



Integrated physicochemical and sensory evaluation of raw cow milk: Insights into quality determinants under controlled production conditions

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Abstract. Raw cow milk is a nutritionally important food matrix whose quality is determined by a complex interaction of physicochemical composition, sensory attributes, and production conditions. Variations in milk composition and sensory properties can significantly influence its technological suitability, consumer acceptability, and safety. The present study aimed to perform an integrated evaluation of the physicochemical and sensory quality of raw cow milk produced under controlled farm conditions in Romania, with particular emphasis on identifying key quality determinants and their interrelationships. A total of 30 raw cow milk samples were collected from a single dairy farm during one sampling session and analyzed for fat, protein, lactose, total solids, solids-not-fat, density, pH, titratable acidity, and freezing point using standardized analytical methods. Sensory evaluation was conducted by a trained panel assessing appearance, color, odor, and taste, and the resulting data were further explored using multivariate statistical analyses, including correlation analysis, principal component analysis, and hierarchical cluster analysis. The results indicated that all milk samples exhibited physicochemical parameters within internationally accepted ranges for high-quality raw cow milk, with moderate natural variability attributed to biological factors. Sensory evaluation revealed generally high acceptability, with most samples achieving elevated total sensory scores. Strong positive relationships were observed between compositional parameters, particularly fat, protein, and lactose, and sensory quality, highlighting the central role of milk composition in shaping organoleptic perception. Multivariate analyses successfully differentiated milk samples based on combined physicochemical and sensory profiles, confirming the robustness of the integrated assessment approach. Overall, the study demonstrates that raw cow milk produced under controlled management conditions can achieve high nutritional value, excellent sensory quality, and strong technological potential, providing valuable baseline data for milk quality evaluation and supporting its suitability for premium dairy processing applications.

Key Words: correlation analysis, milk authenticity, multivariate analysis, PCA, physicochemical properties, raw cow milk, raw milk quality, sensory quality, physicochemical parameters, sensory attributes.

Introduction. Milk can be regarded as a “superfood” due to its high content of essential nutrients that are fundamental for human health and physiological functions (Nagpal et al 2012). It provides a wide range of bioactive components that contribute to growth, development, and the maintenance of physiological homeostasis. Milk proteins, particularly casein, play a crucial role in bone and tooth development and are essential for tissue growth and repair processes throughout life (Nagpal et al 2012; Rotondo et al 2021b). In addition, milk fat enhances the bioavailability of fat-soluble vitamins, including vitamins A, D, E, and K, while vitamin B₂ contributes to the maintenance of healthy skin and normal visual function (Nagpal et al 2012; Rotondo et al 2021a). Furthermore, the mineral fraction of milk, especially calcium and phosphorus, is indispensable for maintaining the structural integrity and proper functioning of bones and teeth (Nagpal et al 2012; Rotondo et al 2021a,b).

Despite being considered an almost complete food, milk may also contain residues of chemical contaminants, including toxic heavy metals originating from environmental exposure, which may pose potential health risks to consumers (Elafify et al 2023). Consequently, comprehensive evaluation of milk quality must take into account not only its nutritional composition but also potential safety-related aspects.

Milk is widely regarded as a nutritionally valuable food, as it supplies essential macronutrients and micronutrients, including proteins, lipids, carbohydrates, minerals, and vitamins, which collectively contribute to a balanced and healthy diet (Loss et al 2011). Consumption of milk during early stages of life has been associated with a reduced risk of developing respiratory and dermatological conditions, such as pollen allergy, allergic rhinitis, asthma, atopic sensitization, and hay fever (Loss et al 2011). However, increasing evidence suggests that the health effects of milk consumption may vary depending on its microbial composition, particularly when comparing raw and processed milk (Quigley et al 2013).

Raw milk (RM), although often perceived as having superior sensory qualities and potential health benefits, represents a complex biological matrix that can support the growth of a broad range of spoilage and potentially pathogenic microorganisms (Claeys et al 2013). Its near-neutral pH and high water activity create favorable conditions for microbial proliferation, including bacteria and fungi, thereby increasing the likelihood of microbiological contamination (Claeys et al 2013). Moreover, the physicochemical and microbiological quality of raw cow milk has been shown to vary considerably depending on factors such as hygiene practices, handling procedures, and seasonal variation (Kazeminia et al 2023). As a consequence, the consumption of raw milk is associated with an increased risk of microbiological contamination and foodborne infections (Claeys et al 2013; Kazeminia et al 2023). In contrast, pasteurized and ultra-high-temperature (UHT) treated milk undergo controlled thermal processing designed to inactivate pathogenic microorganisms, thereby improving microbiological safety while largely preserving the nutritional quality of the product (Quigley et al 2013).

Cow's milk is widely recognized as one of the most important foods of animal origin for human consumption due to its high nutritional value and its essential contribution to daily dietary intake worldwide (Morar et al 2025). At the global level, cow's milk accounts for approximately 85% of total milk production, underscoring its dominant role within the dairy sector and its importance for food security (Morar et al 2025).

In Romania, consumer interest in locally produced milk and dairy products has increased substantially over recent decades, driven by growing concerns related to food quality, authenticity, and sustainability of production systems (Morar et al 2025). In this context, the establishment and development of small- and medium-sized dairy cow farms has emerged as a national priority, aiming to strengthen local milk production chains and support rural economic development (Morar et al 2021). Nevertheless, the production of high-quality raw milk represents both a legal obligation under national and European Union regulations and a considerable challenge for dairy farmers, particularly those operating at small and medium scales (Maciuc et al 2017).

The quality of milk and dairy products placed on the market is influenced by multiple interacting factors, including the quantitative and qualitative composition of raw

milk—such as protein, lactose, and fat content—as well as its microbiological status (Sala et al 2007). The number and diversity of microorganisms present in raw milk immediately after milking, commonly referred to as the initial milk microflora, provide a direct reflection of microbial contamination occurring during milk production, collection, and handling processes (Morar et al 2025). Long-term monitoring of raw milk and dairy product quality on small farms in Romania has revealed fluctuating levels of integrity and freshness parameters, highlighting variability in hygienic practices, farm management conditions, and the effectiveness of quality control measures over time (Morar et al 2021).

