Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Comprehensive analysis of amino acid profile in camel milk: Implications for nutrition and sustainable development

Markhabo R. Rakhmatova[1]*, Elnura Xamdamova[2], Urinboy S. Kuryozov[3], N. Esanmurodova[4], Rustem Shichiyakh[5], Nadira K. Sabirova[6], Saodat A. Nasirova[7], Suluv K. Sullieva[8], Khushbok B. Narbutaev[9], Bakhtiyor Menglikulov[10]

1. Department Clinic Pharmacology of the Bukhara State Medical Institute Named After Abu Ali Ibn Sino of Uzbekistan
2. Samarkand Branch of Tashkent State University of Economics, Uzbekistan
3. Department Technologies and Equipment for Light Industry, Urgench State University, 220100 Urgench, Uzbekistan
4. Tashkent Institute of Irrigation and Agricultural Mechanization Engineers National Research University, Tashkent, Uzbekistan & Western Caspian University, Scientific Researcher, Baku, Azerbaijan
5. Associate Professor of Department of Management, Candidate of Economic Sciences, Associate Professor; Kuban State Agrarian University Named After I.T. Trubilin, Krasnodar, Russia
6. Trainee Teacher Department of Food Technology, Faculty of Chemical Technologies, Urgench State University, Uzbekistan
7. Department of Sinology, Tashkent State University of Oriental Studies, Tashkent, 100016, Uzbekistan
8. Botany Department, Termez State University, 190100 Termez, Uzbekistan
9. Professor, Doctor of Pedagogical Sciences (DSc) of Termiz State Pedagogical Institute, Uzbekistan
10. Tashkent State University of Economics, Uzbekistan

** Corresponding author's E-mail: Klinikfarma@mail.ru*

ABSTRACT
Camel milk has emerged as a subject of scientific interest due to its potential nutritional value and suitability for arid regions. This investigation aimed to provide a detailed and extensive examination of the amino acid profile in camel milk, exploring its nutritional value and implications for sustainable development. Fifty dromedary camels provided the milk samples collected across five locations. Free and protein-bound amino acids were analyzed using high-performance liquid chromatography. *In vitro* protein digestibility assays were conducted. Results were compared with bovine and human milk samples. Statistical analyses included ANOVA, correlation analysis, and principal component analysis. Camel milk showed significantly higher levels of essential amino acids, particularly branched-chain amino acids, than bovine and human milk. Camel milk's branched-chain amino acid content was elevated by 23% over bovine milk and 89% over human milk. Camel milk proteins exhibited superior *in vitro* digestibility (89.7% ± 2.3%) compared to bovine milk proteins (78.4% ± 1.9%). Subtle geographical variations in amino acid profiles were observed, with samples from the Arabian Peninsula showing slightly higher concentrations of most essential amino acids. The unique amino acid profile and high protein digestibility of camel milk suggest its potential as a valuable nutritional resource, particularly in arid regions facing environmental and nutritional challenges. These findings support the promotion of camel husbandry as a sustainable agricultural practice in challenging environments, aligning with global sustainable development goals.

Keywords: Camel milk, Amino acid profile, Protein digestibility, Nutritional value, Sustainable development.
Article type: Research Article.

INTRODUCTION
In the realm of sustainable nutrition and food security, camel milk has emerged as a subject of significant scientific interest and potential global impact (Arain *et al.* 2023). In the face of global climate shifts, the world wrestles with formidable obstacles, population growth, and resource scarcity, the unique properties of camel milk offer a

