frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 10 September 2025
DOI 10.3389/fsufs.2025.1602232

OPEN ACCESS

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RECEIVED 29 March 2025
ACCEPTED 26 August 2025
PUBLISHED 10 September 2025

CITATION
Kapshakbayeva Z, Utegenova A, Assirzhanova Z, Agibaeva A, Omarova K, Jumazhanova M, Kyrykbayeva S, Baybalinova G, Khaimuldinova A, Baikadamova A and Zhakupbekova S (2025) Valorizing indigenous goat milk: functional, nutritional, and sensory properties of Halloumi cheese from northern Kazakhstan.
Front. Sustain. Food Syst. 9:1602232.
doi: 10.3389/fsufs.2025.1602232

Valorizing indigenous goat milk: functional, nutritional, and sensory properties of Halloumi cheese from northern Kazakhstan

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Introduction: Consumer interest in functional dairy foods has grown, yet limited data exist on Halloumi cheese produced from indigenous goat milk in Kazakhstan. This study aimed to evaluate the nutritional, functional, and sensory attributes of goat milk Halloumi compared with sheep and cow milk variants.
Methods: Fresh goat, sheep, and cow milk from northern Kazakhstan was processed into Halloumi cheese under standardized conditions. Nutritional composition, amino acid and fatty acid profiles, antioxidant capacity (DPPH and ABTS assays), microbiological safety, and sensory properties were assessed. Statistical significance was determined using one-way ANOVA with Tukey's post-hoc test ($p < 0.05$).
Results and discussion: Goat milk Halloumi exhibited significantly higher antioxidant activity (DPPH 75.5 ± 1.2%; ABTS 15.8 ± 0.5 mg Trolox/g) than sheep (70.2 ± 1.0%; 13.6 ± 0.4 mg TE/g) and cow variants (62.8 ± 0.8%; 11.9 ± 0.3 mg TE/g). It also contained higher levels of essential amino acids and a favorable fatty acid profile enriched in medium-chain and omega-3 fatty acids. Microbiological testing confirmed safety and elevated lactic acid bacteria counts, while sensory evaluation indicated strong consumer acceptance. The findings demonstrate that indigenous goat milk Halloumi combines superior nutritional composition, antioxidant potential, and sensory quality. Benchmarking against other cheeses further suggests its distinct functional properties, although cross-study differences in assay protocols should be considered.
Conclusion: Goat milk Halloumi represents a safe, functional dairy product that supports sustainable, resilient, and health-oriented food systems. Its production from indigenous goat milk also highlights the value of regional resources in diversifying dairy products and strengthening local food security.

KEYWORDS

goat milk Halloumi, functional foods, antioxidant capacity, bioactive peptides, nutritional composition

1 Introduction

Over the past decade, consumer interest in functional foods has grown substantially, leading to increased focus on dairy products with health-enhancing qualities. Functional foods, which offer health benefits beyond basic nutritional value, are valued for their ability to improve overall well-being and lower the risk of chronic illnesses. Among these, goat milk-based products have gained prominence due to their distinct bioactive components, such as peptides, medium-chain fatty acids (MCFAs), and antioxidants. These components contribute to the superior digestibility, high nutritional value, and potential health-promoting properties of goat milk products (Barłowska et al., 2018; López-Villafaña et al., 2023; Thakur et al., 2024).

Halloumi cheese, originating from Cyprus and recognized as a Protected Designation of Origin (PDO) product in the European Union since 2021, is traditionally made from goat milk or a mixture of sheep and goat milk. Its production has been documented since at least 1,554, underscoring its deep cultural and historical roots (European Commission, 2021). Halloumi is valued for its semi-hard texture, high protein content, and culinary versatility. In this context, Halloumi-style cheese made from goat milk in Kazakhstan represents a regional adaptation of this traditional cheese, rather than a novel product. Goat milk Halloumi possesses distinctive characteristics, including a milder flavor, creamier texture, and a richer bioactive composition. Studies have shown that goat milk contains higher concentrations of medium-chain fatty acids (MCFAs), essential amino acids, and bioactive peptides compared to cow and sheep milk, enhancing its nutritional quality and digestibility (Ali et al., 2022; Saremnezhad et al., 2024; Kapshakbayeva et al., 2018). These features make goat milk Halloumi particularly attractive to health-conscious consumers. Nonetheless, its potential as a functional dairy product remains underexplored. Most existing research has focused on traditional Halloumi or other goat milk cheeses, leaving a significant gap in understanding the specific nutritional, sensory, and functional benefits of goat milk Halloumi. Addressing this gap is important for advancing functional dairy research and supporting the development of sustainable, regionally produced alternatives that align with evolving consumer preferences.

This study provides a detailed assessment of the nutritional profile, antioxidant activity, microbiological parameters, and sensory attributes of Halloumi cheese produced from goat milk. By benchmarking these features against Halloumi made from sheep and cow milk, the research underscores the potential of goat milk Halloumi as a functional dairy product suited to health-aware consumers. The findings enhance the current understanding of bioactive dairy foods and point to promising directions for future exploration, including clinical health validations, industrial scalability, and broader inclusion in functional food formulations.

2 Materials and methods

2.1 Materials

Fresh milk from goats, sheep, and cows was sourced from private farms located in the Astana and Pavlodar regions of Northern Kazakhstan. The goat milk originated from resilient local breeds well adapted to regional environmental conditions. These breeds are well-adapted to the local climate and feeding conditions, producing milk characterized by a distinct flavor profile and high nutritional quality. Goat, sheep and cow milk were all sourced from the same region to ensure consistency in environmental, feeding, and management factors that could influence milk composition. All milk samples were collected in sterile containers, transported under refrigeration at 4 °C, and processed within 12 h to preserve compositional integrity. Calcium chloride (≥99% purity) and other analytical-grade reagents, including methanol and hydrochloric acid, were procured from Merck (Darmstadt, Germany). DPPH and ABTS reagents, along with Trolox standards and amino acid kits, were supplied by Sigma-Aldrich (St. Louis, MO, USA). Whatman No.1 filter paper (Cytiva, Buckinghamshire, UK) was used for filtration steps. The 37-component fatty acid methyl ester (FAME) standard mix was obtained from Sigma-Aldrich, and powdered calf rennet (SG-50 "Normal," chymosin: pepsin 1:1) was purchased from Moscow Rennet Plant (Russia). Microbiological media (nutrient agar, XLD, MacConkey, and Baird-Parker agars) were supplied by HiMedia Laboratories (India).