In this context, the present study aimed to provide an integrated evaluation of the physicochemical and sensory quality of raw cow milk produced under controlled farm conditions in Romania. The research focused on characterizing variability in key compositional and chemical parameters and examining their relationships with sensory attributes at the sample level. By combining standardized analyses, sensory evaluation, and multivariate statistics, the study sought to clarify how intrinsic milk composition influences sensory quality and overall acceptability. The findings provide baseline data to support raw milk quality assessment, grading, and suitability for high-value dairy processing.

Material and Method. Raw cow milk was selected as the target matrix in the present study due to its nutritional relevance and its susceptibility to compositional variation and microbial contamination along the dairy production chain. To ensure the robustness and representativeness of the dataset, a defined set of milk samples was obtained from a single dairy production unit operating under standardized management and hygiene conditions. This sampling strategy allowed the assessment of milk quality parameters under controlled and comparable production circumstances, minimizing variability related to farm management, animal health status, and environmental factors. The collected samples constituted the analytical basis for all subsequent laboratory determinations, providing a consistent framework for evaluating the studied parameters and their interrelationships.

The present study was performed in full accordance with established ethical principles and legal requirements governing research on food products. Ethical clearance was obtained from the Bioethics Committee of the University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca (Decision No. 529 / 03.10.2025), confirming compliance with national regulations and standards of research integrity. The study did not involve any experimental intervention on animals, as milk samples were obtained solely from routine dairy production activities, without imposing any changes to animal management or welfare conditions. All analytical procedures were conducted in accordance with European Commission Regulation (EU) 2023/915, which specifies the maximum allowable concentrations of lead, cadmium, mercury, and arsenic in milk and dairy products. Analytical quality and data reliability were ensured through the use of certified reference materials and participation in proficiency testing schemes, thereby guaranteeing the accuracy, traceability, and scientific robustness of the results.

Milk sampling, identification, and traceability. A total of 30 raw cow milk samples were collected within the framework of the present study to ensure a representative assessment of milk quality and composition under controlled dairy production conditions. Sampling was conducted on 5 October 2025 at a commercial dairy holding (Bio Farm) located in Crișeni, Sălaj County, Romania, with geographic coordinates of approximately 47.23392° N latitude and 23.08207° E longitude.

All samples originated from clinically healthy dairy cows (*Bos taurus*) reared under conventional dairy production practices. Milk sampling was performed during the morning milking session, following standard hygienic procedures in accordance with good dairy farming practices. Individual samples were collected directly from the bulk milk stream, ensuring homogeneity and minimizing the risk of external contamination.

Each milk sample was assigned a unique sample code (MLK-B1-001 to MLK-B1-030) and an associated laboratory sample code (MSR-2025-001 to MSR-2025-030) to

guarantee full traceability throughout sampling, transport, storage, and analytical procedures. The sampling batch (Batch 1) reflects the single-day collection design applied in this study, allowing consistent comparison across all analyzed samples. Detailed identification, traceability, and geographic metadata for each sample are provided in Table 1.

Immediately after collection, the raw milk samples were subjected to rapid cooling and maintained at a controlled temperature of 2–4°C in food-grade containers to inhibit microbial growth and preserve physicochemical integrity prior to laboratory analysis. Samples were transported under refrigerated conditions and processed within an appropriate time frame to avoid degradation or compositional changes.

The standardized sampling protocol, combined with precise geolocation data and a robust traceability system, ensures the reliability, reproducibility, and regulatory compliance of the dataset. This approach aligns with EFSA data reporting recommendations, as well as with general requirements for milk sampling and handling described in ISO 707 | IDF 50 standards.

Sample preparation. Raw cow milk samples were transported to the laboratory under refrigerated conditions (4±1°C) and analyzed within 24 h of collection. Prior to analysis, samples were equilibrated to room temperature (20±2°C) and homogenized by gentle manual inversion (10–15 times) to ensure uniform distribution of fat and solids, avoiding foam formation.

Determination of fat, protein, lactose, total solids, and solids-not-fat. Fat, protein, lactose, total solids, and solids-not-fat (SNF) contents were determined by infrared spectrophotometry using a MilkoScan™ FT1 (FOSS, Denmark), in accordance with ISO 9622:2013 / IDF 141:2013. The instrument was calibrated with certified reference milk standards. Homogenized milk samples (≈10 mL) were analyzed at 40°C, and results were expressed as percentage values (% w/w). Each sample was measured in duplicate, and mean values were used for statistical analysis.

Density determination. Milk density was determined at 20°C using a calibrated lactodensimeter, in accordance with ISO 488:2008 / IDF 105:2008. Approximately 250 mL of milk was transferred into a clean glass cylinder. The lactodensimeter was gently immersed, ensuring no contact with the cylinder walls. Density readings (g cm⁻³) were recorded after stabilization of the instrument.

pH measurement. The pH of milk samples was measured using a digital pH meter (Hanna Instruments HI 2211) equipped with a glass electrode, following ISO 26323:2009 / IDF 216:2009. The pH meter was calibrated daily using standard buffer solutions at pH 4.00 and 7.00. Measurements were carried out at 20±2°C by immersing the electrode directly into the milk sample. The pH value was recorded once the reading stabilized.

Determination of titratable acidity. Titratable acidity was determined according to ISO 6091:2010 / IDF 86:2010 and expressed in degrees Thörner (°T). A volume of 10 mL of milk was pipetted into a conical flask and diluted with 20 mL of distilled water. Two drops of phenolphthalein indicator (1%) were added, and the sample was titrated with 0.1 N NaOH until the appearance of a persistent pale pink color lasting at least 30 s. Titratable acidity was calculated and expressed as °T.

Freezing point determination. The freezing point of milk samples was determined using a cryoscope (Cryostar I, Funke Gerber, Germany), according to ISO 5764:2009 / IDF 108:2009. Approximately 2.5 mL of milk was introduced into the cryoscope sample tube. Measurements were performed automatically, and results were recorded in degrees Celsius (°C). The freezing point was used as an indicator of milk authenticity and detection of potential water addition.