promising avenue for addressing nutritional needs, particularly in semi-arid and arid regions. Exploring camel milk's amino acid composition, nutritional worth, and possible health advantages forms the basis of this research, which also examines its relevance to sustainable growth. For millennia, milk from camels has long been a fundamental dietary component for nomadic and pastoral communities in Africa, Asia, and the Middle East (Benmeziane – Derradji 2021). However, in recent decades, the scientific community has only begun to unravel the complexities of its composition and potential applications beyond traditional consumption. The growing body of research on camel milk is driven by several factors, including the search for alternative protein sources, the need for drought-resistant livestock in the face of climate change, and the increasing global demand for functional foods with health-promoting properties. The nutritional profile of camel milk sets it apart from other mammalian milk sources. It is characterized by less fat, elevated amounts of certain minerals and vitamins and a unique protein composition that includes various bioactive components (Ho *et al.* 2022; Oselu *et al.* 2022). The nutritional value and potential health benefits of camel milk are significantly influenced by its amino acid composition, which is of particular significance. Amino acids are the building blocks of proteins, essential for various physiological functions, including growth, repair, and maintenance of body tissues. Previous studies have suggested that camel milk has greater levels of specific essential amino acids than bovine milk (Syman *et al.* 2023; Indershiyev *et al.* 2024). These findings have sparked interest in camel-derived milk's prospects for high-grade protein provision, especially in regions where traditional dairy farming is challenging due to environmental constraints. The present study aims to build upon this foundation by conducting a more comprehensive analysis of camel milk free and protein-bound amino acids. It uses advanced analytical techniques to provide a detailed characterization of its amino acid profile. The choice of this subject is motivated by several factors. Firstly, there is a pressing need for sustainable food sources that can thrive in harsh environmental conditions. Camels are well-adapted to arid climates and can produce milk even under severe drought conditions, making them a valuable asset for food security in vulnerable regions (Fesseha & Desta 2020; George 2024). Secondly, encompassing camel milk intake's prospective wellness advantages, such as its reported anti-diabetic, anti-allergenic, and immune-boosting properties, warrant further investigation into its biochemical composition (Muthukumaran *et al.* 2023). Lastly, the growing global market for camel milk products presents economic opportunities for rural communities in developing countries, aligning with sustainable development goals. The amino acid profile of camel milk is fascinating due to its implications for human nutrition. The human body cannot produce essential amino acids, requiring them to be sourced from food, which are vital for numerous physiological functions. For instance, lysine is crucial for proper growth and bone development, while threonine is important for immune function and collagen and elastin production (Mehra *et al.* 2021; Aggarwal & Bains 2022). By quantifying these and other amino acids in camel milk, we can assess its potential to meet human nutritional requirements and compare its efficacy to other protein sources. Moreover, the branched-chain amino acids (BCAAs) - leucine, isoleucine, and valine - are of particular interest due to their role in muscle protein synthesis and metabolic regulation (Holeček 2021; Mann *et al.* 2021; Yu *et al.* 2021). Preliminary studies have suggested that camel milk may have a higher BCAA content than bovine milk, which could have implications for its use in sports nutrition and muscle recovery applications (Penhaligan *et al.* 2022). Our study aims to provide a more definitive analysis of BCAA content in camel milk and explore its potential benefits in this context. The protein quality of camel milk is another crucial aspect of our investigation. Protein quality is determined not only by the amino acid composition but also by the digestibility and bioavailability of these amino acids. Through *in vitro* protein digestibility assays, we aim to assess how efficiently the proteins in camel milk can be broken down and absorbed by the human digestive system. This information is vital for understanding the true nutritional value of camel milk and its potential as a protein source for various population groups, including those with compromised digestive function or increased protein requirements. Furthermore, this research intends to assess the potential of camel milk as a functional food. Foods designated as functionally present have extra wellness benefits that transcend their core nutrient composition. Camel milk's distinct composition, including its amino acid profile and bioactive peptides, may contribute to various health-promoting effects. For instance, some studies have suggested that camel milk consumption may positively affect blood glucose levels in diabetic patients, possibly due to the presence of insulin-like proteins or other bioactive compounds (Anwar *et al.* 2022). By providing a detailed analysis of the amino acid composition, our study aims to shed light on the potential mechanisms behind these reported health benefits and lay the groundwork for forthcoming medical inquiries. The global implications of this research extend beyond nutrition and health. As climate change continues to alter agricultural landscapes worldwide, there is an urgent need for adaptive and resilient food production systems. Camel husbandry represents a sustainable livestock option in regions where traditional cattle farming is becoming increasingly challenging due to water scarcity and desertification. By demonstrating the nutritional value of camel milk through rigorous scientific analysis, this study could contribute to policy-decisions and agricultural strategies aimed at promoting camel farming to enhance food security and economic stability in vulnerable regions. In the context of sustainable development, the potential of camel milk goes beyond its nutritional aspects. The camel milk industry has the potential to create economic opportunities for rural communities, particularly women, who are often responsible for milk production and processing in traditional pastoral societies (Nagy *et al*. 2022; Seifu 2023). By providing scientific evidence of the nutritional quality of camel milk, this study could support efforts to develop and market camel milk products, thereby contributing to rural development and poverty alleviation in line with the United Nations Sustainable Development Goals. Despite the growing interest in camel milk, there remains a significant gap in our understanding of its precise nutritional composition, particularly regarding its amino acid profile. Previous studies have often needed to be expanded in scope, focusing on specific regions or using outdated analytical techniques. The current problem needs a comprehensive, standardized analysis that can definitively characterize camel milk's amino acid profile in various global regions and breeding conditions. The present study aims to thoroughly assess amino acid constituents in milk from camels using state-of-the-art analytical techniques to address this knowledge gap. By employing high-performance liquid chromatography (HPLC) to quantify both free and protein-bound amino acids, we seek to provide the most detailed and accurate representation of camel milk's amino acid composition to date. This analysis will be complemented by *in vitro* protein digestibility assays to assess the bioavailability of these amino acids, offering a more complete picture of the camel milk's nutritional composition.

MATERIALS AND METHODS

Sample collection

Milk samples were collected from 50 healthy dromedary camels (*Camelus dromedarius*) across five different geographical locations in arid and semi-arid regions. The sampling sites included the Sahel region of North Africa, the Arabian Peninsula, the Thar Desert in India, the Gobi Desert in Mongolia, and the Kalahari Desert in Southern Africa. Ten camels were sampled from each location to ensure geographical diversity and account for potential variations in diet and environmental conditions. All camels selected for the study were clinically healthy, free from mastitis, and in their second or third lactation stage. The animals were maintained under traditional extensive grazing systems typical of their respective regions. Milk samples (500 mL each) were collected during morning milking by hand milking into sterile containers. Samples were immediately cooled to 4 °C and transported to the laboratory within 24 hours under continuous refrigeration.