2.2 Halloumi cheese production

Cheese production was conducted using a standardized method adapted for laboratory scale. This approach ensured that differences observed in the final products were attributable to the milk type rather than variations in processing conditions. The comprehensive setup enabled an in-depth evaluation of the functional food potential of goat milk Halloumi cheese compared to sheep and cow milk variants. Milk from each source was pasteurized at 72–74 °C for 20 s to reduce microbial load while minimizing degradation of heat-sensitive components. Calcium chloride (0.02%, *w/v*) was added to promote curd formation by enhancing casein micelle stability. Coagulation was induced using 1.5 g of rennet (SG-50 "Normal," a natural powdered calf rennet containing chymosin and bovine pepsin in a 1:1 ratio; Moscow Rennet Plant, Russia) per 100 kg of milk. The milk was maintained at 32–34 °C for 40 min to achieve optimal curd formation. The curd was cut into approximately 1 cm cubes, gently stirred, and heated to 40 °C for 20 min to facilitate whey separation. The resulting curds were transferred into molds and pressed under 10 kg/cm^2 for 2 h, followed by an additional self-pressing period of 1 h to ensure uniform moisture content and texture. Pressed cheese blocks were cooked in whey at 85–90 °C for 30 min, ensuring the internal cheese temperature reached 75 °C. This cooking step enhanced the cheese's elastic texture and shelf stability. After cooling, the cheese blocks were salted at 5% (*w/w*), a critical step for flavor enhancement and microbial control. Cheeses were stored at 4 °C for 30 days for ripening. The same production method was applied to all milk types to ensure consistency across treatments, enabling valid comparisons of physicochemical composition, antioxidant activity, and sensory properties.

2.3 Nutritional and biochemical analysis

2.3.1 Proximate composition

Proximate analysis, including moisture, fat, protein, and ash content, was performed using standard AOAC methods (AOAC, 2019). Fat content was determined using the Gerber method, while protein content was analyzed using the Kjeldahl method. Carbohydrate content was calculated by difference. Each analysis was performed in triplicate and results were expressed as a percentage of fresh weight.

2.3.2 Amino acid analysis

Amino acid analysis was conducted to determine the composition of essential and non-essential amino acids in goat, sheep, and cow milk Halloumi cheese. Cheese samples were hydrolyzed in 6 M HCl at 110 °C for 24 h under vacuum, a process designed to release amino acids from proteins while preserving their integrity. The hydrolyzed samples were analyzed using an automated amino acid analyzer (LA8080 Amino Acid Analyzer, AminoSAAYA, Hitachi High-Tech Corporation, Japan), equipped for ion-exchange chromatography. Amino acids were separated based on their charge properties and detected through post-column derivatization with ninhydrin, which produces a measurable color reaction proportional to the amino acid concentration. Quantification was performed by comparison with external standards of individual amino acids (Sigma-Aldrich, St. Louis, MO, USA), ensuring high accuracy. The results were expressed as mg of amino acid per 100 g of cheese on a dry weight basis, providing insights into the nutritional and bioactive potential of the cheese. The results were expressed as mg of amino acid per 100 g of cheese on a dry weight basis to provide a detailed profile of its essential and non-essential amino acid content.

2.3.3 Fatty acid composition

The fatty acid composition of goat, sheep, and cow milk Halloumi cheese was analyzed to evaluate its nutritional profile and potential health benefits. Lipids were extracted from cheese samples using the Folch method, which employs a chloroform-methanol mixture (2:1, *v/v*) to efficiently isolate total lipids while preserving their integrity. The extracted lipids were converted into fatty acid methyl esters (FAMEs) through transesterification using methanolic HCl, ensuring complete derivatization for accurate gas chromatographic analysis. FAMEs were analyzed using a Shimadzu GC-2010 Plus gas chromatograph (Shimadzu Corporation, Japan) fitted with a flame ionization detector (FID) and a DB-23 capillary column (Agilent Technologies, USA; 60 m × 0.25 mm × 0.25 μm film thickness). The system was specifically calibrated to optimize the separation of saturated and unsaturated fatty acids, operating with an injector temperature of 250 °C, detector temperature of 280 °C, and an oven temperature program set at an initial 140 °C for 5 min, then ramped to 240 °C at 4 °C/min. Helium was used as the carrier gas at a constant flow rate of 1.2 mL/min. Individual fatty acids were identified by comparing their retention times with those of external reference standards (Supelco 37 FAME Mix, Sigma-Aldrich, USA). Quantitative results were expressed as percentages of total identified FAMEs, and individual fatty acid contents were also reported as mg per 100 g of cheese to provide a comprehensive profile of saturated, monounsaturated, and polyunsaturated fatty acids. This analysis underscores the functional food potential of goat milk Halloumi cheese by revealing its rich medium-chain fatty acid content, which contributes to improved digestibility and bioactive properties. Moreover, the proportions of omega-3 and omega-6 polyunsaturated fatty acids were determined, and their ratio was calculated to characterize the overall fatty acid profile of the cheese samples.

2.4 Antioxidant properties

2.4.1 DPPH radical scavenging assay

The antioxidant activity of the cheese samples was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, a widely recognized method for determining the free radical scavenging capacity of food extracts. The procedure followed the protocol described by Hilario et al. (2010), with slight modifications to optimize the analysis for cheese matrices. Cheese extracts were prepared by homogenizing 2 g of cheese in 20 mL of methanol, followed by sonication for 30 min to facilitate the extraction of antioxidant compounds. The homogenate was filtered through Whatman No. 1 filter paper (Cytiva, Buckinghamshire, UK) to obtain a clear extract. A stock solution of DPPH (0.1 mM) was prepared in methanol. For the assay, 3 mL of the DPPH solution was mixed with 1 mL of cheese extract and incubated in the dark at room temperature for 30 min to allow the reaction between the antioxidants in the cheese extract and DPPH radicals. The decrease in absorbance at 517 nm, corresponding to the reduction of DPPH radicals, was measured using a UV–Vis spectrophotometer (UV-2600, Shimadzu, Japan). The antioxidant activity was calculated as the percentage of DPPH inhibition using the formula:

$$\text{DPPH inhibition}\,(\%) = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

where A_{control} is the absorbance of the DPPH solution without cheese extract and A_{sample} is the absorbance of the DPPH solution with the cheese extract. Results were expressed as the percentage of inhibition, providing an estimate of the antioxidant capacity of the cheese. This method is used to quantify the ability of goat milk Halloumi cheese to neutralize free radicals, which serve as indicators of potential health-related antioxidant capacity.