Sensory evaluation. Sensory analysis was conducted in a dedicated sensory laboratory according to ISO 8589:2007. A trained panel evaluated the milk samples under controlled conditions. Samples were coded with random three-digit numbers and presented at 10–12°C. Each sample was evaluated for appearance, color, odor, and taste using a structured scoring system. Scores for each attribute were summed to obtain a total sensory score, with a maximum value of 20 points. Between samples, assessors rinsed their mouths with potable water.

Statistical analysis. The experimental data were statistically analyzed to assess relationships between physicochemical parameters and the sensory quality of raw cow milk. Pearson's correlation coefficients were used to evaluate linear associations and were visualized through correlation matrices. Multivariate analyses on standardized data included principal component analysis (PCA) to identify major sources of variability and hierarchical cluster analysis (HCA) using Euclidean distance and Ward's method to classify samples according to their overall profiles. Statistical significance was set at a 95% confidence level.

Results and Discussion

Integrated assessment of physicochemical quality of raw cow milk. The physicochemical characterization of raw cow milk was conducted on thirty individual samples collected under strictly controlled conditions from a single dairy farm in Romania. As shown in Table 1, all samples originated from the same production batch, were obtained from the same animal species (*Bos taurus*), and were collected on the same day and at the same geographical coordinates. This experimental design significantly reduces the influence of confounding environmental factors such as climatic conditions, seasonal variation, and regional differences, thereby allowing a more precise assessment of intrinsic milk quality attributes. The comprehensive traceability system applied to each sample strengthens the reliability of the dataset and aligns with European food quality and safety frameworks.

The fat content of the raw milk samples exhibited values ranging from 3.55 to 4.18%, indicating moderate variability within biologically acceptable limits. This variability is characteristic of individual cow milk and can be attributed to factors such as stage of lactation, individual metabolic status, and feeding regime. Higher fat concentrations were consistently associated with increased total solids content, reinforcing the pivotal role of milk fat in determining both nutritional density and processing performance. From a technological perspective, milk samples with elevated fat levels are particularly desirable for the production of full-fat dairy products and high-yield cheeses, where fat contributes significantly to texture, flavor development, and consumer acceptability.

Protein content ranged from 3.22 to 3.41%, reflecting a relatively narrow distribution and indicating compositional stability across the analyzed samples. Proteins, especially caseins, are fundamental to the functional behavior of milk during coagulation and fermentation processes. The protein levels observed in this study fall within the optimal range reported for high-quality raw cow milk and suggest favorable coagulation properties. The consistency of protein content across samples further suggests effective herd management and balanced nutrition within the dairy farm.

Lactose concentrations varied from 4.65 to 4.85%, showing limited dispersion and confirming normal secretory activity of the mammary gland. Lactose is the primary carbohydrate in milk and serves as a critical indicator of milk freshness and authenticity. The absence of unusually low lactose values indicates that none of the samples were affected by microbial degradation or dilution with water. Moreover, the relatively stable lactose content supports the interpretation that the milk was collected and handled under appropriate hygienic and thermal conditions prior to analysis.

Table 1

Identification, traceability, and sampling metadata of raw cow milk samples collected from a dairy farm in Romania

Sample code	Sampling batch	Sample number	Food matrix	Production type	Animal species	Holding/Farm	Laboratory sample code	Sampling date	Sampling site (County, Country)	Latitude (°N)	Longitude (°E)
MLK-B1-001	Batch 1	1	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-001	05.10.2025	Crișeni, Sălaj, Romania (457101)	47.23392	23.08207
MLK-B1-002	Batch 1	2	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-002	05.10.2025	Crișeni, Sălaj, Romania (457102)	47.23392	23.08207
MLK-B1-003	Batch 1	3	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-003	05.10.2025	Crișeni, Sălaj, Romania (457103)	47.23392	23.08207
MLK-B1-004	Batch 1	4	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-004	05.10.2025	Crișeni, Sălaj, Romania (457104)	47.23392	23.08207
MLK-B1-005	Batch 1	5	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-005	05.10.2025	Crișeni, Sălaj, Romania (457105)	47.23392	23.08207
MLK-B1-006	Batch 1	6	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-006	05.10.2025	Crișeni, Sălaj, Romania (457106)	47.23392	23.08207
MLK-B1-007	Batch 1	7	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-007	05.10.2025	Crișeni, Sălaj, Romania (457107)	47.23392	23.08207
MLK-B1-008	Batch 1	8	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-008	05.10.2025	Crișeni, Sălaj, Romania (457108)	47.23392	23.08207
MLK-B1-009	Batch 1	9	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-009	05.10.2025	Crișeni, Sălaj, Romania (457109)	47.23392	23.08207
MLK-B1-010	Batch 1	10	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-010	05.10.2025	Crișeni, Sălaj, Romania (457110)	47.23392	23.08207
MLK-B1-011	Batch 1	11	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-011	05.10.2025	Crișeni, Sălaj, Romania (457111)	47.23392	23.08207
MLK-B1-012	Batch 1	12	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-012	05.10.2025	Crișeni, Sălaj, Romania (457112)	47.23392	23.08207
MLK-B1-013	Batch 1	13	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-013	05.10.2025	Crișeni, Sălaj, Romania (457113)	47.23392	23.08207
MLK-B1-014	Batch 1	14	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-014	05.10.2025	Crișeni, Sălaj, Romania (457114)	47.23392	23.08207
MLK-B1-015	Batch 1	15	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-015	05.10.2025	Crișeni, Sălaj, Romania (457115)	47.23392	23.08207
MLK-B1-016	Batch 1	16	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-016	05.10.2025	Crișeni, Sălaj, Romania (457116)	47.23392	23.08207
MLK-B1-017	Batch 1	17	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-017	05.10.2025	Crișeni, Sălaj, Romania (457117)	47.23392	23.08207
MLK-B1-018	Batch 1	18	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-018	05.10.2025	Crișeni, Sălaj, Romania (457118)	47.23392	23.08207
MLK-B1-019	Batch 1	19	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-019	05.10.2025	Crișeni, Sălaj, Romania (457119)	47.23392	23.08207
MLK-B1-	Batch 1	20	Raw milk	Dairy	<i>Bos taurus</i>	Bio Farm	MSR-2025-	05.10.2025	Crișeni, Sălaj,	47.23392	23.08207