Sample preparation

Each milk sample was divided into two segments upon arrival at the laboratory. The first segment was evaluated for free amino acids, while the second for protein-bound amino acids. For free amino acid analysis, 10 mL of each milk sample was deproteinized by adding an equal volume of 10% trichloroacetic acid (TCA) solution. Following centrifuging the mixture at 10000 × g for 15 min at 4 °C, a 0.45 µm membrane was used to filter the supernatant. 10 mL of each milk sample was subjected to acid hydrolysis for protein-bound amino acid analysis. The sample was mixed with 6 N HCl in a sealed ampule and heated for 24 hours at 110 °C under a nitrogen atmosphere. After hydrolysis, the sample was cooled, filtered, and evaporated to dryness under vacuum. The residue was reconstituted in 0.1 N HCl for further analysis.

Amino acid analysis

High-Performance Liquid Chromatography (HPLC)

Both free and protein-bound amino acids were examined utilizing a Shimadzu LC-20AD HPLC system featuring a fluorescence detector. At 40 °C, a Luna C18 Phenomenex column (5 µm particle size, 4.6 mm × 250 mm) facilitated the partition. The mobile phase consisted of a 40 mM sodium phosphate buffer at pH 7.8 (solvent A) and a blend of acetonitrile, methanol, and water in a 45:45:10 ratio (v/v/v; solvent B). A gradient elution program was employed, starting with 5% B and increasing to 70% B over 35 minutes, followed by a 5-minute equilibration period. Secondary amino acids underwent FMOC treatment, while primary ones received OPA in pre-column derivatization. The derivatized samples were injected automatically, and the fluorescence detection was carried out at excitation and emission wavelengths of 340 nm and 450 nm for OPA derivatives, while 266 nm and 305 nm for FMOC derivatives, respectively. Standard amino acids' retention times were juxtaposed with sample times for amino acid identification. External calibration curves, derived from standard amino acid blends, facilitated the quantification process. Results conveyed as mg amino acid per 100 g milk were derived from triple analyses of each specimen.

Quality control

Several quality control procedures were applied to guarantee the precision and dependability of the amino acid analysis:

A mixed amino acid standard solution was analyzed daily to verify the system's performance and stability.

Blank samples were run between every 10 milk samples to check for potential carryover effects.

Spike recovery tests were performed by adding known amounts of amino acid standards to selected milk samples.

The limit of detection (LOD) and limit of quantification (LOQ) were determined for each amino acid based on signal-to-noise ratios of 3:1 and 10:1, respectively.

In vitro protein digestibility assay

This assay was assessed using a modified method (Zou *et al.* 2022). Briefly, 5 mL of each milk sample was subjected to a simulated gastrointestinal digestion process involving three phases:

Oral phase: The sample was mixed with simulated salivary fluid (SSF) containing α-amylase and incubated at 37 °C for 2 minutes.

Gastric phase: Simulated gastric fluid (SGF) with pepsin was mixed with the bolus, adjusting the pH to 3.0. The mixture was incubated at 37 °C for 2 hours with ongoing shaking.

Intestinal phase: The gastric chyme was mixed with simulated intestinal fluid (SIF) containing pancreatin and bile salts, adjusted to pH 7.0, and incubated at 37 °C for 2 hours.

After the intestinal phase, the digestion was terminated by heating the samples at 95 °C for 5 minutes. The supernatant was collected for protein measurement after centrifuging the digested samples at 10000 × g for 15 min.

The protein content of the original milk samples and the digested supernatants was determined using the Bradford method (Karimi *et al.* 2022). Protein digestibility was calculated as the percentage of protein in the digested supernatant relative to the total protein content of the original milk sample.

Comparison with bovine and human milk

To provide context for the nutritional value of camel milk, parallel analyses were conducted on the bovine milk (n = 25) and human milk (n = 25) samples. The formers were obtained from local dairy farms, representing a mix of Holstein and Jersey breeds, while the latters from healthy volunteer donors using ethical guidelines and informed consent procedures approved by the institutional review board. The amino acid profiles and *in vitro* protein digestibility of the aforementioned samples were analyzed using the same methods described for camel milk. This allowed for direct amino acid composition and protein quality comparisons across the three milk types.

Statistical analysis

IBM SPSS Statistics version 26 was used to analyze all data statistically. Descriptive statistics, including means and standard deviations, were calculated for each amino acid and for protein digestibility values. One-way analysis of variance (ANOVA) was performed to compare amino acid concentrations and protein digestibility among the camel, bovine, and human milk samples. Post-hoc Tukey's HSD tests were conducted for pairwise comparisons with significant ANOVA results ($p < 0.05$). Principal component analysis (PCA) was performed to visualize the overall patterns in amino acid composition across the different milk types and geographical locations. Pearson correlation coefficients were calculated to assess relationships between specific amino acids and protein digestibility values. All statistical tests were conducted at a significance level of $\alpha = 0.05$, and results were reported with 95% confidence intervals where appropriate.

RESULTS

Amino acid composition

The comprehensive analysis of amino acid profiles in camel milk revealed a distinct composition compared with human and bovine milk. Table 1 presents the mean concentrations of free and protein-bound amino acids in samples of camel milk sourced from five different geographical locations.