2.4.2 ABTS radical cation decolorization assay

The antioxidant capacity of the cheese samples was evaluated using the ABTS radical cation decolorization assay, a reliable method for assessing the ability of food extracts to neutralize free radicals. The procedure followed the method described by Perna et al. (2015), with minor adaptations to optimize it for cheese matrices. ABTS radicals were generated by reacting 7 mM ABTS solution with 2.45 mM potassium persulfate, and the mixture was allowed to stand in the dark at room temperature for 12–16 h to form a stable radical cation solution. The ABTS radical solution was diluted with phosphate-buffered saline (PBS, pH 7.4) to an absorbance of 0.70 ± 0.02 at 734 nm, ensuring consistent reaction conditions. Cheese extracts were prepared by homogenizing 2 g of cheese in 20 mL of methanol, followed by sonication for 30 min to extract antioxidant compounds effectively. The homogenate was filtered through Whatman No. 1 filter paper (Cytiva, Buckinghamshire, UK) to obtain a clear extract. For the assay, 1 mL of the cheese extract was mixed with 3 mL of the diluted ABTS radical solution, and the reaction mixture was incubated in the dark at room temperature for 10 min. The decrease in absorbance at 734 nm, indicative of the reduction of ABTS radicals, was measured using a UV–Vis spectrophotometer (UV-2600, Shimadzu, Japan). The antioxidant capacity of the cheese samples was quantified as Trolox equivalents (μmol TE/g cheese) by comparing the sample's scavenging activity with a standard Trolox calibration curve. The assay is designed to measure the free radical scavenging capacity of Halloumi cheese samples, offering insight into its potential as a functional food with associated health benefits.

2.5 Microbiological and sensory analysis

2.5.1 Microbiological analysis

The microbiological quality of goat milk Halloumi cheese was assessed to evaluate its safety and compliance with international food standards. A range of tests was conducted to evaluate the general microbial load and the presence of specific pathogenic microorganisms, following standard microbiological protocols for dairy products.

2.5.1.1 Total viable count (TVC)

The TVC was determined to evaluate the overall microbial population in the cheese samples, including both beneficial and spoilage organisms. Cheese samples were homogenized in sterile saline solution, and serial dilutions were prepared. Appropriate dilutions were plated onto nutrient agar and incubated at 30 °C for 48 h to allow colony development. Colonies were counted, and results were expressed as colony-forming units per gram (cfu/g) of cheese.

2.5.1.2 Detection of *Salmonella* spp.

The presence of *Salmonella* spp., a critical foodborne pathogen, was assessed using Xylose Lysine Deoxycholate (XLD) agar. Cheese samples were enriched in buffered peptone water and incubated at 37 °C for 24 h to enhance bacterial recovery. Enriched samples were streaked onto XLD agar plates, which were incubated at 37 °C for 24–48 h. Colonies exhibiting characteristic features, such as a red appearance with black centers, were further confirmed using biochemical tests including Triple Sugar Iron (TSI), Lysine Iron Agar (LIA), and Urea tests. The presence or absence of *Salmonella* spp. was used to evaluate compliance with food safety regulations.

2.5.1.3 Detection of *Escherichia coli*

Escherichia coli was tested as an indicator of fecal contamination and sanitary quality during cheese production and handling. Cheese samples were homogenized in sterile saline, and aliquots were plated onto MacConkey agar (HiMedia Laboratories, India), a selective medium for gram-negative bacteria. Plates were incubated at 37 °C for 24 h. Colonies showing typical pink coloration were further confirmed as *E. coli* using standard biochemical tests, including the indole and methyl red reactions.

2.5.1.4 Detection of *Staphylococcus aureus*

The presence of *Staphylococcus aureus* was evaluated using Baird-Parker agar (HiMedia Laboratories, India). Cheese samples were preenriched in tryptone soy broth supplemented with 10% NaCl and incubated at 37 °C for 24–48 h. Colonies exhibiting typical morphology, such as black or gray pigmentation with clear zones, were subjected to confirmatory coagulase testing. Results were used to assess the hygienic status and potential contamination risk associated with cheese production.

2.5.2 Sensory evaluation

The sensory evaluation of Halloumi cheese produced from goat, sheep, and cow milk was conducted by a panel of 12 trained individuals. A 9-point hedonic scale was used, where 1 indicated "extremely dislike" and 9 indicated "extremely like." Each panelist rated four key attributes: flavor, texture, aroma, and overall acceptability. The assessment focused on preference-based responses rather than detailed sensory profiling. All panelists had prior experience in evaluating dairy products, ensuring uniformity in scoring. This approach facilitated quantitative comparisons across cheese types to identify variations in consumer-oriented acceptability.

2.6 Comparative evaluation of goat, sheep, and cow milk Halloumi

To establish a basis for comparative evaluation, goat milk Halloumi cheese was systematically analyzed alongside Halloumi produced from sheep and cow milk. The assessment focused on key parameters, including nutritional composition, antioxidant activity, and sensory attributes, to characterize the functional potential and consumer relevance of each variant. This comparative framework was designed to support a comprehensive analysis of goat milk Halloumi in relation to other milk-based formulations, particularly with respect to its bioactive composition and health-related indicators. The methodological approach was developed to provide an integrated evaluation of goat milk Halloumi cheese within the broader context of functional dairy products, with specific relevance to Kazakhstan's evolving dairy industry and consumer interest in health-oriented innovations.

2.7 Statistical analysis

Data were expressed as mean ± standard deviation (SD) from triplicate analyses. Statistical differences between groups were assessed using one-way analysis of variance (ANOVA), with Tukey's *post-hoc* test applied to pinpoint specific group differences. A threshold of $p < 0.05$ was set to determine statistical significance. All statistical analyses were performed using SPSS software (version 25.0, IBM Corp., Armonk, NY, USA). Superscript letters in the tables indicate

TABLE 1 Proximate composition of goat, sheep, and cow milk Halloumi cheese.

Component	Goat milk Halloumi	Sheep milk Halloumi	Cow milk Halloumi
Fat (% dry matter)	44.1 ± 1.6^{c}	42.5 ± 1.2^{b}	39.8 ± 1.4^{a}
Protein (% dry matter)	40.3 ± 0.5^{c}	39.4 ± 0.7^{b}	38.6 ± 0.6^{a}
Moisture (%)	44.2 ± 0.5^{a}	43.8 ± 0.6^{a}	44.5 ± 0.4^{a}
Carbohydrates (%)	1.2 ± 0.1^{c}	1.0 ± 0.1^{b}	0.9 ± 0.1^{a}
Salt (%)	$1.5–2.5^{a}$	$2.3–3.5^{b}$	$2.4–3.6^{b}$
Active acidity (pH)	$5.9–6.1^{a}$	$5.9–6.2^{a}$	$5.8–6.0^{a}$

Values are presented as mean ± standard deviation. Different superscript letters (a, b, c) within a row indicate significant differences between the means ($p < 0.05$) based on one-way ANOVA followed by Tukey's *post-hoc* test.

statistically significant differences between means within each row when the null hypothesis (H_0) was rejected ($p < 0.05$).