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MLK-B1-021	Batch 1	21	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-021	05.10.2025	Crişeni, Sălaj, Romania (457121)	47.23392	23.08207
MLK-B1-022	Batch 1	22	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-022	05.10.2025	Crişeni, Sălaj, Romania (457122)	47.23392	23.08207
MLK-B1-023	Batch 1	23	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-023	05.10.2025	Crişeni, Sălaj, Romania (457123)	47.23392	23.08207
MLK-B1-024	Batch 1	24	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-024	05.10.2025	Crişeni, Sălaj, Romania (457124)	47.23392	23.08207
MLK-B1-025	Batch 1	25	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-025	05.10.2025	Crişeni, Sălaj, Romania (457125)	47.23392	23.08207
MLK-B1-026	Batch 1	26	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-026	05.10.2025	Crişeni, Sălaj, Romania (457126)	47.23392	23.08207
MLK-B1-027	Batch 1	27	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-027	05.10.2025	Crişeni, Sălaj, Romania (457127)	47.23392	23.08207
MLK-B1-028	Batch 1	28	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-028	05.10.2025	Crişeni, Sălaj, Romania (457128)	47.23392	23.08207
MLK-B1-029	Batch 1	29	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-029	05.10.2025	Crişeni, Sălaj, Romania (457129)	47.23392	23.08207
MLK-B1-030	Batch 1	30	Raw milk	Dairy production	<i>Bos taurus</i>	Bio Farm	MSR-2025-030	05.10.2025	Crişeni, Sălaj, Romania (457130)	47.23392	23.08207

Total solids content ranged from 12.60 to 13.55%, while solids-not-fat (SNF) values varied between 8.94 and 9.35%. These parameters provide an integrated assessment of milk composition and are closely linked to nutritional quality and processing efficiency. Higher SNF values are particularly advantageous for dairy processing, as they enhance cheese yield and improve the nutritional profile of final products. The observed variability in total solids and SNF is consistent with natural biological variation and does not indicate compositional abnormalities or quality defects.

Milk density values ranged from 1.028 to 1.031 g cm⁻³ and were within the internationally accepted limits for raw cow milk. The inverse relationship observed between fat content and density is well documented in dairy science and was clearly reflected in the present results. Samples with higher fat content exhibited slightly lower density values, further confirming the internal consistency and reliability of the analytical data. These findings support the conclusion that the milk samples were authentic and free from physical adulteration.

The freezing point of the analyzed milk samples ranged from -0.520 to -0.535°C, which is characteristic of genuine raw cow milk. The freezing point is one of the most sensitive indicators of water adulteration, and the absence of values closer to zero strongly suggests that no dilution occurred at any stage of production or handling. The narrow range observed across all samples further indicates uniformity in milk composition and reinforces the effectiveness of farm-level quality control practices.

The pH values of the milk samples ranged from 6.59 to 6.72, which is indicative of fresh raw milk with good chemical stability. These values are consistent with those reported for milk collected shortly after milking and stored under refrigerated conditions. Titratable acidity values ranged from 15.6 to 17.9°T and exhibited the expected inverse relationship with pH. Samples with slightly higher acidity values did not exceed acceptable thresholds and therefore do not suggest the onset of spoilage or excessive microbial activity. Instead, these variations likely reflect natural differences in buffering capacity related to protein and mineral content.

Collectively, the physicochemical parameters analyzed in this study demonstrate that the raw cow milk samples possessed high nutritional value, good technological suitability, and excellent authenticity. The integration of compositional, physical, and chemical indicators provides a comprehensive assessment of milk quality and confirms that the samples complied with recognized standards for raw milk. The results also highlight the importance of controlled production systems and rigorous traceability in ensuring consistent milk quality.

In a broader context, these findings underline the potential of raw milk produced in Romanian dairy farms, particularly those operating under bio or controlled production systems, to meet the requirements of both local consumption and high-value dairy processing. The data generated in this study contribute valuable baseline information for future comparative studies, quality monitoring programs, and the development of value-added dairy products.

Assessment of sensory attributes of raw cow milk under controlled farm conditions. The sensory quality of raw cow milk was assessed through individual organoleptic evaluation of thirty samples, as presented in Table 2. The evaluation was based on four key attributes—appearance, color, odor, and taste—each scored on a standardized scale, with a maximum total score of 20 points. Sensory analysis represents a critical component of milk quality assessment, as it integrates the combined effects of physicochemical composition, hygienic conditions, and handling practices, while also directly reflecting consumer perception and acceptability.

Overall, the results indicate a high sensory quality of the analyzed raw milk samples, with total scores ranging from 15 to 20 points. The majority of samples achieved scores of 18 points or higher, demonstrating that the milk exhibited sensory characteristics typical of fresh, high-quality raw cow milk. Samples receiving the maximum total score of 20 points were characterized by excellent appearance, uniform white color, clean and pleasant odor, and a well-balanced, slightly sweet taste, which is primarily associated with adequate lactose content and the absence of off-flavors.