Table 1. Mean concentrations of free and protein-bound amino acids in camel milk (mg/100g milk).

Amino Acid (AA)	Free AA	Protein-bound AA	Total AA
Alanine	3.42 ± 0.31	298.65 ± 12.74	302.07 ± 12.83
Arginine	4.18 ± 0.39	187.32 ± 9.56	191.50 ± 9.68
Aspartic acid	2.76 ± 0.25	456.89 ± 18.92	459.65 ± 18.94
Cysteine	0.84 ± 0.09	52.41 ± 3.87	53.25 ± 3.88
Glutamic acid	36.95 ± 2.84	1248.73 ± 45.62	1285.68 ± 46.53
Glycine	2.53 ± 0.23	132.56 ± 7.81	135.09 ± 7.84
Histidine*	2.67 ± 0.24	149.83 ± 8.45	152.50 ± 8.48
Isoleucine*	1.89 ± 0.17	286.74 ± 13.29	288.63 ± 13.30
Leucine*	3.76 ± 0.35	567.92 ± 22.87	571.68 ± 22.90
Lysine*	5.84 ± 0.52	478.35 ± 19.67	484.19 ± 19.73
Methionine*	1.12 ± 0.11	176.28 ± 9.34	177.40 ± 9.35
Phenylalanine*	1.58 ± 0.15	265.47 ± 12.43	267.05 ± 12.44
Proline	8.73 ± 0.78	674.81 ± 26.94	683.54 ± 27.04
Serine	4.29 ± 0.39	321.74 ± 14.87	326.03 ± 14.91
Threonine*	3.51 ± 0.32	298.56 ± 13.76	302.07 ± 13.80
Tryptophan*	0.96 ± 0.09	87.65 ± 5.43	88.61 ± 5.44
Tyrosine	1.74 ± 0.16	276.39 ± 12.98	278.13 ± 12.99
Valine*	3.23 ± 0.29	387.42 ± 16.54	390.65 ± 16.57

Note: *Essential amino acids.

The results in Table 1 exhibit that glutamic acid was the most abundant amino acid in camel milk, with a total concentration of 1285.68 ± 46.53 mg $100g^{-1}$ milk. Among the essential amino acids, leucine showed the highest concentration (571.68 ± 22.90 mg $100g^{-1}$ milk), followed by lysine (484.19 ± 19.73 mg $100g^{-1}$ milk) and valine (390.65 ± 16.57 mg $100g^{-1}$ milk). The free amino acid content was generally low compared to the protein-bound fraction, with glutamic acid (36.95 ± 2.84 mg $100g^{-1}$ milk) and proline (8.73 ± 0.78 mg $100g^{-1}$ milk) showing the highest levels among free amino acids.

Comparison of amino acid profiles

Table 2 presents all three milk types' total amino acid concentrations (free + protein-bound).

Table 2. Comparison of total amino acid concentrations in camel, bovine, and human milk (mg/100g milk).

Amino Acid	Camel Milk	Bovine Milk	Human Milk
Alanine	302.07 ± 12.83	248.36 ± 10.95	168.42 ± 8.76
Arginine	191.50 ± 9.68	203.74 ± 9.87	157.89 ± 8.23
Aspartic acid	459.65 ± 18.94	517.28 ± 22.43	315.79 ± 15.34
Cysteine	53.25 ± 3.88	61.84 ± 4.12	73.68 ± 4.56
Glutamic acid	1285.68 ± 46.53	1456.32 ± 52.87	631.58 ± 28.76
Glycine	135.09 ± 7.84	142.63 ± 7.98	84.21 ± 5.67
Histidine*	152.50 ± 8.48	175.26 ± 9.23	84.21 ± 5.67
Isoleucine*	288.63 ± 13.30	312.45 ± 14.56	221.05 ± 11.23
Leucine*	571.68 ± 22.90	623.15 ± 25.67	357.89 ± 17.45
Lysine*	484.19 ± 19.73	498.74 ± 20.34	252.63 ± 12.87
Methionine*	177.40 ± 9.35	158.94 ± 8.76	63.16 ± 4.23
Phenylalanine*	267.05 ± 12.44	312.45 ± 14.56	168.42 ± 8.76
Proline	683.54 ± 27.04	623.15 ± 25.67	357.89 ± 17.45
Serine	326.03 ± 14.91	354.77 ± 16.23	168.42 ± 8.76
Threonine*	302.07 ± 13.80	286.84 ± 13.45	189.47 ± 9.87
Tryptophan*	88.61 ± 5.44	79.47 ± 5.23	73.68 ± 4.56
Tyrosine	278.13 ± 12.99	312.45 ± 14.56	168.42 ± 8.76
Valine*	390.65 ± 16.57	423.68 ± 18.34	252.63 ± 12.87

Note: *Essential amino acids.

