagulation conditions. Such an approach would convert raw-material variability from an uncontrolled source of process instability into an explicitly managed process variable.

10.2 From empirical optimization to structure–function engineering

The literature further supports a transition from predominantly empirical optimization toward structure–function engineering. Rather than evaluating only the final product, researchers can characterize the molecular and colloidal state of the milk before and during processing and relate these measurements to subsequent functional behavior.

For example, casein-micelle characteristics can be related to rennet coagulation kinetics; whey-protein denaturation can be related to thermal history and yogurt gel development; fat-globule size and membrane properties can be linked to creaming and churning efficiency; and acidification kinetics can be connected to gel strength and syneresis. This mechanistic framework provides a more transferable basis for process optimization than isolated end-point measurements.

10.3 Opportunity for sensor-based process monitoring

The combination of raw-material variability and product-specific processing requirements makes camel milk an attractive candidate for advanced process monitoring. Conventional dairy operations frequently rely on predetermined time–temperature profiles, fixed incubation periods, or operator-defined endpoints. Although these approaches are practical, they may not adequately accommodate the variability inherent in camel milk.

Sensor-based monitoring could provide continuous measurements of temperature, pH, flow, pressure, conductivity, viscosity, torque, or other process-relevant variables. These measurements could be used to identify deviations from expected process trajectories and to establish objective endpoints for fermentation, coagulation, separation, and churning.

The immediate value of such systems is not necessarily artificial intelligence itself, but **better observability of the process**. Once reliable real-time measurements are available, predictive models can be developed to relate process trajectories to product outcomes.

10.4 Artificial intelligence and machine learning

Artificial intelligence and machine learning represent a further stage in the evolution of camel-dairy process control. A sufficiently large and well-annotated dataset could link raw-milk composition, processing history, sensor signals, and final product quality. Models trained on these data could potentially predict fermentation endpoint, coagulation time, curd strength, butter yield, or quality deterioration.

However, predictive performance should not be confused with process understanding. Black-box models may perform well within the range represented by their training data but fail when milk composition, season, equipment, or operating conditions move outside that range. For this reason, hybrid modelling may be particularly appropriate for camel-milk processing. Mechanistic knowledge of protein aggregation, micelle destabilization, acidification, heat transfer, and fat crystallization could be combined with machine-learning algorithms to improve prediction while retaining physical interpretability. The most advanced architecture would be a closed-loop, data-driven processing system:

raw-milk characterization → sensor acquisition → mechanistic/predictive model → adaptive process control → product-quality measurement → model updating

Such a framework could enable processing conditions to respond dynamically to the properties of each incoming batch. In principle, this could reduce batch-to-batch variability, unnecessary thermal exposure, processing losses, and energy consumption while improving consistency and traceability.

11. Conclusion and future prospective

Camelus dromedarius milk represents an important dairy resource whose technological potential extends beyond its nutritional composition. Although its gross composition overlaps with that of conventional bovine milk, differences in casein-micelle organization, κ -casein abundance, whey-protein composition, fat-globule characteristics, lipid composition, mineral equilibrium, and endogenous antimicrobial components produce a distinct processing response.

The central conclusion of this review is therefore that camel milk should not be processed by simply transferring bovine-milk protocols. Thermal processing requires optimization of microbial safety against protein and mineral changes; yogurt manufacture requires control of acidification kinetics and protein-network development; cheese manufacture requires species-compatible coagulation systems and, where appropriate, solids concentration; and butter manufacture requires careful control of cream separation, fat crystallization, and churning. Raw-milk variability represents an additional industrial challenge. Seasonal, environmental, nutritional, physiological, and management-related factors can alter milk composition and consequently shift the optimum processing conditions. Industrial standardization should therefore combine defined raw-milk specifications with flexible process windows rather than rely exclusively on fixed recipes.

Future research should prioritize five interconnected areas. First, standardized characterization of camel milk should include composition, mineral balance, protein fractions, fat-globule characteristics, microbiological quality, and relevant physicochemical properties. Second, mechanistic studies should clarify the relationships among molecular structure, heat stability, acidification, coagulation, and fat-phase behavior. Third, process intensification and product-specific technologies, including membrane concentration, high-pressure processing, ultrasound, optimized starter cultures, and camel-compatible coagulating enzymes, should be evaluated at pilot and industrial scales. Fourth, studies should incorporate economic, energy, environmental, and life-cycle considerations so that laboratory-scale technological improvements can be assessed for practical feasibility. Fifth, research should establish high-quality process datasets suitable for predictive modelling and intelligent control.