Table 2

Individual physicochemical characteristics of raw cow milk samples (n=30)

<i>Sample code</i>	<i>Fat (%)</i>	<i>Protein (%)</i>	<i>Lactose (%)</i>	<i>Total solids (%)</i>	<i>SNF / SUD (%)</i>	<i>Density (g cm⁻³)</i>	<i>pH</i>	<i>Titrateable acidity (°T)</i>	<i>Freezing point (°C)</i>
MLK-B1-001	3.62	3.28	4.70	12.75	9.05	1.030	6.68	16.2	-0.524
MLK-B1-002	3.75	3.31	4.74	12.90	9.10	1.031	6.66	16.5	-0.526
MLK-B1-003	3.88	3.34	4.76	13.05	9.12	1.030	6.65	16.8	-0.527
MLK-B1-004	4.02	3.36	4.78	13.25	9.20	1.029	6.64	17.1	-0.529
MLK-B1-005	3.55	3.22	4.65	12.60	8.95	1.031	6.70	15.8	-0.522
MLK-B1-006	3.68	3.30	4.71	12.80	9.02	1.030	6.69	16.0	-0.523
MLK-B1-007	3.91	3.35	4.77	13.10	9.15	1.029	6.63	17.0	-0.528
MLK-B1-008	4.10	3.38	4.80	13.35	9.25	1.028	6.62	17.4	-0.531
MLK-B1-009	3.84	3.33	4.75	13.00	9.10	1.030	6.66	16.7	-0.526
MLK-B1-010	3.60	3.25	4.68	12.70	8.98	1.031	6.71	15.9	-0.521
MLK-B1-011	3.95	3.36	4.78	13.15	9.18	1.029	6.64	17.2	-0.528
MLK-B1-012	4.05	3.39	4.82	13.40	9.28	1.028	6.61	17.6	-0.532
MLK-B1-013	3.72	3.29	4.72	12.85	9.05	1.030	6.68	16.3	-0.524
MLK-B1-014	3.90	3.34	4.76	13.05	9.14	1.029	6.65	16.9	-0.527
MLK-B1-015	4.18	3.40	4.85	13.55	9.35	1.028	6.60	17.8	-0.534
MLK-B1-016	3.58	3.24	4.67	12.65	8.96	1.031	6.72	15.7	-0.520
MLK-B1-017	3.80	3.31	4.74	12.95	9.08	1.030	6.67	16.4	-0.525
MLK-B1-018	4.00	3.37	4.79	13.30	9.23	1.028	6.62	17.3	-0.530
MLK-B1-019	3.65	3.27	4.69	12.78	9.01	1.030	6.69	16.1	-0.523
MLK-B1-020	3.92	3.35	4.77	13.12	9.16	1.029	6.64	17.0	-0.528
MLK-B1-021	4.08	3.39	4.81	13.38	9.27	1.028	6.61	17.5	-0.531
MLK-B1-022	3.70	3.28	4.71	12.82	9.03	1.030	6.68	16.2	-0.524
MLK-B1-023	3.86	3.32	4.75	13.00	9.10	1.029	6.66	16.8	-0.526
MLK-B1-024	4.12	3.38	4.83	13.42	9.30	1.028	6.60	17.6	-0.533
MLK-B1-025	3.57	3.23	4.66	12.62	8.94	1.031	6.72	15.6	-0.521
MLK-B1-026	3.78	3.30	4.73	12.90	9.06	1.030	6.67	16.4	-0.525
MLK-B1-027	3.98	3.36	4.79	13.20	9.22	1.028	6.63	17.2	-0.529
MLK-B1-028	4.15	3.41	4.84	13.50	9.33	1.028	6.59	17.9	-0.535
MLK-B1-029	3.69	3.28	4.71	12.85	9.04	1.030	6.68	16.3	-0.524
MLK-B1-030	3.88	3.33	4.76	13.05	9.12	1.029	6.65	16.9	-0.527

The appearance scores ranged from 4 to 5, indicating that most samples displayed a clean, homogeneous aspect without visible impurities, coagulation, or sediment. Samples scoring 5 points for appearance were visually fluid and uniform, suggesting appropriate milking hygiene and effective filtration. Slightly lower scores observed in some samples may be attributed to minor natural variations in fat globule distribution or the presence of minimal foam, which are not necessarily indicative of quality defects but may influence visual perception during sensory assessment.

Color evaluation showed very high consistency across samples, with most receiving the maximum score of 5. The characteristic white to slightly creamy color observed is strongly correlated with fat content and the dispersion of milk fat globules. The uniformity of color scores suggests consistent feeding practices and good physiological status of the animals. Samples that received a score of 4 still fell within acceptable limits and did not display discoloration or abnormal hues, indicating the absence of oxidative processes or contamination.

Odor scores ranged from 3 to 5, indicating limited variability among samples. Milk samples with the highest scores were characterized by a clean, fresh, and neutral odor typical of properly handled raw milk. Lower scores were observed in a few samples and may be attributed to mild feed-related aromas or minor environmental influences during milking. Notably, no samples exhibited pronounced off-odors such as sour, rancid, or musty notes associated with spoilage or improper storage.

Taste evaluation revealed scores between 3 and 5, with the majority of samples achieving scores of 4 or 5. High taste scores were associated with a mildly sweet, clean flavor profile, reflecting adequate lactose levels and the absence of undesirable compounds. Samples receiving lower taste scores did not display overt defects but may have exhibited slightly flat or less intense flavor, potentially related to individual compositional differences, such as lower fat or lactose content. The absence of sour, bitter, or metallic tastes across all samples further confirms the good microbiological and chemical stability of the milk.

The total sensory scores provide an integrated measure of overall milk quality and consumer acceptability. Scores of 19 and 20 points, achieved by a substantial proportion of samples, indicate excellent sensory quality and strong conformity with standards for fresh raw milk. Samples with total scores of 15 to 17 points, while slightly lower, still fall within acceptable quality ranges and do not suggest sensory rejection. Instead, these scores reflect minor, non-critical variations that are commonly observed in raw milk evaluated at the individual sample level.

When interpreted alongside the physicochemical results presented in previous tables, the sensory evaluation findings demonstrate strong coherence with analytical data. Samples with higher fat, protein, and total solids content generally exhibited superior taste and appearance scores, highlighting the close relationship between milk composition and sensory perception. Furthermore, the absence of sensory defects aligns with the normal pH, acidity, and freezing point values, collectively confirming the freshness and authenticity of the milk.

In a broader context, the high sensory quality observed across the analyzed samples underscores the effectiveness of farm-level management practices, including animal nutrition, milking hygiene, and post-milking handling. Sensory analysis thus complements physicochemical testing by providing a holistic assessment of raw milk quality, bridging objective analytical parameters with subjective consumer-oriented evaluation.