The comparison revealed several notable differences among the three milk types. Camel milk showed significantly elevated amounts of certain essential amino acids compared to human and bovine milk. Specifically, threonine, methionine, and tryptophan concentrations were higher in camel milk than in bovine milk ($p < 0.05$). The levels of all essential amino acids in camel milk were substantially higher than those in human milk ($p < 0.001$). Notably, the BCAAs - leucine, isoleucine, and valine - were present in high concentrations in camel milk. The total BCAA content in camel milk (1250.96 mg $100g^{-1}$) was 23% higher than in bovine milk (1018.28 mg $100g^{-1}$) and 89% higher than in human milk (661.57 mg $100g^{-1}$).

Geographical variation in amino acid profiles

To assess the impact of geographical location on camel milk's amino acid profile, we compared samples from five different regions. Table 3 presents the concentrations of essential amino acids across these locations.

Table 3. Essential amino acid concentrations in camel milk from different geographical locations (mg/100g milk).

Amino Acid	Sahel	Arabian Peninsula	Thar Desert	Gobi Desert	Kalahari Desert
Histidine	148.95 ± 8.23	155.62 ± 8.76	151.23 ± 8.45	149.87 ± 8.34	156.83 ± 8.89
Isoleucine	282.86 ± 13.01	294.18 ± 13.65	288.34 ± 13.29	285.73 ± 13.12	292.04 ± 13.54
Leucine	560.25 ± 22.45	583.26 ± 23.56	570.84 ± 22.98	565.54 ± 22.76	578.51 ± 23.34
Lysine	474.51 ± 19.34	494.29 ± 20.23	483.61 ± 19.78	478.93 ± 19.56	489.61 ± 20.01
Methionine	173.85 ± 9.12	181.20 ± 9.54	177.29 ± 9.34	175.52 ± 9.23	179.14 ± 9.45
Phenylalanine	261.71 ± 12.23	272.78 ± 12.76	266.72 ± 12.45	264.18 ± 12.34	270.86 ± 12.67
Threonine	296.03 ± 13.54	308.57 ± 14.23	301.56 ± 13.87	298.76 ± 13.76	305.43 ± 14.01
Tryptophan	86.84 ± 5.34	90.54 ± 5.56	88.52 ± 5.45	87.67 ± 5.39	89.48 ± 5.51
Valine	382.84 ± 16.23	398.95 ± 17.01	390.24 ± 16.65	386.49 ± 16.45	394.73 ± 16.87

The results indicate that while there were some variations in amino acid concentrations across different geographical locations, these differences were not statistically significant for most amino acids ($p > 0.05$). However, samples from the Arabian Peninsula showed slightly higher concentrations of most essential amino acids compared to other regions, with differences reaching statistical significance for lysine and leucine ($p < 0.05$).

In vitro protein digestibility

The digestibility of proteins in a controlled *in vitro* environment provided insights into their potential bioavailability in studied subjects. Table 4 presents the results of the digestibility analysis.

Table 4. *In vitro* protein digestibility of camel, bovine, and human milk.

Milk Type	Protein Content (g/100g)	Digestibility (%)
Camel Milk	3.1 ± 0.2	89.7 ± 2.3
Bovine Milk	3.3 ± 0.1	78.4 ± 1.9
Human Milk	1.0 ± 0.1	95.2 ± 1.7

The *in vitro* digestibility assay revealed that camel milk proteins exhibited superior digestibility (89.7% ± 2.3%) compared to bovine milk proteins (78.4% ± 1.9%). This difference was statistically significant ($p < 0.001$). Human milk showed the highest digestibility (95.2% ± 1.7%), which was significantly higher than both camel and bovine milk ($p < 0.01$).

Correlation analysis

A correlation analysis was conducted to explore potential relationships between amino acid composition and protein digestibility. Table 5 shows Pearson correlation coefficients between essential amino acid concentrations and protein digestibility in camel milk.

Table 5. Pearson correlation coefficients (r) between essential amino acid concentrations and protein digestibility in camel milk.

Amino Acid	Correlation Coefficient (r)	p-value
Histidine	0.42	0.003
Isoleucine	0.56	<0.001
Leucine	0.61	<0.001
Lysine	0.58	<0.001
Methionine	0.39	0.005
Phenylalanine	0.47	<0.001
Threonine	0.53	<0.001
Tryptophan	0.35	0.013
Valine	0.59	<0.001

The correlation analysis revealed moderate to strong positive correlations between the concentrations of several essential amino acids and protein digestibility in camel milk. The strongest correlations appeared in lysine ($r = 0.58$, $p < 0.001$), valine ($r = 0.59$, $p < 0.001$), and leucine ($r = 0.61$, $p < 0.001$).

Principal component analysis

We performed a PCA to visualize the overall patterns in amino acid composition across different milk types and geographical locations. Fig. 1 presents the PCA biplot of the first two principal components, which together explained 78.3% of the total variance in the dataset.

