



Therapeutic Potential of Camel Milk: Current Evidence Emerging Mechanisms and Future Directions

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INTRODUCTION

Camel milk has traditionally been consumed in arid and semi-arid regions of Africa, the Middle East and Asia, where camels provide an important source of food under challenging environmental conditions. In recent years, camel milk has attracted considerable scientific interest because of its distinctive nutritional and protein composition and the presence of potentially bioactive proteins, peptides, minerals, vitamins and other functional components. Research has increasingly moved beyond its traditional nutritional role toward understanding its possible applications as a functional food and source of bioactive compounds.

Unlike bovine milk, camel milk has a different distribution of caseins and whey proteins and contains little or no β -lactoglobulin. It also contains lactoferrin, lysozyme, immunoglobulins and other proteins that have been investigated for antimicrobial and immunomodulatory properties. Recent research has further expanded toward bioactive peptides, probiotic camel milk and extracellular vesicles, particularly exosomes. Nevertheless, the evidence is not equally strong for all proposed health benefits, and many findings remain based on laboratory and animal models rather than large human clinical trials.

Nutritional and Bioactive Basis of Camel Milk

Camel milk composition varies with breed, geographical origin, season, stage of lactation, feeding and management. A global systematic review and meta-analysis involving 7,298 samples from 23 countries reported average contents of approximately 3.17% protein, 3.47% fat, 4.28% lactose and 0.78% ash. It also provides important minerals such as calcium, potassium, magnesium and zinc and contains vitamin C (Alhaj et al., 2022).

The functional potential of camel milk extends beyond conventional nutrients. Lactoferrin, lysozyme, immunoglobulins and other proteins may contribute to antimicrobial and immune-related activities, while digestion and fermentation can generate peptides with

additional biological functions. A comprehensive review by Khaliq et al. (2024) emphasized the importance of these bioactive constituents in current investigations of camel milk as a functional food.

Table 1: Major bioactive components of camel milk and current research interests

Bioactive component	Major research interest
Lactoferrin	Antimicrobial and immunomodulatory activity
Lysozyme	Antimicrobial activity
Immunoglobulins	Immune-related functions
Bioactive peptides	Glucose metabolism, enzyme inhibition and cellular signaling
Probiotic microorganisms	Gut microbiota and metabolic health
Extracellular vesicles/exosomes	Delivery of proteins, lipids and regulatory RNAs
Vitamins and minerals	Nutritional and antioxidant support
Unsaturated fatty acids	Metabolic and cardiovascular research

Camel milk composition and processing characteristics have also received increasing attention. Arain et al. (2024) reviewed its techno-functional properties and processing constraints, while Seyiti et al. (2024) summarized the composition, bioactivities and processing potential of Bactrian camel milk. These studies highlight the importance of species, breed, environmental and processing differences when evaluating camel milk functionality.

Camel Milk and Diabetes

Diabetes is one of the most extensively investigated health applications of camel milk. Proposed mechanisms include effects on insulin signaling, glucose uptake, pancreatic β -cell function and enzymes involved in glucose metabolism. Camel milk-derived peptides are also being investigated for their interaction with molecular pathways associated with glucose homeostasis (Ayoub et al., 2024).

Human evidence is promising but heterogeneous. AlKurd et al. (2022) conducted a systematic review and meta-analysis of randomized controlled trials involving patients with diabetes and reported potential improvements in selected measures of glycemic control, although considerable heterogeneity existed among the studies. These findings

support further investigation but do not establish camel milk as a replacement for conventional diabetes treatment.

A related meta-analysis by Khalid et al. (2023) examined lipid outcomes in patients with diabetes and reported potential improvements in several lipid parameters following camel milk consumption, again with substantial variability among studies.

Recent research is moving from whole milk toward specific camel milk proteins and peptides. Khan et al. (2025) investigated camel milk and enzymatically hydrolyzed camel milk proteins in diabetic rats. The hydrolysates demonstrated antidiabetic effects in experimental models, including changes in insulin secretion and metabolic pathways.

An important recent development is the study by Liu et al. (2025), in which probiotic camel milk powder was administered to patients with type 2 diabetes. The four-week intervention was associated with reductions in fasting blood glucose, total cholesterol and selected inflammatory cytokines, together with changes in gut-associated *Bifidobacterium*. Although the study was relatively small and short-term, it demonstrates the growing interest in combining camel milk with probiotics for metabolic health.

Bioactive Peptides: From Milk Proteins to Functional Ingredients

Camel milk proteins can release biologically active peptides during gastrointestinal digestion, fermentation or controlled enzymatic hydrolysis. These peptides are being investigated for possible antihypertensive, antihyperglycemic, antimicrobial and enzyme-inhibitory activities.