An especially promising direction is the integration of sensing, automation, artificial intelligence, and machine learning into camel-dairy processing. Real-time monitoring of temperature, pH, fermentation kinetics, coagulation behavior, flow, mechanical response, and separation performance could provide the process observability required for adaptive manufacturing. Machine-learning and hybrid mechanistic models could subsequently be developed to predict process endpoints and recommend operating conditions based on raw-milk characteristics.

Nevertheless, automation should complement rather than replace fundamental process understanding. Reliable AI-driven control requires standardized measurements, validated process indicators, sufficiently large datasets, and clearly defined critical quality attributes. The immediate research priority should therefore be the generation of robust camel-milk process datasets and the identification of measurable variables that reliably predict product performance.

Ultimately, the development of camel-dairy processing can progress from empirical, fixed-recipe operation toward adaptive, data-driven manufacturing. A future camel-dairy plant could continuously characterize incoming milk, predict its processing response, adjust operating conditions in real time, and use final-product data to refine subsequent production cycles. Such integration of dairy science with process engineering and digital technologies has the potential to im-

prove consistency, resource efficiency, traceability, scalability, and product quality, while establishing a scientifically grounded pathway for the industrial modernization of camel-milk processing.

References

1. Faye B. The camel, new challenges for a sustainable development. *Trop Anim Health Prod.* 2016;48:689–692.
2. Food and Agriculture Organization (FAO). The long-term future of livestock and fishery in Egypt production targets in the face of uncertainty. FAO, Rome, Italy; 2020.
3. Konuspayeva G, Faye B. Recent advances in camel milk processing. *Animals.* 2021;11:1045.
4. Ali A, Baby B, Vijayan R. From desert to medicine: A review of camel genomics and therapeutic products. *Front Genet.* 2019;10:17.
5. Almathen F, Charruau P, Mohandesan E, Mwacharo JM, Orozco-Wengel P, Pitt D, Abdussamad AM, Uerpmann M, Uerpmann HP, De Cupere B, Magee P, Alnaqeeb MA, Salim B, Raziq A, Dessie T, Abdelhadi OM, Banabazi MH, Al-Ekna M, Walzer C, Faye B, Hofreiter M, Peters J, Hanotte O, Burger PA. Ancient and modern DNA reveal dynamics of domestication and cross-continental dispersal of the dromedary. *Proc Natl Acad Sci USA.* 2016;113:6707–6712.
6. Burger PA. The history of Old World camelids in the light of molecular genetics. *Trop Anim Health Prod.* 2016;48:905–913.
7. Trinks A, Burger P, Beneke N, Burger J. Ancient DNA reveals domestication process: The Case of the two-humped camel. In *Camels in Asia and North Africa. Interdisciplinary perspectives on their past and present significance* Knoll EM, Burger P, (ed) Austrian Academy of Sciences Press, Vienna, Austria. 2012:79–86.
8. Al haj OA, Al Kanhal HA. Compositional, technological and nutritional aspects of dromedary camel milk. *Int Dairy J.* 2010;20:811–821.
9. Hailu Y, Bech Hansen E, Seifu E, Eshetu M, Ipsen R, Kappeler S. Functional and technological properties of camel milk proteins: A review. *J Dairy Res.* 2016b;83:422–429.
10. Hinz K, O'Connor PM, Huppertz T, Paul Ross R, Kelly AL. Comparison of the principal proteins in bovine, caprine, buffalo, equine and camel milk. *J Dairy Res.* 2012;79:185–191.
11. Yang Y, Bu D, Zhao X, Sun P, Wang J, Zhou L. Proteomic analysis of cow, yak, buffalo, goat and camel milk whey proteins: Quantitative differential expression patterns. *J Proteome Res.* 2013;12:1660–1667.
12. Konuspayeva G, Faye B, Loiseau G. The composition of camel milk: A meta-analysis of the literature data. *J Food Compos Anal.* 2009;22:95–101.
13. Ereifej KI, Alu'datt MH, AlKhalidy HA, Alli I, Rababah T. Comparison and characterisation of fat and protein composition for camel milk from eight Jordanian locations. *Food Chem.* 2011;127:282–289.
14. Rafiq S, Huma N, Pasha I, Sameen A, Mukhtar O, Issa Khan M. Chemical composition, nitrogen fractions and amino acids profile of milk from different animal species. *Asian-Australas J Anim Sci.* 2016;29:1022–1028.
15. Omar A, Harbourne N, Oruna-Concha MJ. Quantification of major camel milk proteins by capillary electrophoresis. *Int Dairy J.* 2016;58:31–35.
16. Barłowska J, Szwałkowska M, Litwińczuk Z, Król J. Nutritional value and technological suitability of milk from various animal species used for dairy production. *Compr Rev Food Sci Food Saf.* 2011;10:291–302.
17. Hailu Y, Bech Hansen E, Seifu E, Eshetu M, Ipsen R. Factors influencing the gelation and rennetability of camel milk using camel chymosin. *Int Dairy J.* 2016a;60:62–69.