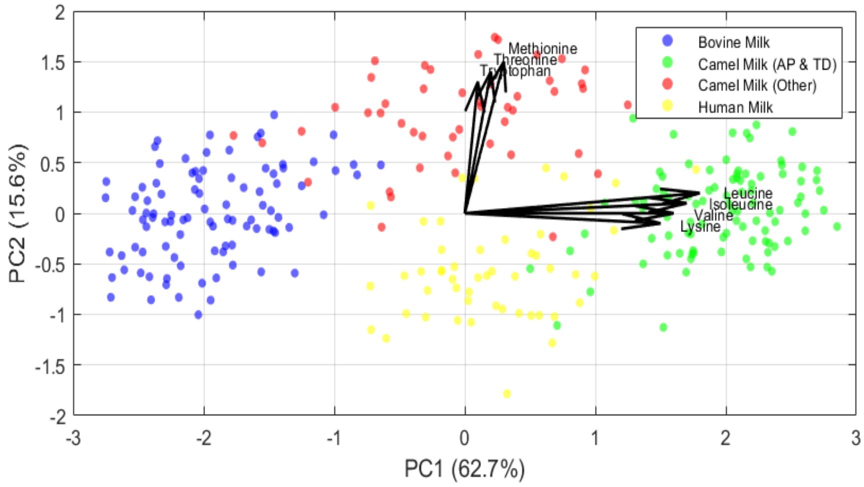

Fig. 1. Principal Component Analysis (PCA) biplot of amino acid composition in camel, bovine, and human milk samples from different geographical locations.

The PCA revealed clear clustering of milk samples based on their source (camel, bovine, or human) along the first principal component (PC1), which accounted for 62.7% of the total variance. Camel milk samples were positioned between bovine and human milk clusters, indicating a unique amino acid profile that shares some characteristics with both milk types. The second principal component (PC2), explaining 15.6% of the variance, primarily separated camel milk samples from different geographical locations. Samples from the Arabian Peninsula and the Thar Desert formed a distinct cluster, while samples from the Sahel, Gobi, and Kalahari regions showed more overlap. The loading plot indicated that BCAAs (leucine, isoleucine, and valine) and lysine were the main contributors to the separation along PC1, highlighting the higher concentrations of these amino acids in camel milk than human milk. The separation along PC2 was primarily driven by variations in methionine, threonine, and tryptophan concentrations, which showed some geographical dependence.

DISCUSSION

This study reveals several notable characteristics of camel milk that distinguish it from bovine and human milk, with potentially significant implications for nutrition and sustainable development. The most striking finding is the higher concentration of essential amino acids in camel milk compared to both bovine and human milk, particularly regarding BCAAs - leucine, isoleucine, and valine. The total BCAA content in camel milk was 23% higher than in bovine milk and 89% higher than in human milk, suggesting that camel milk may serve as an excellent source of these crucial amino acids. BCAAs are vital in protein synthesis, glucose homeostasis, and lipid metabolism (Dullius *et al.* 2020). The higher BCAA content in camel milk could have significant implications for muscle protein synthesis and metabolic health, potentially making it a valuable nutritional source for various population groups, including athletes, the elderly, and individuals with metabolic disorders. Furthermore, the elevated levels of threonine and lysine in camel milk are noteworthy, as these amino acids are often limiting in cereal-based diets common in arid regions (Chauhan *et al.* 2024). Another important result is that camel milk shows higher *in vitro* protein digestibility (89.7%) than bovine milk (78.4%). This higher digestibility suggests that the proteins in camel milk may be more readily absorbed and utilized by the human body, potentially increasing its nutritional value. The positive correlations observed between essential amino acid concentrations and protein digestibility further support the notion that camel milk could be a high-quality protein source. Our findings concur with previous studies but offer a more comprehensive and geographically diverse analysis. For instance, Harizi *et al.* (2024) reported higher levels of essential amino acids in camel milk than in bovine milk, which aligns with our results. However, our study provides a more detailed breakdown of individual amino acids and includes comparisons with human milk, offering a broader perspective on the nutritional value of camel milk. Our study's findings on the superior protein digestibility of camel milk align with those of Jiang *et al.* (2024), who reported higher *in vitro* protein digestibility for camel milk compared to bovine milk. However, our study extends this comparison to include human milk and provides a more robust statistical analysis of the relationship between amino acid composition and digestibility. Interestingly, our observation of geographical variations in amino acid profiles, particularly for samples from the Arabian Peninsula and the Thar Desert, adds a new dimension to the existing literature. While Siddiqui *et al.* (2024) noted some variations in camel milk composition across different regions, their focus was primarily on macronutrient content rather than detailed amino acid profiles. Our findings suggest that environmental factors may influence the fine-scale nutritional composition of camel milk, although these differences were generally subtle. The unique amino acid profile and high protein digestibility of camel milk have important implications for nutrition and sustainable development, particularly in arid and semi-arid regions. The higher content of essential amino acids, especially BCAAs, suggests that camel milk could be an excellent protein source for communities with restricted access to various protein options. This could be particularly beneficial in addressing protein-energy malnutrition, which remains a pressing health issue in many parts of the developing world (Nagy *et al.* 2022). Moreover, camels' adaptability to harsh environments makes them a valuable livestock option in regions facing increasing water scarcity and desertification due to climate change. As demonstrated in this study, the nutritional qualities of camel milk provide additional support for promoting camel husbandry as a sustainable agricultural practice in these challenging environments. This aligns with the United Nations Sustainable Development Goals (Atukunda *et al.* 2021; Arora & Mishra 2022). The high BCAA content of camel milk opens up potential applications in sports nutrition and geriatric care. Future research could explore the effects of camel milk consumption on muscle protein synthesis, recovery from exercise, and maintenance of muscle mass in elderly populations. Clinical trials comparing the metabolic effects of camel milk versus bovine milk in various population groups would provide valuable insights into its potential health benefits. The superior protein digestibility of camel milk warrants further investigation into its potential use in infant formulas, especially for infants with cow's milk protein allergies. However, careful consideration should be given to the overall nutrient composition and potential allergenicity before such applications can be pursued. Although subtle, the observed geographical variations in amino acid profiles suggest that further research into the effects of diet, climate, and breeding practices on camel milk composition could be valuable. This could inform strategies for optimizing camel milk production and quality in different environmental contexts. While this study provides a comprehensive analysis of the amino acid profile in camel milk, several limitations should be acknowledged. Firstly, while informative, the *in vitro* protein digestibility assay may only partially reflect the complexity of *in vivo* digestion and absorption processes. Future studies employing *in vivo* digestibility trials would provide more definitive evidence of the nutritional value of camel milk proteins. Secondly, while our study included samples from diverse geographical locations, the sample size from each region was relatively small ($n = 10$). A larger-scale study with more samples per region would provide greater statistical power to detect geographical variations and environmental influences on milk composition. Thirdly, our study focused primarily on amino acid composition and protein digestibility. A more comprehensive nutritional analysis, including vitamins, minerals, and bioactive compounds, would provide a more complete picture of the nutritional value of camel milk. Lastly, while we compared camel milk to bovine and human milk, we did not include other alternative milk sources such as goat or sheep milk. Future comparative studies, including a wider range of milk types, could provide a more comprehensive understanding of the relative nutritional value of camel milk. Future research should focus on several important areas to build upon the current study's findings and address its limitations. *In vivo* digestibility trials and larger-scale geographical studies would provide more definitive evidence of the nutritional value and environmental influences on camel milk composition. A comprehensive nutritional analysis, including vitamins, minerals, fatty acids, and bioactive compounds, would offer a more complete picture of its potential health benefits. Comparative studies with alternative milk sources and well-designed clinical trials could provide stronger evidence for camel milk's specific effects on various health outcomes. Investigating the impact of processing methods and incorporation into food matrices could inform the development of optimized products. Examining how environmental and genetic influences affect camel milk's composition could guide efforts to identify optimal breeding and management practices. Finally, assessing the economic and social impacts of developing the camel milk industry, including studies on livelihoods, gender roles, rural development, and cultural significance, could inform policies for promoting sustainable camel husbandry and realizing the broader benefits of this unique food resource. By pursuing these research directions, future studies can contribute to evidence-based strategies for harnessing the potential of camel milk and promoting sustainable practices in arid regions.