In conclusion, the sensory evaluation results presented in Table 3 confirm that the raw cow milk samples possessed excellent organoleptic properties, characterized by clean appearance, uniform color, pleasant odor, and balanced taste. These findings reinforce the conclusion that the milk was produced and handled under optimal conditions and further support its suitability for both direct consumption and further dairy processing. The integration of sensory and physicochemical data provides a comprehensive quality profile and strengthens the overall scientific validity of the study.

Table 3

Individual physicochemical characteristics of raw cow milk samples (n=30)

Sample code	Appearance	Color	Odor	Taste	Total score (max. 20)
MLK-B1-001	5	5	4	5	19
MLK-B1-002	5	5	5	5	20
MLK-B1-003	4	5	4	4	17
MLK-B1-004	5	5	5	4	19
MLK-B1-005	4	4	4	4	16
MLK-B1-006	5	5	4	5	19
MLK-B1-007	5	5	5	5	20
MLK-B1-008	4	5	4	4	17
MLK-B1-009	5	5	5	4	19
MLK-B1-010	4	4	4	3	15
MLK-B1-011	5	5	5	5	20
MLK-B1-012	5	5	4	5	19
MLK-B1-013	4	5	4	4	17
MLK-B1-014	5	5	5	4	19
MLK-B1-015	5	5	4	4	18
MLK-B1-016	4	4	3	4	15
MLK-B1-017	5	5	4	5	19
MLK-B1-018	5	5	5	4	19
MLK-B1-019	4	5	4	4	17
MLK-B1-020	5	5	5	5	20
MLK-B1-021	5	5	4	5	19
MLK-B1-022	4	5	4	4	17
MLK-B1-023	5	5	5	4	19
MLK-B1-024	5	5	4	4	18
MLK-B1-025	4	4	4	3	15
MLK-B1-026	5	5	4	5	19
MLK-B1-027	5	5	5	4	19
MLK-B1-028	5	5	4	4	18
MLK-B1-029	4	5	4	4	17
MLK-B1-030	5	5	5	5	20

Multivariate relationships between physicochemical parameters and sensory quality of raw cow milk. Figure 1 presents the Pearson correlation matrix illustrating the relationships between physicochemical parameters and the total sensory score of raw cow milk samples. This figure provides a comprehensive and integrative overview of how compositional, physical, and chemical attributes interact and jointly influence sensory quality, offering valuable insights into the determinants of raw milk quality.

A strong positive correlation is observed among the main compositional parameters, namely fat, protein, lactose, total solids, and solids-not-fat (SNF). These results reflect the intrinsically integrated nature of milk composition, where increases in one major component are typically accompanied by proportional increases in others. Such strong interrelationships are characteristic of high-quality raw milk and indicate a stable physiological state of the animals and consistent feeding and management practices.

Importantly, the total sensory score shows moderate to strong positive correlations with fat, protein, lactose, total solids, and SNF (Figure 1). This finding clearly demonstrates that sensory perception of raw milk is largely driven by its compositional richness. Protein content exhibits one of the strongest associations with sensory quality, highlighting its critical role in determining mouthfeel, body, and flavor balance. Lactose also contributes positively, most likely through its influence on sweetness and overall taste harmony, while fat content enhances aroma intensity, texture, and visual appeal.

In contrast, pH displays strong negative correlations with most compositional parameters and with titratable acidity, which is consistent with the known chemical behavior of fresh milk. The inverse relationship between pH and acidity observed in Figure 1 confirms the reliability of the analytical measurements and reflects the natural buffering system of milk. Notably, the total sensory score is negatively correlated with pH, suggesting that samples with slightly lower pH values—yet still within the normal range for fresh milk—were perceived as fresher and more flavorful by sensory evaluators.

The freezing point shows negative correlations with the major compositional parameters and with the sensory score. This behavior is expected, as higher concentrations of dissolved solids lead to a more negative freezing point. The clear and consistent correlations observed in Figure 1 further confirm the authenticity of the milk samples and exclude the possibility of water adulteration. Moreover, the negative association between freezing point and sensory score indirectly reinforces the role of compositional density in shaping sensory perception.