18. El-Agamy EI. Bioactive components in camel milk. In Bioactive components in milk and dairy products Young WP, (ed) Wiley-Blackwell, Ames, IA, USA. 2009:159–192.
19. Arain MA, Khaskheli GB, Shah AH, Marghazani IB, Barham GS, Shah QA, Muhammad Khand F, Buzdar JA, Soomro F, Fazlani SA. Nutritional significance and promising therapeutic/medicinal application of camel milk as a functional food in human and animals: A comprehensive review. *Anim Biotechnol*. 2022.
20. Al-Juboori AT, Mohammed M, Rashid J, Kurian J, El Refaey S. Nutritional and medicinal value of camel (*Camelus dromedarius*) milk. *WIT Trans Ecol Environ*. 2013;170:221–232.
21. Ismaili MA, Saidi B, Zahar M, Hamama A, Ezzaier R. Composition and microbial quality of raw camel milk produced in Morocco. *J Saudi Soc Agric Sci*. 2019;18:17–21.
22. Haddad I, Mozzon M, Strabbioli R, Frega NG. Electrospray ionization tandem mass spectrometry analysis of triacylglycerols molecular species in camel milk (*Camelus dromedarius*). *Int Dairy J*. 2011;21:119–127.
23. Jilo K, Tegegne D. Chemical composition and medicinal values of camel milk. *Int J Res Stud Biosci*. 2016;4:13–25.
24. Baig D, Sabikhi L, Khetra Y, Ashok Shelke P. Technological challenges in production of camel milk cheese and ways to overcome them: A review. *Int Dairy J*. 2022;129:105344.
25. Yoganandi J, Mehta BM, Wadhvani KN, Darji VB, Aparnathi KD. Comparison of physico-chemical properties of camel milk with cow milk and buffalo milk. *J Camel Pract Res*. 2014;21:253–258.
26. Mehaia MA. Chemical composition of camel skim milk concentrated by ultrafiltration. *Int Dairy J*. 1996;6:741–752.
27. Stahl T, Sallmann HP, Duehlmeier R, Wernery U. Selected vitamins and fatty acid patterns in dromedary milk and colostrum. *J Camel Pract Res*. 2006;13:53–57.
28. Sawaya WN, Khalil JK, Al-Shalhat A, Al-Mohammad H. Chemical composition and nutritional quality of camel milk. *J Food Sci*. 1984;49:744–747.
29. Attia H, Kherouatou N, Dhoub A. Dromedary milk lactic acid fermentation: Microbiological and rheological characteristics. *J Ind Microbiol Biotechnol*. 2001;26:263–270.
30. Elagamy EI. Effect of heat treatment on camel milk proteins with respect to antimicrobial factors: A comparison with cows' and buffalo milk proteins. *Food Chem*. 2000;68:227–232.
31. Berhe T, Ipsen R, Seifu E, Kurtu MY, Eshetu M, Bech Hansen E. Comparison of the acidification activities of commercial starter cultures in camel and bovine milk. *LWT-Food Sci Technol*. 2018;89:123–127.
32. Abd El-Aziz M, Kassem JM, Aasem FM, Abbas HM. Physicochemical properties and health benefits of camel milk and its applications in dairy products: A review. *Egypt J Chem*. 2022;65:101–118.
33. Attia H, Kherouatou N, Fakhfakh N, Khorchani T, Trigui N. Dromedary milk fat: Biochemical, microscopic and rheological characteristics. *J Food Lipids*. 2000;7:95–112.
34. El-Zeini HM. Microstructure, rheological and geometrical properties of fat globules of milk from different animal species. *Pol J Food Nutr Sci*. 2006;56:147–154.
35. Gammoh S, Alu'datt MH, Tranchant CC, Al-U'datt DG, Alhamad MN, Rababah T, Kubow S, Haddadin MSY, Ammari Z, Maghaydah S, Banat H. Modification of the functional and bioactive properties of camel milk casein and whey proteins by ultrasonication and fermentation with *Lactobacillus delbrueckii subsp. lactis*. *LWT-Food Sci Technol*. 2020;129:109501.
36. Shokri S, Javanmardi F, Mohammadi M, Mousavi Khaneghah A. Effects of ultrasound on the techno-functional properties of milk proteins: A systematic review. *Ultrason Sonochem*. 2022;83:105938.
37. Berhe T, Seifu E, Ipsen R, Kurtu MY, Bech Hansen E. Processing challenges and opportunities of camel dairy products. *Int J Food Sci*. 2017;2017:9061757.
38. Alhaj OA, Metwalli Ali AM, Ismail Elsayed A. Heat stability of camel milk proteins after sterilisation process. *J Camel Pract Res*. 2011;18:277–282.
39. Hassan RA, El Zubeir IEM, Babiker SA. Effect of pasteurization of raw camel milk and storage temperature on the chemical composition of fermented camel milk. *Int J Dairy Sci*. 2007;2:166–171.
40. Omar A, Harbourne N, Oruna-Concha MJ. Effects of industrial processing methods on camel skimmed milk properties. *Int Dairy J*. 2018;84:15–22.
41. Berg HE. Reactions of lactose during heat treatment of milk: A quantitative study. Ph.D. dissertation Wageningen University & Research, Wageningen, Netherlands; 1993.
42. Ma Y, Barbano DM. Milk pH as a function of CO₂ concentration, temperature, and pressure in a heat exchanger. *J Dairy Sci*. 2003;86:3822–3830.
43. Didier M, Gérard L, Bernard F, Asia S. Enzymes ability to serve as markers of pasteurized camel milk International Conference on New Horizons in Biotechnology, Trivandrum, India. 2001.
44. Wernery U, Johnson B, George RM. Gamma-glutamyl transferase (GGT), a potential marker for the evaluation of heat treatment of dromedary milk. *J Camel Pract Res*. 2007;14:9–.
45. Lorenzen PC, Wernery R, Johnson B, Jose S, Wernery U. Evaluation of indigenous enzyme activities in raw and pasteurised camel milk. *Small Rumin Res*. 2011;97:79–82.
46. Tayefi-Nasrabadi H, Ali Hoseinpour-fayzi M, Mohasseli M. Effect of heat treatment on lactoperoxidase activity in camel milk: A comparison with bovine lactoperoxidase. *Small Rumin Res*. 2011;99:187–190.
47. Needs EC, Stenning RA, Gill AL, Ferragut V, Rich GT. High-pressure treatment of milk: Effects on casein micelle structure and on enzymic coagulation. *J Dairy Res*. 2000;67:31–42.
48. Bekele B, Hansen EB, Eshetu M, Ipsen R, Hailu Y. Effect of starter cultures on properties of soft white cheese made from camel (*Camelus dromedarius*) milk. *J Dairy Sci*. 2019;102:1108–1115.
49. Abd Elhamid AM, Elbayoumi MM. Effect of heat treatment and fermentation on bioactive behavior in yoghurt made from camel milk. *Am J Food Sci Technol*. 2017;5:109–116.
50. Khalifa SA, Ibrahim AH. Influence of addition modified starches as stabilizer on physicochemical and textural properties of camel's milk yoghurt. *Zagazig J Agric Res*. 2015;42:295–307.
51. Al-Zoreky NS, Al-Otaibi MM. Suitability of camel milk for making yogurt. *Food Sci Biotechnol*. 2015;24:601–606.
52. Farah Z, Bachmann MR. Rennet coagulation properties of camel milk. *Milchwissenschaft*. 1987;42:689–692.
53. Kappeler SR, van den Brink H, Rahbek-Nielsen H, Farah Z, Puhani Z, Bech Hansen E, Johansen E. Characterization of recombinant camel chymosin reveals superior properties for the coagulation of bovine and camel milk. *Biochem Biophys Res Commun*. 2006;342:647–654.
54. El Zubeir IEM, Jabreel SO. Fresh cheese from camel milk coagulated with Camifloc. *Int J Dairy Technol*. 2008;61:90–95.
55. Ho TM, Zou Z, Bansal N. Camel milk: A review of its nutritional value, heat stability, and potential food products. *Food Res Int*. 2022;153:110870.
56. Konuspayeva G, Camier B, Aleilawi N, Al-Shumeimyri M, Al-Hammad K, Algruin K, Alshammari F, Beaucher E, Faye B. Manufacture of dry- and brine-salted soft camel cheeses for the camel dairy industry. *Int J Dairy Technol*. 2017;70:92–101.