3 Results and discussion

3.1 Physico-chemical properties

The proximate composition and statistical analysis of goat milk Halloumi cheese underscore its nutritional and functional advantages over sheep and cow milk Halloumi. As shown in Table 1, goat milk Halloumi exhibited a fat content of 44.1 ± 1.6% (on a dry matter basis), which was significantly higher ($p < 0.05$) than that of cow milk Halloumi (39.8 ± 1.4%) and marginally higher than sheep milk Halloumi (42.5 ± 1.2%).

Protein content was also notably higher in goat milk Halloumi (40.3 ± 0.5%) compared to sheep milk Halloumi (39.4 ± 0.7%) and cow milk Halloumi (38.6 ± 0.6%), with statistical analysis confirming significant differences ($p < 0.05$) across these groups. The superior protein content of goat milk Halloumi reflects its potential as a protein-rich dietary option, supporting muscle repair and overall health. These findings align with the work of Barłowska et al. (2018), who highlighted the enhanced nutritional density of goat milk cheeses, attributing these benefits to their higher protein and fat concentrations. Carbohydrate content, although minimal, was calculated by difference, yielding values of 1.2 ± 0.1% for goat milk Halloumi, 1.0 ± 0.1% for sheep milk Halloumi, and 0.9 ± 0.1% for cow milk Halloumi. The differences in carbohydrate content were statistically significant ($p < 0.05$), which may reflect variations in lactose metabolism among the different milk types during fermentation. Moisture content was relatively consistent across all cheese types, goat milk Halloumi at 44.2 ± 0.5%, sheep milk Halloumi at 43.8 ± 0.6%, and cow milk Halloumi at 44.5 ± 0.4%, with no statistically significant differences observed. The uniform moisture levels suggest that processing conditions were well-controlled, contributing to similar textural attributes across the cheese variants. Active acidity (pH) values were also comparable, with goat milk Halloumi at 5.9–6.1, sheep milk Halloumi at 5.9–6.2, and cow milk Halloumi at 5.8–6.0, indicating stable fermentation processes and microbial environments.

The compositional analysis indicates that goat milk Halloumi exhibits a distinctive macronutrient profile, marked by elevated levels of fat and protein relative to its counterparts. These parameters contribute to its classification as a nutrient-dense dairy product. Statistical evaluation supports the nutritional distinctiveness of goat milk Halloumi within the broader Halloumi category, suggesting its applicability in diets with elevated protein and energy requirements. Depending on individual dietary needs, these compositional features may provide specific nutritional benefits and align with health-focused dietary strategies.

3.2 Nutritional composition

3.2.1 Amino acid profile

The amino acid analysis of goat milk Halloumi cheese (Table 2) demonstrated a well-balanced profile of essential amino acids, including lysine (2281.97 mg/100 g), leucine (2917.91 mg/100 g), and methionine (783.33 mg/100 g). These amino acids are vital for protein synthesis, muscle repair, and immune function. Furthermore, bioactive amino acids such as tryptophan (411.25 mg/100 g) and arginine (1067.80 mg/100 g) were present in higher concentrations compared to sheep milk Halloumi cheese. The total essential amino acid content of goat milk Halloumi (7462.26 mg/100 g) surpassed that of sheep (7343.64 mg/100 g) and cow milk Halloumi (6888.93 mg/100 g), underscoring its nutritional advantages. Statistical analysis revealed significant differences ($p < 0.05$) in essential amino acid content among the three cheese types, with goat milk Halloumi consistently outperforming the others. These findings align with Park et al. (2007), who reported that goat milk generally has a richer amino acid profile than cow milk products. This study expands on such observations by highlighting the bioactive potential of goat milk-derived amino acids, particularly their roles in antioxidant defense and health promotion.

TABLE 2 Comparison of amino acid composition of goat, cow, and sheep milk Halloumi cheese (mg/100 g).

Amino acid	Goat milk Halloumi	Sheep milk Halloumi	Cow milk Halloumi
Lysine	2281.97 ± 12.34^{c}	2262.32 ± 10.21^{b}	1986.84 ± 15.67^{a}
Leucine	2917.91 ± 18.45^{c}	2855.15 ± 16.89^{b}	2768.40 ± 14.34^{a}
Methionine	783.33 ± 8.23^{c}	770.25 ± 7.91^{b}	721.68 ± 9.56^{a}
Tryptophan	411.25 ± 6.42^{c}	400.14 ± 5.98^{b}	386.65 ± 7.12^{a}
Arginine	1067.80 ± 9.67^{c}	1055.78 ± 8.45^{b}	1025.36 ± 10.29^{a}
Total essential	7462.26 ± 45.34^{c}	7343.64 ± 41.23^{b}	6888.93 ± 47.56^{a}

Data are presented as mean ± standard deviation from triplicate analyses. Different superscript letters (a, b, c) within a row indicate significant differences between the means ($p < 0.05$) based on one-way ANOVA followed by Tukey's *post-hoc* test.

The nutritional value of cheese is significantly influenced by its amino acid composition (Paskaš et al., 2024; Ali et al., 2023; Popović-Vranješ et al., 2016). Goat milk, in particular, has gained attention for its nutritional benefits, including a more favorable amino acid composition and fatty acid profile compared to cow milk (Pajor et al., 2023). Supplementing goats' diets with marine algae, for instance, can further enhance the fatty acid composition of their milk and cheese, increasing the levels of beneficial long-chain n-3 fatty acids (Pajor et al., 2023). Landi et al. (2021) analyzed raw milk from cow, sheep, and goat raised in the Alto Casertano region of Italy and reported that goat milk contained notably higher levels of taurine (approximately 14.9 mg/100 g) compared to cow (1.4 mg/100 g) and sheep (2.1 mg/100 g) milk. Although we did not directly measure taurine in the cheese samples, the elevated levels of essential amino acids observed in goat milk Halloumi suggest a favorable amino acid profile with potential additional health benefits. These compositional characteristics expand the functional relevance of goat milk Halloumi in the context of human nutrition.