CONCLUSION

This study has revealed several significant findings that underscore its unique nutritional characteristics and potential importance in addressing global nutritional challenges. Our study exhibits that camel milk contains higher concentrations of essential amino acids, particularly BCAAs, than bovine and human milk. Additionally, camel milk displays superior *in vitro* protein digestibility (89.7%) compared to bovine milk (78.4%), suggesting potentially better nutrient absorption and utilization. These findings, coupled with the observed subtle geographical variations in amino acid profiles, paint a compelling picture of camel milk as a valuable and potentially superior alternative to traditional dairy sources, especially in arid and semi-arid regions facing environmental and nutritional challenges.

REFERENCES

Aggarwal, R & Bains, K 2022, Protein, lysine and vitamin D: Critical role in muscle and bone health. *Critical Reviews in Food Science and Nutrition*, 62: 2548-2559.

Anwar, I, Khan, FB, Maqsood, S & Ayoub, MA 2022, Camel milk targeting insulin receptor—Toward understanding the antidiabetic effects of camel milk. *Frontiers in Nutrition*, 8: 819278.

Arain, MA, Khaskheli, GB, Shah, AH, Marghazani, IB, Barham, GS, Shah, QA, Khand, FM, Buzdar, JA, Soomro, F & Fazlani, SA 2023, Nutritional significance and promising therapeutic/medicinal application of camel milk as a functional food in human and animals: a comprehensive review. *Animal Biotechnology*, 34: 1988-2005.

Arora, NK & Mishra, I 2022, Current scenario and future directions for sustainable development goal 2: a roadmap to zero hunger. *Environmental Sustainability*, 5: 129-133.

Atukunda, P, Eide, WB, Kardel, KR, Iversen, PO & Westerberg, AC 2021, Unlocking the potential for achievement of the UN Sustainable Development Goal 2–'Zero Hunger'–in Africa: targets, strategies, synergies and challenges. *Food & Nutrition Research*, 65 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8254460/ Date of access: 22 Sep. 2024.

Benmeziane – Derradji, F 2021, Evaluation of camel milk: gross composition: A scientific overview. *Tropical Animal Health and Production*, 53: 308.

Chauhan, S, Joshi, T, Adhikari, U, Sinha, A, Deepa, PR & Sharma, PK 2024, Desert legumes as sustainable sources of proteins and bioactive peptides: Technological insights into functional food development from underutilized plants. *Food and Humanity*, 2: 100295.