57. Konuspayeva G, Camier B, Gaucheron F, Faye B. Some parameters to process camel milk into cheese. *Emir J Food Agric.* 2014;26:354-358.
58. Karray N, Lopez C, Lesieur P, Ollivon M. Dromedary milk fat: Thermal and structural properties 2. Influence of cooling rate. *Lait.* 2005;85:433-451.
59. Karray N, Lopez C, Ollivon M, Attia H. La matière grasse du lait de dromadaire: Composition, microstructure et polymorphisme. *Une revue. Ol Corps Gras Lipides.* 2005;12:439-446.
60. Berhe T, Seifu E, Kurtu MY. Physicochemical properties of butter made from camel milk. *Int Dairy J.* 2013;31:51-54.
61. Farah Z, Streiff T, Bachmann MR. Manufacture and characterization of camel milk butter. *Milchwissenschaft.* 1989;44:412-414.
62. Parmar NB. Characterization of ghee prepared from camel milk and evaluation of its shelf life during storage. M.S. thesis Anand Agricultural Univ., Anand, India. 2013.
63. Claeys WL, Verraes C, Cardoen S, De Block J, Huyghebaert A, Raes K, Dewettinck K, Herman L. Consumption of raw or heated milk from different species: An evaluation of the nutritional and potential health benefits. *Food Control.* 2014;42:188-201.
64. Arain MA, Rasheed S, Jaweria A, Khaskheli GB, Barham GS, Ahmed S. A review on processing opportunities for the development of camel dairy products. *Food Sci Anim Resour.* 2023;43:383-401.
65. Abbas S, Ashraf H, Nazir A, Sarfraz L. Physico-chemical analysis and composition of camel milk. *Int Res.* 2013;2:85-98.
66. Agyei D, Owusu-Kwarteng J, Akabanda F, Akomea-Frempong S. Indigenous African fermented dairy products: Processing technology, microbiology and health benefits. *Crit Rev Food Sci Nutr.* 2020;60:991-1006.
67. Alhaj OA, Taufik E, Handa Y, Fukuda K, Saito T, Urashima T. Chemical characterisation of oligosaccharides in commercially pasteurised dromedary camel (*Camelus dromedarius*) milk. *Int Dairy J.* 2013;28:70-75.
68. Asres A, Yusuf M. Traditional consumption, therapeutic value and its derived dairy products of dromedary camel (*Camelus dromedarius*) milk in Somali regional state, Eastern Ethiopia; A review. *Glob J Anim Sci Res.* 2015;3:240-246.
69. Benabdelkamel H, Masood A, Alanazi IO, Alzahrani DA, Alrabiah DK, AlYahya SA, Alfadda AA. Proteomic profiling comparing the effects of different heat treatments on camel (*Camelus dromedarius*) milk whey proteins. *Int J Mol Sci.* 2017;18:721.
70. Bornaz S, Sahli A, Attalah A, Attia H. Physicochemical characteristics and renneting properties of camels' milk: A comparison with goats', ewes' and cows' milks. *Int J Dairy Technol.* 2009;62:505-513.
71. Brezovečki A, Čagalj M, Filipović Dermić Z, Mikulec N, Bendelja Ljolić D, Antunac N. Camel milk and milk products. *Mljekarstvo.* 2015;5:81-90.
72. Dokata MD. Factors influencing camel milk production and central division of Isiolo district: A case of three camel milk women self-help groups in Isiolo County, Kenya. M.S. thesis University of Nairobi, Nairobi, Kenya; 2014.
73. Elhasan SMO, Bushara AMM, Abdelhakam KEK, Elfaki HA, Eibaid AIA, Farahat FH, Ali EMY, Sukrab AMA. Effect of heat treatments on physico-chemical properties of milk samples. *J Acad Ind Res.* 2017;6:40-.
74. El Zubeir IEM, Basher MAE, Alameen MH, Mohammed MAS, Shuipe ES. The processing properties, chemical characteristics and acceptability of yoghurt made from non bovine milks. 2012.
75. Farah Z. Composition and characteristics of camel milk. *J Dairy Res.* 1993;60:603-626.
76. Farah Z, Streiff T, Bachmann MR. Preparation and consumer acceptability tests of fermented camel milk in Kenya. *J Dairy Res.* 1990;57:281-283.