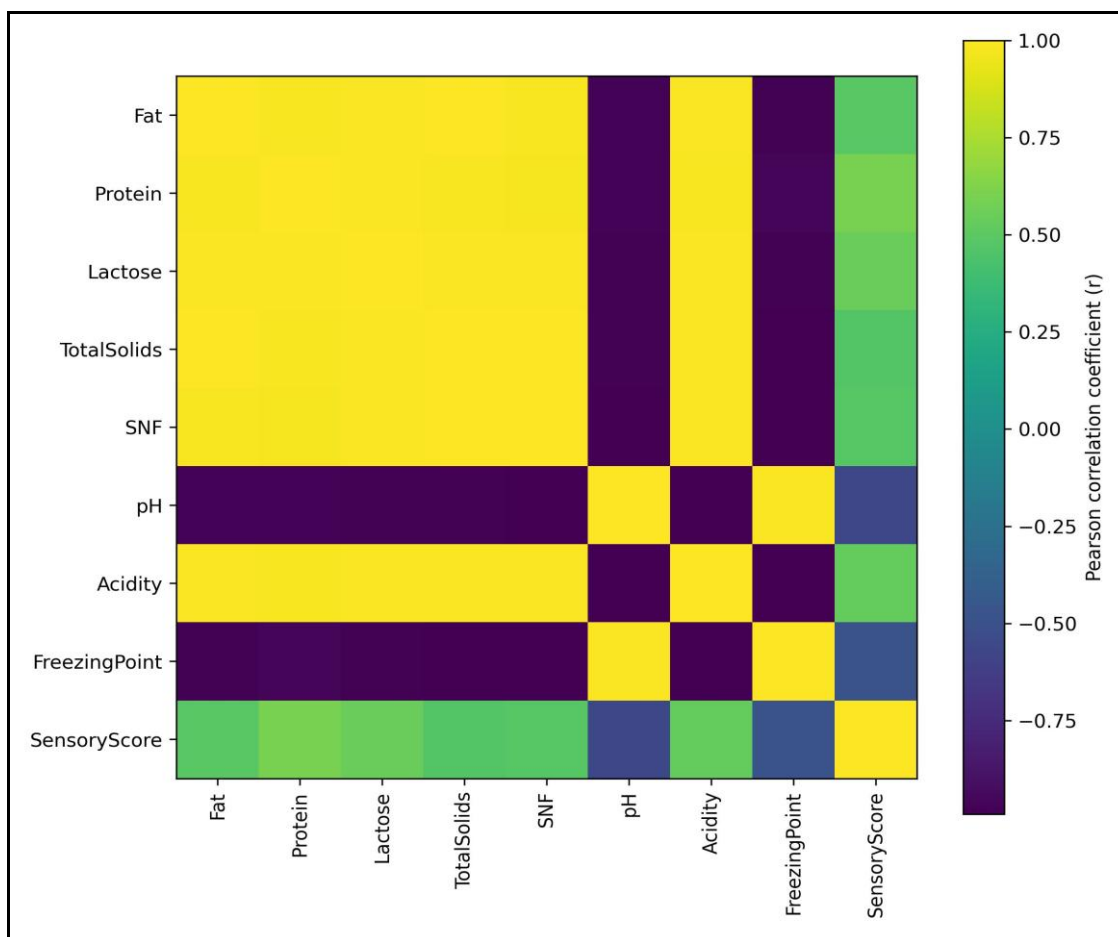


Figure 1. Pearson correlation matrix illustrating the relationships between physicochemical parameters and total sensory score of raw cow milk samples (n=30).

Titrateable acidity demonstrates a positive correlation with both compositional parameters and sensory score, indicating that naturally higher acidity levels—within acceptable limits—are associated with enhanced sensory attributes. This suggests that slight increases in acidity may contribute positively to perceived freshness and flavor complexity, without indicating microbial spoilage.

Overall, Figure 1 highlights the central role of physicochemical composition in determining the sensory quality of raw cow milk. The strong coherence between analytical parameters and sensory outcomes underscores the robustness of the quality assessment approach used in this study. The correlation matrix not only validates the sensory evaluation results but also provides mechanistic insight into how individual milk components collectively influence consumer-relevant quality attributes.

From a broader perspective, the relationships illustrated in Figure 1 emphasize the importance of maintaining balanced milk composition through appropriate herd management, nutrition, and hygienic milking practices. These findings support the use of integrated physicochemical and sensory analyses as powerful tools for quality control and for the differentiation of high-quality raw milk intended for premium dairy products.

Figure 2 illustrates the relationship between protein content and the total sensory score of raw cow milk samples, providing a direct, sample-based visualization of how protein concentration influences sensory quality. A clear positive trend can be observed, indicating that higher protein levels are generally associated with increased sensory scores. Samples with protein contents above approximately 3.30% predominantly achieved sensory scores of 19–20 points, whereas samples with lower protein concentrations tended to exhibit reduced sensory acceptance. This pattern highlights the critical role of milk proteins, particularly caseins, in shaping key sensory attributes such as mouthfeel, body, and overall flavor balance. The dispersion of data points further suggests that while protein content is a major determinant of sensory quality, it acts in conjunction with other compositional factors, including fat and lactose, which collectively contribute to sensory perception. Overall, the relationship depicted in Figure 2 confirms that protein concentration is a strong driver of sensory acceptability in raw cow milk and supports its use as a key indicator in quality assessment and milk valorization strategies.