The balanced amino acid profile of goat milk Halloumi indicates its suitability for use as a functional dairy product. Essential amino acids such as lysine and leucine are known to support muscle protein synthesis and immune system function. Notably, arginine contributes to cardiovascular health through its role in promoting nitric oxide (NO) production, which aids in vasodilation and vascular regulation (Lorin et al., 2013). Additionally, tryptophan, as a precursor to serotonin and melatonin, has been linked to mood regulation and improved sleep quality (Friedman, 2018). The elevated concentrations

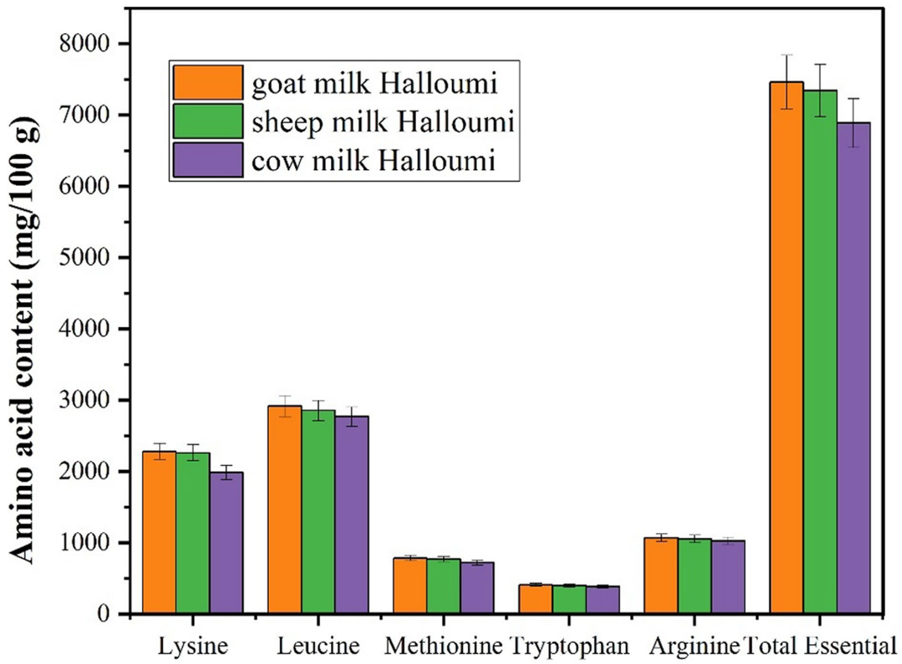

FIGURE 1
Comparison of amino acid composition in goat milk, sheep milk, and cow milk Halloumi cheeses (mg/100 g). Error bars represent the standard deviation of triplicate analyses.

of these amino acids in goat milk Halloumi suggest a favorable nutritional profile, with the potential to support health; however, clinical studies are needed to confirm any specific health benefits.

The digestibility of goat milk proteins, as emphasized by Haenlein (2004), further enhances its appeal for individuals with dietary sensitivities. These findings support the notion that goat milk Halloumi cheese is not only a flavorful and versatile food but also a valuable contributor to health-focused diets. To further illustrate these findings, a bar graph comparing the amino acid content of goat, sheep, and cow milk Halloumi is provided in Figure 1. This visual demonstrates the consistent nutritional advantages observed in goat milk Halloumi.

3.2.2 Fatty acid composition

Compared to sheep and cow milk Halloumi, goat milk Halloumi cheese contains higher concentrations of medium-chain fatty acids (MCFAs), including caproic, caprylic, and capric acids, which are associated with improved digestibility and metabolic benefits. These MCFAs are known for their roles in energy metabolism, antimicrobial properties, and enhanced digestibility, while also contributing to the unique flavor profile of goat milk products (Park et al., 2007; Paszczyk and Łuczyńska, 2020; Haenlein, 2004) (Figure 2). Statistical analysis revealed that the levels of MCFAs in goat milk Halloumi were significantly higher than those in sheep and cow milk Halloumi ($p < 0.05$). This aligns with recent findings by Sonu and Basavaprabhu (2020), who reported that goat milk is a rich source of medium-chain fatty acids, particularly caproic, caprylic, and capric acids, which improve digestibility and provide metabolic benefits. Goat milk Halloumi demonstrated significantly higher levels of these MCFAs compared to both sheep and cow milk Halloumi, consistent with Paszczyk and Łuczyńska (2020), who reported that goat cheeses are richer sources of short- and medium-chain fatty acids than cow cheeses, making them metabolically beneficial and more digestible.

Also, goat milk Halloumi exhibited a higher concentration of omega-3 fatty acids (1.45 mg/100 g) compared to sheep (1.32 mg/100 g) and cow Halloumi (0.98 mg/100 g), with statistically significant differences observed between the three groups ($p < 0.05$). This reinforces its potential cardiovascular health benefits. The omega-6 to omega-3 ratio in goat milk Halloumi was estimated at approximately 18.3, which is comparatively lower than that of sheep (19.5) and cow (28.6) Halloumi cheese, suggesting a relatively more favorable fatty acid profile with respect to cardiovascular health. This finding aligns with the work of authors (Djordjevic et al., 2019; Lešić et al., 2016; Anusha Siddiqui et al., 2024; Pietrzak-Fiecko and Kamelska-Sadowska, 2020), who emphasized that fatty acid composition in dairy products is essential for functional properties, particularly in cheeses, due to their role in nutritional and sensory attributes. As well, Filipczak-Fiutak et al. (2021) observed that goat cheeses, including Halloumi, contain elevated levels of free fatty acids, such as caproic and butyric acids, which further enhance their distinct flavor and nutritional appeal. The statistical differences in fatty acid concentrations between goat, sheep, and cow milk Halloumi provide robust evidence of goat milk Halloumi's superior profile. Taken together, the results indicate that goat milk Halloumi possesses a distinctive fatty acid composition, which may support its role in balanced diets and its use in developing functional dairy products with improved nutritional quality.

3.3 Antioxidant properties

3.3.1 DPPH radical scavenging activity

The DPPH assay demonstrated a strong free radical scavenging activity in goat milk Halloumi cheese, with inhibition rates consistently exceeding 70% at higher extract concentrations (Figure 3). Statistical analysis revealed that the antioxidant capacity of goat milk

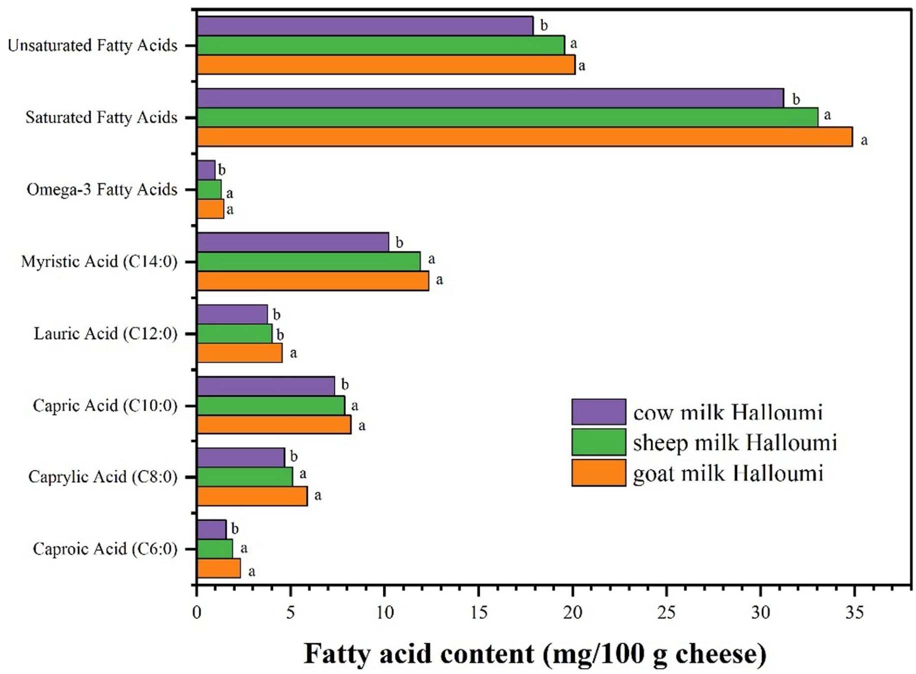

FIGURE 2
Comparative fatty acid composition (mg/100 g cheese) of goat, sheep, and cow milk Halloumi cheese. Data are presented as mean ± standard deviation from triplicate analyses. Different superscript letters (a, b) within a row indicate significant differences between the means ($p < 0.05$) based on one-way ANOVA followed by Tukey's *post-hoc* test.