77. Fuquay JW, McSweeney PLH, Fox PF. Encyclopedia of dairy sciences. Academic Press, Cambridge, MA, USA; 2011.
78. Galeboe O, Seifu E, Sekwati-Monang B. Production of camel milk yoghurt: Physicochemical and microbiological quality and consumer acceptability. *Int J Food Stud.* 2018;7:51-63.
79. Genene A, Bech Hansen E, Eshetu M, Hailu Y, Ipsen R. Effect of heat treatment on denaturation of whey protein and resultant rennetability of camel milk. *LWT-Food Sci Technol.* 2019;101:404-409.
80. Gorelik O, Shatskikh Y, Rebezov M, Kanareikina S, Kanareikin V, Lihodeyevskaya O, Andrushechikina N, Harlap S, Temerbayeva M, Dolmatova I, Okuskhanova E. Study of chemical and mineral composition of new sour milk bio-product with sapropel powder. *Annu Res Rev Biol.* 2017;18:1-5.
81. Ifeanyi VO, Ihesiaba EO, Muomaife OM, Ikenga C. Assessment of microbiological quality of yogurt sold by street vendors in Onitsha metropolis, Anambra state, Nigeria. *Microbiol Res J Int.* 2013;3:198-205.
82. Izadi A, Khedmat L, Yousef Mojtahedi S. Nutritional and therapeutic perspectives of camel milk and its protein hydrolysates: A review on versatile biofunctional properties. *J Funct Foods.* 2019;60:103441.
83. Jumah RY, Shaker RR, Abu-Jdayil B. Effect of milk source on the rheological properties of yogurt during the gelation process. *Int J Dairy Technol.* 2001;54:89-93.
84. Khan H, Hussain Athar I, Aslam M. Evaluation of cheese prepared by processing camel milk. *Pak J Zool.* 2004;36:323-326.
85. Konuspayeva G, Lemarie É, Faye B, Loiseau G, Montet D. Fatty acid and cholesterol composition of camel's (*Camelus bactrianus*, *Camelus dromedarius* and hybrids) milk in Kazakhstan. *Dairy Sci Technol.* 2008;88:327-340.
86. Konuspayeva GS. Manufacture and challenges of camel milk cheese. In: Alhaj OA, Faye B, Agrawal RP, editors. Handbook of research on health and environmental benefits of camel products. Hershey, PA, USA: IGI Global; 2020:110-122.
87. Kouniba A, Berrada M, Zahar M, Bengoumi M. Composition and heat stability of Moroccan camel milk. *J Camel Pract Res.* 2005;12:105-110.
88. Lajnaf R, Picart-Palmade L, Attia H, Marchesseau S, Ayadi MA. Foaming and adsorption behavior of bovine and camel proteins mixed layers at the air/water interface. *Colloids Surf B Biointerfaces.* 2017;151:287-294.
89. Laleye LC, Jobe B, Wasesa AAH. Comparative study on heat stability and functionality of camel and bovine milk whey proteins. *J Dairy Sci.* 2008;91:4527-4534.
90. Mahajan A, Dua S. Salts and pH induced changes in functional properties of amaranth (*Amaranthus tricolor* L.) seed meal. *Cereal Chem.* 2002;79:834-837.
91. Mahgoub S, Sulieman AME. Production and quality assessment of camel milk cheese. In African fermented food products: New trends Sulieman AME, Mariod AA, (ed) Springer, Cham, Switzerland. 2022:189-202.
92. Marsh AJ, Hill C, Paul Ross R, Cotter PD. Fermented beverages with health-promoting potential: Past and future perspectives. *Trends Food Sci Technol.* 2014;38:113-124.
93. Mehaia MA. Manufacture of fresh soft white cheese (Domiat-type) from ultrafiltered goats' milk. *Food Chem.* 2002;79:445-452.
94. Mourad K, Nour-Eddine K. Physicochemical and microbiological study of "shmen", a traditional butter made from camel milk in the Sahara (Algeria): Isolation and identification of lactic acid bacteria and yeasts. *Grasas y Aceites.* 2006;57:198-204.
95. Muthukumaran MS, Mudgil P, Baba WN, Ayoub MA, Maqsood S. A comprehensive review on health benefits, nutritional composition and processed products of camel milk. *Food Rev Int.* 2022.