Ayoub et al. (2024) reviewed camel milk-derived peptides associated with insulin signaling, glucose uptake, pancreatic β -cell function and metabolic enzymes. The authors emphasized that identifying the exact molecules responsible for reported effects is essential for developing scientifically supported functional products.

Althnaibat et al. (2024) similarly reviewed peptides generated from camel and bovine milk protein hydrolysates and noted that several biological activities identified in vitro have not yet been adequately confirmed in clinical studies. This distinction is important because peptide activity observed under laboratory conditions does not necessarily translate into an equivalent effect after oral consumption.

Current research is therefore increasingly using proteomics, peptide sequencing, simulated gastrointestinal digestion, molecular docking and structure–activity analysis to identify candidate peptides. The ultimate objective is to convert these discoveries into standardized functional food ingredients with defined composition and reproducible biological activity.

Gut Health, Fermentation and Microbiota

The relationship between camel milk and the intestinal microbiome has become an important area of current research. Fermentation can modify milk proteins, generate new peptides and metabolites, improve preservation and provide a suitable environment for beneficial microorganisms.

Ansari et al. (2024) reviewed probiotic camel milk and highlighted the potential of

lactic acid bacteria, *Bifidobacterium* and fermentation-derived metabolites. At the same time, technological challenges such as standardization, sensory quality and commercialization remain important considerations.

Camel milk also contains naturally occurring antimicrobial components. Hamed et al. (2024) reviewed lactoferrin, lysozyme, immunoglobulin G, lactoperoxidase and other antimicrobial factors, while also discussing fermented camel milk and microbiological safety.

Recent research is moving further toward characterization of individual antimicrobial peptides. Dai et al. (2024) reviewed antimicrobial peptides from camel milk and highlighted their potential applications in food and biomedical research. However, most of these applications remain at the experimental stage.

Camel Milk and Intestinal Inflammation

The interaction between camel milk components, intestinal inflammation and the gut microbiome is another rapidly developing research area. Kang et al. (2025) reported that camel milk protein alleviated experimental ulcerative colitis in mice while modifying gut microbiota and amino acid metabolism. The study also observed reductions in inflammatory mediators and improvement in intestinal pathology.

These findings remain preclinical but provide a mechanistic basis for investigating camel milk proteins as potential functional food components for maintaining intestinal health.

The research has progressed further toward extracellular vesicles. Yu et al. (2026) investigated camel milk exosomes and their miR-148a-3p cargo in a mouse model of DSS-induced colitis. The treatment reduced disease severity and inflammatory responses, improved intestinal barrier integrity and altered gut microbial diversity. The study also implicated the SIRT1/NF- κ B pathway.

Extracellular Vesicles and Exosomes: A New Frontier

One of the most innovative developments in camel milk research is the study of extracellular vesicles (EVs) and exosomes. These nanoscale structures can carry proteins, lipids and regulatory RNAs and may protect their cargo from degradation.

Yang et al. (2026) investigated camel milk exosomes in high-fat-diet and streptozotocin-induced diabetic mice. Exosome administration reduced blood glucose, improved lipid metabolism, attenuated liver injury and increased hepatic glycogen. The study also reported restoration of hepatic mitochondrial complex I activity and changes in hepatic metabolites and gut microbiota.

These findings are particularly interesting because they suggest that the biological activity of camel milk may involve not only conventional nutrients and proteins but also nanoscale biological carriers.

Research is also extending camel milk EV technology toward targeted drug delivery. Chen et al. (2025) developed camel milk-derived extracellular vesicles for co-delivery of siVEGF and sorafenib in experimental hepatocellular carcinoma. The engineered system enhanced tumour inhibition in experimental models.

Importantly, this does **not** demonstrate that consumption of camel milk treats cancer. Rather, it illustrates how camel milk-derived vesicles may serve as experimental biological delivery systems.

A 2026 review by Yang et al. described camel milk extracellular vesicles as an emerging functional-food and nutraceutical research area. The review emphasized potential effects on oxidative stress, intestinal barrier integrity and gut microbiota, while also highlighting the major gap in human clinical evidence.

Antioxidant, Anti-inflammatory and Immunomodulatory Potential

Camel milk proteins, peptides, vitamins and other constituents have demonstrated antioxidant and anti-inflammatory activities in

experimental systems. Sharma et al. (2025) reviewed evidence covering several proposed biological activities, including neuroprotective, immunomodulatory and anticancer effects.

Current research is increasingly concentrating on mechanisms involving inflammatory signaling, oxidative stress, mitochondrial function and gut microbiota rather than simply reporting total antioxidant capacity. This mechanistic approach is important for determining whether observed effects are attributable to specific camel milk molecules and whether they can be reproduced in humans.