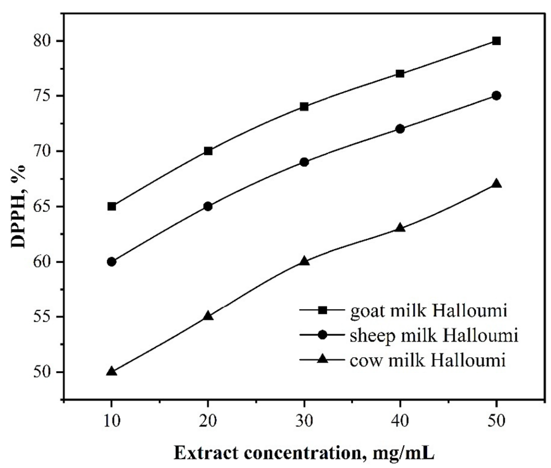

FIGURE 3
DPPH radical scavenging activity of goat, sheep, and cow milk Halloumi cheese extracts at varying concentrations.

Halloumi was significantly higher ($p < 0.05$) than that of sheep and cow milk Halloumi across all tested extract concentrations. This enhanced activity is attributed to the presence of bioactive peptides and phenolic compounds generated during cheese production and ripening. These components are formed through proteolysis and fermentation, where casein and whey proteins in goat milk are enzymatically broken down into peptides with known antioxidant potential. Moreover, goat milk contains higher levels of phenolic compounds and specific amino acids such as tryptophan and tyrosine, which contribute significantly to its enhanced oxidative stability (Pihlanto, 2006).

Although antioxidant potential has been demonstrated in cheeses made from sheep or cow milk using assays like DPPH and ABTS (López-Villafaña et al., 2023; Symeou et al., 2021; Gad and Sayd, 2015), comparative evaluations with goat milk Halloumi have been limited. Halloumi cheese, while not widely studied for antioxidant activity, may exhibit such properties depending on milk source and production methods. For instance, López-Villafaña et al. (2023) showed that the antioxidant peptide content in Panela cheese evolves differently when made from goat versus cow milk, underscoring the influence of milk composition. The present study addresses this gap by demonstrating that goat milk Halloumi exhibits significantly greater ($p < 0.05$) DPPH radical scavenging activity compared to sheep and cow milk Halloumi (Figure 3). This enhancement is likely due to the unique protein and lipid profiles of goat milk that promote the formation of antioxidant peptides during maturation.

Further supporting this, Symeou et al. (2021) found that dietary supplementation of sheep with olive cake silage improved lipid quality and health-related indices in ovine Halloumi cheese, emphasizing how feeding strategies can influence functional properties. Similarly, Elgaml et al. (2017) found that Halloumi cheese produced from goat milk had higher moisture content and total volatile fatty acids than cheeses made from cow milk or a mixture of both. These compositional attributes are known to influence antioxidant potential, as elevated moisture may facilitate the diffusion of bioactive compounds, while volatile fatty acids can enhance the generation of peptides and other antioxidative molecules during proteolysis and lipid metabolism. Such conditions contribute to the improved radical scavenging activity observed in goat milk cheeses (Pihlanto, 2006; Park et al., 2007). The statistical comparisons presented in Figure 3, evaluated by one-way ANOVA followed by Tukey's *post-hoc* test, confirm that goat milk Halloumi extracts have significantly stronger free radical scavenging capacity. These findings support the positioning of goat milk Halloumi as a functional dairy product with greater antioxidant, nutritional, and sensory qualities.

3.3.2 ABTS radical cation decolorization

The ABTS assay further validated the antioxidant capacity of goat milk Halloumi cheese, revealing significantly higher Trolox Equivalent Antioxidant Capacity (TEAC) values compared to sheep and cow milk Halloumi (Table 3). Statistical analysis confirmed that the TEAC values for goat milk Halloumi (15.8 ± 0.5 mg Trolox/g cheese) were significantly higher ($p < 0.05$) than those of sheep milk Halloumi (13.6 ± 0.4 mg Trolox/g cheese) and cow milk Halloumi (11.9 ± 0.3 mg Trolox/g cheese). Similarly, DPPH scavenging activity was significantly greater ($p < 0.05$) in goat milk Halloumi (75.5 ± 1.2%) compared to sheep (70.2 ± 1.0%) and cow milk Halloumi (62.8 ± 0.8%). The observed differences suggest that goat milk Halloumi possesses elevated antioxidant activity, likely influenced by the presence of bioactive peptides and phenolic compounds generated during cheese processing and maturation. These peptides arise from proteolytic breakdown of casein and whey proteins, producing fragments with notable radical-scavenging properties. Furthermore, the lipid fraction of goat milk, enriched in medium-chain fatty acids, may contribute to the overall antioxidant potential, reinforcing the functional characteristics of goat milk Halloumi. The observed outcomes are consistent with López-Villafaña et al. (2023), who reported the progressive evolution of antioxidative properties in protein-derived peptides during the shelf life of Mexican Panela goat milk cheese. Similarly, Galán et al. (2021) reported elevated antioxidant activity in fresh goat cheese, which they associated with the generation of bioactive peptides and phenolic compounds during production - components known to enhance the cheese's functional and health-supportive qualities. In parallel, Ali et al. (2022) discussed the notable antioxidant potential of functional dairy matrices, emphasizing the role of peptides derived from milk proteins in mitigating oxidative stress and supporting physiological well-being. The current observations regarding goat milk Halloumi are consistent with these reports, reflecting its distinct biochemical profile and potential contribution to functional nutrition.