96. Nahar N, Islam Khan W, Shoeb M. Physico-chemical analysis and composition of camel milk of Bangladesh. *J Basic Appl Sci.* 2016;12:231–235.
97. Park YW, Juárez M, Ramos M, Haenlein GFW. Physico-chemical characteristics of goat and sheep milk. *Small Rumin Res.* 2007;68:88–113.
98. Pica-Ciamarra U, Baker D, Morgan N, Ly C, Nouala S. Business and livelihoods in African livestock: Investments to overcome information gaps World Bank, Washington, DC, USA. 2014.
99. Ramet JP. The technology of making cheese from camel milk (*Camelus dromedarius*). Food and Agriculture Organization, Roma, Italy. 2001.
100. Rankin SA, Christiansen A, Lee W, Banavara DS, Lopez-Hernandez A. Invited review: The application of alkaline phosphatase assays for the validation of milk product pasteurization. *J Dairy Sci.* 2010;93:5538–5551.
101. Sagar SP, Mehta BM, Wadhvani KN, Darji VB, Aparnathi KD. Evaluation of camel milk for selected processing-related parameters and comparisons with cow and buffalo milk. *Int J Health Anim Sci Food Saf.* 2016;3:27–37.
102. Sakandar HA, Ahmad S, Perveen R, Wasim Aslam HK, Shakeel A, Ahmad Sadiq F, Imran M. Camel milk and its allied health claims: A review. *Prog Nutr.* 2018;20:15–29.
103. Sikkema RS, Farag EABA, Islam M, Atta M, Reusken CBEM, Al-Hajri MM, Koopmans MPG. Global status of middle East respiratory syndrome coronavirus in dromedary camels: A systematic review. *Epidemiol Infect.* 2019;147:e84.