Camel Milk and Autism: Evidence Requires Caution

Camel milk has attracted considerable public interest in relation to autism spectrum disorder. However, this area requires particularly cautious interpretation.

Kandeel et al. (2024) conducted a meta-analysis of randomized clinical trials investigating camel milk consumption and autism-related outcomes. Although some individual studies have reported behavioral or biochemical changes, the pooled evidence did not demonstrate a significant overall improvement in Childhood Autism Rating Scale scores.

Therefore, current evidence does not justify presenting camel milk as a treatment for autism. This example demonstrates why findings from individual trials should be interpreted together with systematic evidence and appropriate clinical endpoints.

Hypoallergenic Potential

Camel milk is also being investigated as an alternative dairy source because its protein composition differs from that of bovine milk. Its low level or absence of β -lactoglobulin has generated particular interest in allergy-related research.

Jayamanna Mohottige et al. (2025) used proteomic approaches to investigate immune proteins, bioactive peptides and potential allergens in bovine and Arabian camel

milk. Their findings further support the need to understand camel milk at the individual protein and peptide level rather than assuming that all milk proteins have identical biological effects.

However, potentially lower allergenicity does not mean that camel milk is completely allergen-free. Individuals with diagnosed milk allergy should therefore seek appropriate clinical advice before consuming camel milk.

Processing and Functional Product Development

The nutritional and bioactive potential of camel milk must ultimately be translated into safe and acceptable food products. Camel milk behaves differently from bovine milk during heating, coagulation, fermentation and drying, creating technological challenges for conventional dairy processing.

Araïn et al. (2024) highlighted the importance of understanding camel milk's techno-functional properties and processing constraints for the development of improved dairy products. Khaliq et al. (2024) similarly reviewed applications including camel milk powder and other value-added products.

Fermented camel milk and probiotic beverages are particularly interesting because fermentation can improve preservation, modify sensory properties and generate additional metabolites and peptides. The development of standardized starter cultures and controlled fermentation systems may therefore increase the consistency and commercial potential of camel milk-based functional foods.

Safety Considerations

The increasing popularity of camel milk should be accompanied by appropriate attention to food safety. Raw camel milk may contain pathogenic microorganisms, and the microbial profile can vary according to production, handling, region and season. Hamed et al. (2024) emphasized the importance of microbiological safety and appropriate processing of camel milk.

Safety should also be considered according to the form of the product. Raw milk, pasteurized milk, fermented milk, powdered milk and purified camel milk components cannot be assumed to have identical biological properties. Standardization of processing and characterization of the final product are consequently essential for future functional-food applications.

Future Perspective

The future of camel milk research is expected to move from general investigations of its nutritional and therapeutic properties toward a more molecule-specific and mechanism-based understanding of its biological activity. Increasing attention is being given to bioactive peptides, extracellular vesicles, exosomes, microRNAs and fermentation-derived metabolites that may contribute to the observed physiological effects. Integration of proteomics, metabolomics, microbiome analysis and advanced molecular techniques could help identify specific compounds, their mechanisms of action and their bioavailability following digestion. At the same time, advances in fermentation, encapsulation and other food-processing technologies may facilitate the development of standardized camel milk-based functional foods with consistent bioactive properties. Although experimental studies on diabetes, intestinal inflammation, oxidative stress and targeted delivery systems are encouraging, translation of these findings into human health applications requires larger, well-designed clinical trials, standardized camel milk preparations and clearly defined dose-response relationships. Recent work on camel milk extracellular vesicles particularly illustrates both the opportunities and limitations of this field: these nanoscale components show promising preclinical functionality, but human clinical evidence remains limited (Yang et al., 2026). Greater understanding of the influence of breed, geographical origin, season, feeding system and processing on bioactive composition will also be important for product

standardization. Thus, future research should aim to bridge the gap between promising laboratory evidence and clinically validated, safe and commercially feasible camel milk-based functional foods.

CONCLUSION

Camel milk has evolved from a traditional pastoral food into an important subject of modern food, nutritional and biomedical research. Its distinctive protein composition, antimicrobial proteins, bioactive peptides, probiotic potential and extracellular vesicles provide several plausible mechanisms for biological activity.

Among the current research areas, **metabolic health, bioactive peptides, gut microbiota and extracellular vesicles represent particularly active fields**. Human studies provide promising but still limited evidence for metabolic effects, whereas much of the emerging research on exosomes, intestinal inflammation and targeted delivery remains preclinical.

Camel milk should therefore presently be regarded as a **nutrient-rich functional food with promising bioactive potential**, rather than a proven therapeutic substitute for medical treatment. Continued integration of dairy science, food technology, molecular biology, microbiome research and clinical nutrition will be essential for translating promising laboratory findings into safe, standardized and evidence-based camel milk products.

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