As shown in Table 3, goat milk Halloumi exhibited significantly higher antioxidant activity in both DPPH and ABTS assays compared to its sheep and cow milk counterparts ($p < 0.05$). This enhanced radical scavenging capacity may be attributed to specific bioactive compounds inherent to goat milk, such as peptides generated during proteolysis, amino acids like tryptophan and tyrosine, and polyunsaturated fatty acids including omega-3 and conjugated linoleic acid. These compounds are known to support oxidative balance by neutralizing free radicals (Pihlanto, 2006; Richard et al., 2008). As summarized in Table 2, goat milk Halloumi also contains higher levels of key amino acids and unsaturated fatty acids, which further contribute to its antioxidant potential. These findings provide mechanistic insight into the functional properties of goat milk-based cheese and underscore its potential application in antioxidant-enriched dairy products (Thakur et al., 2024). In addition to outperforming sheep and cow Halloumi in our assays, broader benchmarking against other cheeses reported in the literature indicates that goat milk Halloumi demonstrates comparatively higher antioxidant potential. However, such cross-study comparisons must be interpreted with caution because assay protocols, cheese composition, and processing conditions vary considerably.

TABLE 3 Comparison of antioxidant activity of goat, sheep, and cow milk Halloumi cheeses (DPPH and ABTS assays).

Assay	Antioxidant measure	Goat milk Halloumi	Sheep milk Halloumi	Cow milk Halloumi
DPPH assay	Scavenging activity (%)	75.5 ± 1.2^{c}	70.2 ± 1.0^{b}	62.8 ± 0.8^{a}
ABTS assay	TEAC (mg Trolox/g cheese)	15.8 ± 0.5^{c}	13.6 ± 0.4^{b}	11.9 ± 0.3^{a}

Data are presented as mean ± standard deviation (SD) from triplicate analyses. Different superscript letters (a, b, c) within a row indicate statistically significant differences between the means ($p < 0.05$), based on one-way ANOVA followed by Tukey's *post-hoc* test.

3.4 Microbiological quality

The microbiological quality of goat milk Halloumi cheese, summarized in Table 4, underscores its compliance with international safety standards and highlights the presence of beneficial lactic acid bacteria (LAB). The total viable count (TVC) and lactic acid bacteria (LAB) levels in goat milk Halloumi were significantly higher ($p < 0.05$) than those observed in cow and sheep milk variants, suggesting enhanced microbial activity of LAB strains well adapted to the specific nutrient profile of goat milk. This statistically significant advantage further underscores the potential of goat milk Halloumi as a functional food. The TVC were within acceptable limits, ensuring the hygienic quality of the cheese and reflecting good manufacturing practices. Notably, the substantial presence of LAB contributes significantly to flavor development, texture enhancement, and potential gut health benefits. LAB play an essential role in fermentation, producing organic acids, bacteriocins, and other antimicrobial compounds that inhibit the growth of pathogenic microorganisms while enhancing the sensory attributes of the cheese. These findings are consistent with the work of Nájera et al. (2021), who described similar microbial profiles in traditional cheeses, where LAB were crucial for maintaining safety and enhancing organoleptic characteristics. The results of this study suggest that goat milk Halloumi cheese offers additional advantages, as LAB strains uniquely adapted to goat milk's nutrient composition enhance the production of bioactive compounds during fermentation.

In addition to the natural antimicrobial activity provided by LAB, recent studies have explored complementary strategies for improving microbiological quality in cheeses. For example, Kyrykbaeva et al. (2025) demonstrated the efficacy of natural hop extracts in inhibiting spoilage organisms and extending the shelf life of cheeses without compromising sensory attributes. While hop extract was not applied in this study, its integration into goat milk Halloumi production could be a promising approach for enhancing microbial safety and product longevity. The incorporation of natural antimicrobial agents such as hop extract, in combination with the activity of LAB, may enhance the microbiological stability and functional properties of goat milk Halloumi cheese. Recent research

TABLE 4 Microbiological quality of goat milk Halloumi cheese.

Parameter	Observed value	Acceptable limit	Remarks
Total viable count (TVC)	5.2 × 10^6 cfu/g	<1 × 10^7 cfu/g	Within acceptable limits for safety
Lactic acid bacteria (LAB)	3.8 × 10^6 cfu/g	2–4 × 10^6 cfu/g	High LAB activity; beneficial for flavor and health
Pathogenic microorganisms	Not detected	Absent	Meets safety requirements
Yeast and mold	<10^2 cfu/g	<10^3 cfu/g	Minimal contamination; acceptable

further supports these observations. Veettil and Chitra (2022) identified lactic acid bacteria (LAB) isolated from goat milk as possessing probiotic potential, noting their tolerance to gastrointestinal conditions and their inhibitory effects against common foodborne pathogens. Grujović et al. (2024) also identified indigenous LAB strains in Serbian goat cheese with high technological and functional potential, reinforcing the importance of LAB in improving cheese quality and functionality. The data presented in Table 4 confirm that goat milk Halloumi cheese meets stringent microbiological safety requirements. The high LAB activity observed in this study not only ensures safety but also enhances the cheese's nutritional and functional potential, positioning it as a health-promoting dairy product.

3.5 Sensory evaluation

Sensory evaluation results indicated high consumer acceptability of goat milk Halloumi cheese, with mean scores above 8.0 on a 9-point hedonic scale for flavor, texture, and aroma (Figure 4). All three Halloumi cheese types—goat, sheep, and cow milk—were evaluated under identical sensory conditions using the same 9-point hedonic scale, where 1 represented "extremely dislike" and 9 represented "extremely like." A panel of 12 trained evaluators assessed the acceptability of flavor, texture, aroma, and overall acceptability. The evaluation focused on consumer-oriented liking rather than descriptive sensory profiling, aligning with standard hedonic testing protocols. The creamy texture and mild tangy flavor, unique to goat milk, were particularly well-received by the panelists. In comparison, sensory scores for sheep milk Halloumi and cow milk Halloumi were slightly lower, reflecting differences in milk composition and sensory profiles. Sheep milk Halloumi, recognized for its richer flavor and firmer texture, achieved high scores for flavor and texture but had slightly reduced overall acceptability compared to goat milk Halloumi. Cow milk Halloumi, while appreciated for its mild flavor, scored lower due to its softer texture and weaker aroma.

The high sensory scores observed for goat milk Halloumi are consistent with findings by Barłowska et al. (2018), who reported that goat milk cheeses tend to receive favorable sensory evaluations, attributed to their distinct fatty acid profile and traditional production methods that contribute to flavor and aroma development. Similarly, Day (2021) emphasized the critical role of volatile compounds in goat milk cheeses, noting that these compounds significantly contribute to aroma and flavor complexity. As shown in Figure 4, goat milk Halloumi outperformed sheep and cow milk Halloumi in all sensory attributes, particularly flavor and aroma, which are critical factors influencing consumer preferences. The tangy flavor and creamy texture of goat milk Halloumi can be attributed to its higher concentration of medium-chain fatty acids and specific volatile compounds, distinguishing it from the richer flavor profile of sheep milk Halloumi and the milder taste of cow milk Halloumi. The distinct sensory characteristics of goat milk Halloumi, including its flavor and texture, may enhance its consumer appeal and complement its functional properties, supporting its suitability for inclusion in health-oriented dairy formulations.