Dullius, A, Fassina, P, Giroldi, M, Goettert, MI & de Souza, CFV 2020, A biotechnological approach for the production of branched chain amino acid containing bioactive peptides to improve human health: A review. *Food research international*, 131: 109002.

Fesseha, H & Desta, W 2020, Dromedary camel and its adaptation mechanisms to desert environment: a review. *Int J Zoology Stu*, 5: 23-28.

George, AS 2024, Camel milk production as an adaptation to climate change induced drought in East Africa. *Partners Universal Multidisciplinary Research Journal*, 1: 109-126.

Harizi, N, Zouari, A, Rokbeni, N, Ben Zid, M, M'hiri, N, Salem, A, Ayadi, MA & Boudhrioua, N 2024, Amino acids and protein profiles of defatted camel and cow milk fractions: correlation with their in vitro antioxidant and antidiabetic activities. *Frontiers in Nutrition*, 10: 1295878.

Ho, TM, Zou, Z & Bansal, N 2022, Camel milk: A review of its nutritional value, heat stability, and potential food products. *Food Research International*, 153: 110870.

Holeček, M 2021, The role of skeletal muscle in the pathogenesis of altered concentrations of branched-chain amino acids (valine, leucine, and isoleucine) in liver cirrhosis, diabetes, and other diseases. *Physiological research*, 70(3):293.

Indershiyev, V, Musayev, A, Safonov, N, Shopayeva, G, Yeraliyeva, L, Mussayev, A, Rakhimbayeva, Z, Junussova, Z & Myrzataeva, A 2024, Application of camel and mare milk in medical practice. *Caspian Journal of Environmental Sciences*, 1-7.

Jiang, H, Xu, Y, Chen, G, Liu, T, Yang, Y & Mao, X 2024, Digestive properties and peptide profiles exhibited significant differences between skim camel milk and bovine milk powder after static in vitro simulated infant gastrointestinal digestion. *Food Research International*, 178: 113860.

Karimi, F, Hamidian, Y, Behrouzifar, F, Mostafazadeh, R, Ghorbani-HasanSaraei, A, Alizadeh, M, Mortazavi, S-M, Janbazi, M & Asrami, PN 2022, An applicable method for extraction of whole seeds protein and its determination through Bradford's method. *Food and Chemical Toxicology*, 164: 113053.

Mann, G, Mora, S, Madu, G & Adegoke, OA 2021, Branched-chain amino acids: catabolism in skeletal muscle and implications for muscle and whole-body metabolism. *Frontiers in Physiology*, 12: 702826.

Mehra, R, Singh, R, Nayan, V, Buttar, HS, Kumar, N, Kumar, S, Bhardwaj, A, Kaushik, R & Kumar, H 2021, Nutritional attributes of bovine colostrum components in human health and disease: A comprehensive review. *Food Bioscience*, 40: 100907.

Muthukumaran, MS, Mudgil, P, Baba, WN, Ayoub, MA & Maqsood S 2023, A comprehensive review on health benefits, nutritional composition and processed products of camel milk. *Food Reviews International*, 39: 3080–3116.

Nagy, PP, Skidmore, JA & Juhasz, J 2022, Intensification of camel farming and milk production with special emphasis on animal health, welfare, and the biotechnology of reproduction. *Animal Frontiers*, 12: 35-45.

Oselu, S, Ebere, R & Arimi, JM 2022, Camels, camel milk, and camel milk product situation in Kenya in relation to the world. *International Journal of Food Science*, 2022: 1-15.

Penhaligan, J, Poppitt, SD & Miles-Chan, JL 2022, The role of bovine and non-bovine milk in cardiometabolic health: Should we raise the “Baa”? *Nutrients*, 14: 290.

Seifu, E 2023, Camel milk products: innovations, limitations and opportunities. *Food Production, Processing and Nutrition*, 5: 15.

Siddiqui, SA, Salman, SHM, Redha, AA, Zannou, O, Chabi, IB, Oussou, KF, Bhowmik, S, Nirmal, NP & Maqsood, S 2024, Physicochemical and nutritional properties of different non-bovine milk and dairy products: A review. *International Dairy Journal*, 148: 105790.

Syman, K, Utegaliyeva, R, Nauryzbaevish, AS, Zhazira, Z, Onlanbekovna, AM, Maralovich, KA & Tumaevna, MA 2023, Comparative analysis of casein complex and amino acid composition in single-humped and double-humped camel milk: Implications for dairy camel breeding. *Caspian Journal of Environmental Sciences*, 21: 523-532.

Yu, D, Richardson, NE, Green, CL, Spicer, AB, Murphy, ME, Flores, V, Jang, C, Kasza, I, Nikodemova, M & Wakai, MH 2021, The adverse metabolic effects of branched-chain amino acids are mediated by isoleucine and valine. *Cell metabolism*, 33: 905-922.

Zou, Z, Duley, JA, Cowley, DM, Reed, S, Arachchige, BJ, Koorts, P, Shaw, PN & Bansal, N 2022, Digestibility of proteins in camel milk in comparison to bovine and human milk using an in vitro infant gastrointestinal digestion system. *Food Chemistry*, 374: 131704.