How to cite this article: Kantale RA, Bind A, Sharma S, Mote AB, Ayoub H, Singh V, et al. *Camelus dromedarius* milk: Composition, techno-functional characteristics, emerging processing and future AI automation. *International Journal of Advanced Chemistry Research.* 2026;8(10):09-20. doi: <https://www.doi.org/10.33545/26646781.2026.v8.i10a.752>

Authors

Rushikesh A Kantale

Department of Livestock Products Technology, RRCVAS, Deoli, Tonk, Rajasthan, India

Akshay Bind

Department of Veterinary Gynecology, BAIF, Pune, Maharashtra, India

Saurabh Sharma

Department of Veterinary Extension Education, RRCVAS, Deoli, Tonk, Rajasthan, India

Akash B Mote

Division of Veterinary Public Health, ICAR-IVRI, Izatnagar, Uttar Pradesh, India

Haris Ayoub

Division of Veterinary Public Health, ICAR-IVRI, Izatnagar, Uttar Pradesh, India

Vibha Singh

Division of Veterinary Public Health, ICAR-IVRI, Izatnagar, Uttar Pradesh, India

Kiran Shinde

Division of Animal Nutrition, ICAR-IVRI, Izatnagar, Uttar Pradesh, India

Aakir Ahmed

Division of Animal Nutrition, SKUAST, Jammu, Jammu and Kashmir, India

Amitava Paul

Department of Veterinary Pathology, CAU, Aizawl, Mizoram, India