3.6 Comparative evaluation of goat, sheep, and cow milk Halloumi

Goat milk Halloumi demonstrated comparable nutritional and sensory attributes to Halloumi made from sheep milk, with both variants achieving high consumer acceptability and favorable textural properties (Table 5). However, goat milk Halloumi offered a milder flavor profile, primarily due to its distinct fatty acid composition, including a higher proportion of medium-chain fatty acids (MCFAs). These MCFAs contribute not only to improved digestibility but also to the unique taste of goat milk products. This aligns with Gómez-Cortés et al. (2018), who emphasized the functional and metabolic benefits of MCFAs in goat milk-based foods. Traditional Halloumi, primarily made from goat milk or a blend of sheep and goat milk, is renowned for its pronounced salty and tangy flavor. However, the milder taste of goat milk Halloumi enhances its appeal among health-conscious consumers, especially those seeking lower sodium options. This finding is consistent with Barłowska et al. (2018), who reported that goat milk cheeses are often preferred for their lighter sensory profile and enhanced digestibility. Additionally, the higher bioactive peptide content in goat milk Halloumi contributes to its significant antioxidant properties, supporting its health-promoting potential, as noted by López-Villafaña et al. (2023). From a sensory perspective, goat milk Halloumi offers a creamier texture compared to sheep milk Halloumi, which is typically firmer due to the higher protein content of sheep milk. This distinction was evident in the comparative sensory evaluation scores (Table 5), where goat milk Halloumi outperformed cow milk Halloumi in flavor and texture, while achieving similar scores to sheep milk Halloumi in aroma and overall acceptability. Cow milk Halloumi, although appreciated for its mild flavor, scored lower due to its less creamy texture and weaker aroma profile.

The antioxidant capacity of goat milk Halloumi was notably higher than that of both sheep and cow milk Halloumi, further emphasizing its functional benefits. This is consistent with the findings of Saremnezhad et al. (2024), who reported that the presence of volatile compounds and bioactive peptides contributes to the functional properties of goat milk cheeses. They further observed that increasing the proportion of goat milk in mixtures with sheep milk to

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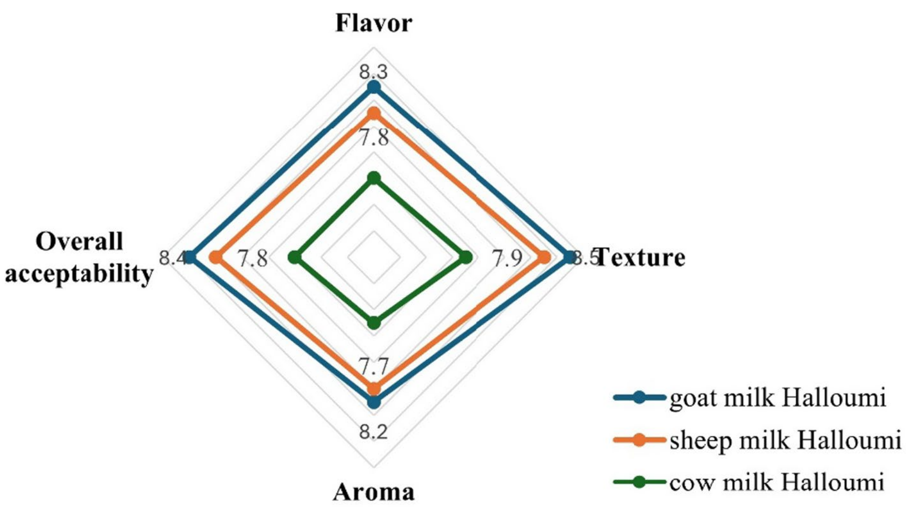

FIGURE 4
Sensory evaluation (flavor, texture, aroma, and overall acceptability) of Halloumi cheese made of goat, sheep, and cow milk. Scores are based on a 9-point hedonic scale, where 1-extremely dislike and 9-extremely like.

TABLE 5 Descriptive comparison of nutritional and sensory characteristics of goat, sheep, and cow milk Halloumi cheeses.

Attribute	Goat milk Halloumi	Sheep milk Halloumi	Cow milk Halloumi
Flavor	Mild, slightly tangy	Rich, tangy, and salty	Mild, less distinct
Texture	Creamy	Firm and chewy	Less creamy
Antioxidant capacity	High	Moderate	Low
Digestibility	Excellent	High	Moderate
Sodium content	Moderate	High	High
Overall acceptability	Excellent	Good	Good

75% and 100% resulted in enhanced antioxidant activity. Moreover, the moderate sodium content of goat milk Halloumi compared to sheep milk Halloumi positions as a suitable alternative for consumers with dietary sodium restrictions. Taken together, these findings characterize goat milk Halloumi as a nutritionally rich and functionally relevant dairy product with potential applications in health-focused dietary patterns.

4 Conclusion and future work

This study demonstrates that Halloumi cheese produced from indigenous goat milk in Northern Kazakhstan possesses distinct nutritional, functional, and sensory characteristics. The cheese exhibited enhanced antioxidant activity, a balanced profile of essential amino acids, and elevated concentrations of medium-chain and omega-3 fatty acids in comparison to sheep and cow milk variants. Broader benchmarking against other cheeses reported in the literature further suggests that goat milk Halloumi exhibits comparatively higher antioxidant potential, though such cross-study comparisons should be interpreted with caution due to methodological and processing differences. Sensory evaluation confirmed high acceptability, particularly in terms of flavor and texture. Microbiological analysis revealed substantial levels of lactic acid bacteria, indicating both hygienic quality and potential contributions to gut health. Thus, these findings demonstrate the relevance of goat milk Halloumi within the domain of health-oriented dairy research.

Further investigations are warranted to refine processing protocols for improved physicochemical stability and compositional consistency. Clinical studies are needed to evaluate the bioavailability and physiological effects of the identified bioactive compounds, with particular attention to antioxidant activity, lipid metabolism, and gastrointestinal function. Longitudinal assessments of product quality under varying storage conditions, along with studies on resource efficiency and environmental impact, will support its role in sustainable nutrition systems. These directions may contribute to expanding the functional applications of goat milk-based dairy products and inform their integration into diversified dietary strategies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZK: Conceptualization, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AU: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. ZA: Conceptualization, Data curation, Funding acquisition, Validation, Writing – review & editing. AA: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. KO: Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft. MJ: Data curation, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. SK: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. GB: Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. AK: Conceptualization, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. AB: Writing – original draft, Writing – review & editing. SZ: Data curation, Investigation, Methodology, Resources, Validation, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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