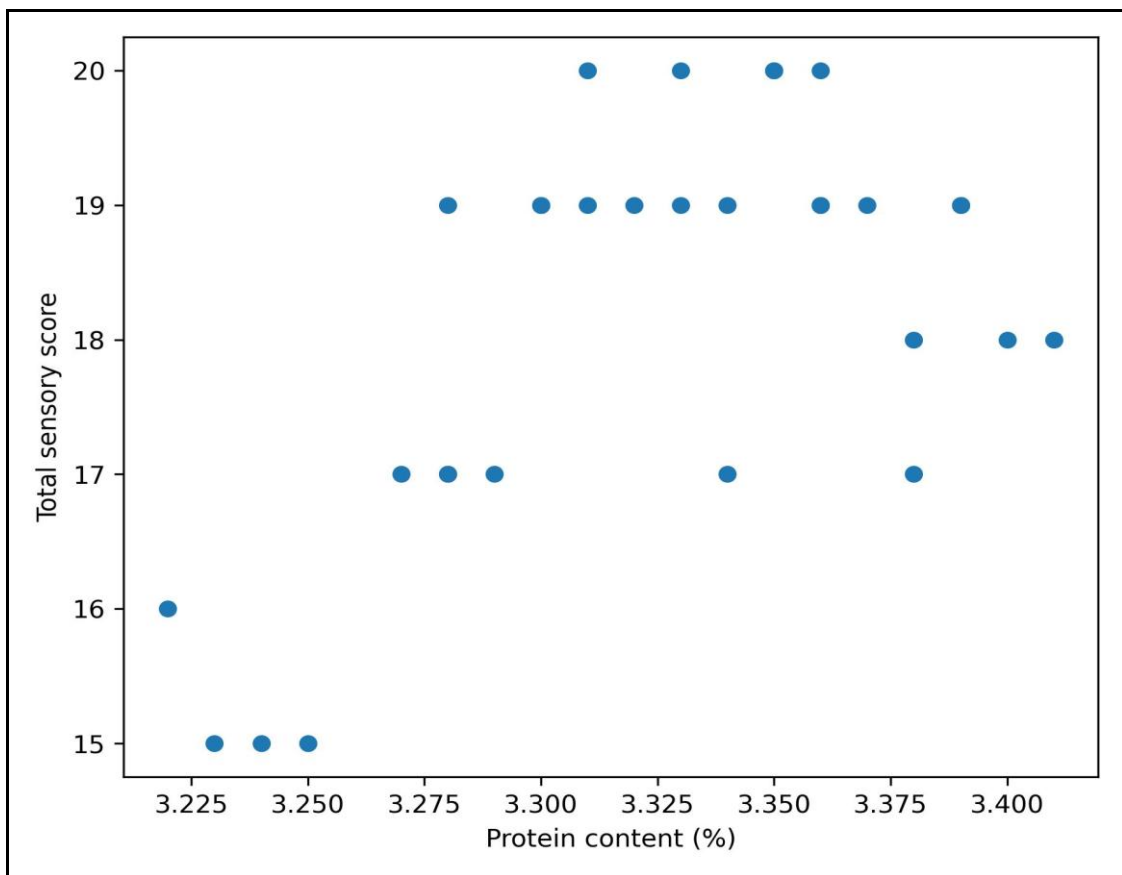


Figure 2. Relationship between protein content (%) and total sensory score of raw cow milk samples (n=30).

Figure 3 illustrates the relationship between fat content and the total sensory score of raw cow milk samples, highlighting the contribution of milk fat to sensory perception. A generally positive association can be observed, with samples exhibiting higher fat contents tending to achieve elevated sensory scores. Milk samples with fat concentrations above approximately 3.8% predominantly received sensory scores of 19–20 points, indicating enhanced overall acceptability. This trend reflects the well-established role of milk fat in enhancing flavor intensity, creaminess, and mouthfeel, which are key attributes in sensory evaluation.

Nevertheless, the dispersion of data points suggests that fat content alone does not fully determine sensory quality. Several samples with moderate fat levels also achieved high sensory scores, indicating that fat acts synergistically with other

compositional parameters, such as protein and lactose, in shaping sensory attributes. Conversely, samples with lower fat content were more frequently associated with reduced sensory scores, particularly in the range of 15–17 points, underscoring the importance of lipid fraction in achieving desirable sensory characteristics.

Overall, the relationship depicted in Figure 3 confirms that fat content is a significant, yet not exclusive, determinant of sensory quality in raw cow milk. These findings support the integrated interpretation of milk composition, emphasizing that optimal sensory quality results from a balanced interaction between fat, protein, and other solids rather than from a single compositional parameter.

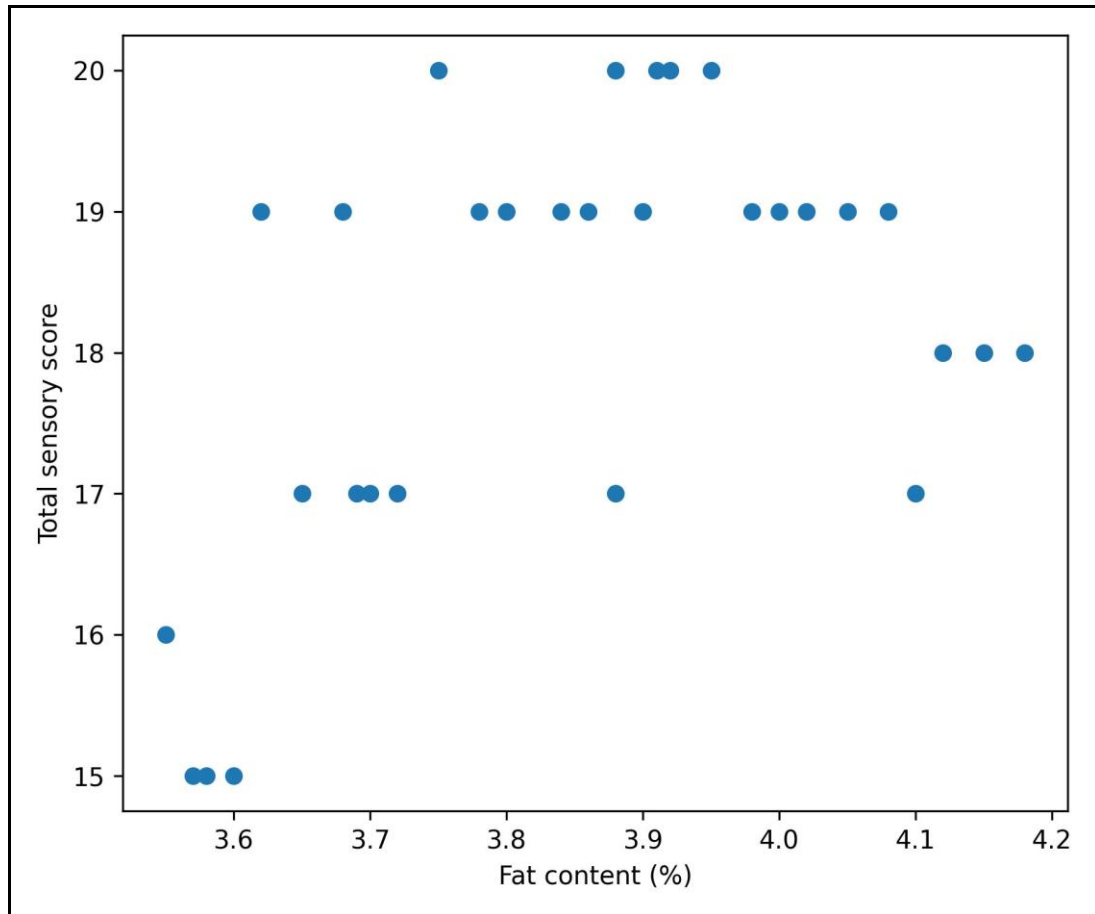


Figure 3. Relationship between fat content (%) and total sensory score of raw cow milk samples (n=30).

Figure 4 presents the hierarchical cluster analysis (HCA) dendrogram illustrating the similarity relationships among raw cow milk samples based on their combined physicochemical characteristics and total sensory scores. The dendrogram reveals a clear hierarchical structure, indicating the presence of distinct clusters of samples that share similar compositional and sensory profiles. The use of Euclidean distance and Ward's linkage method allowed for an effective differentiation of samples according to their overall quality attributes.

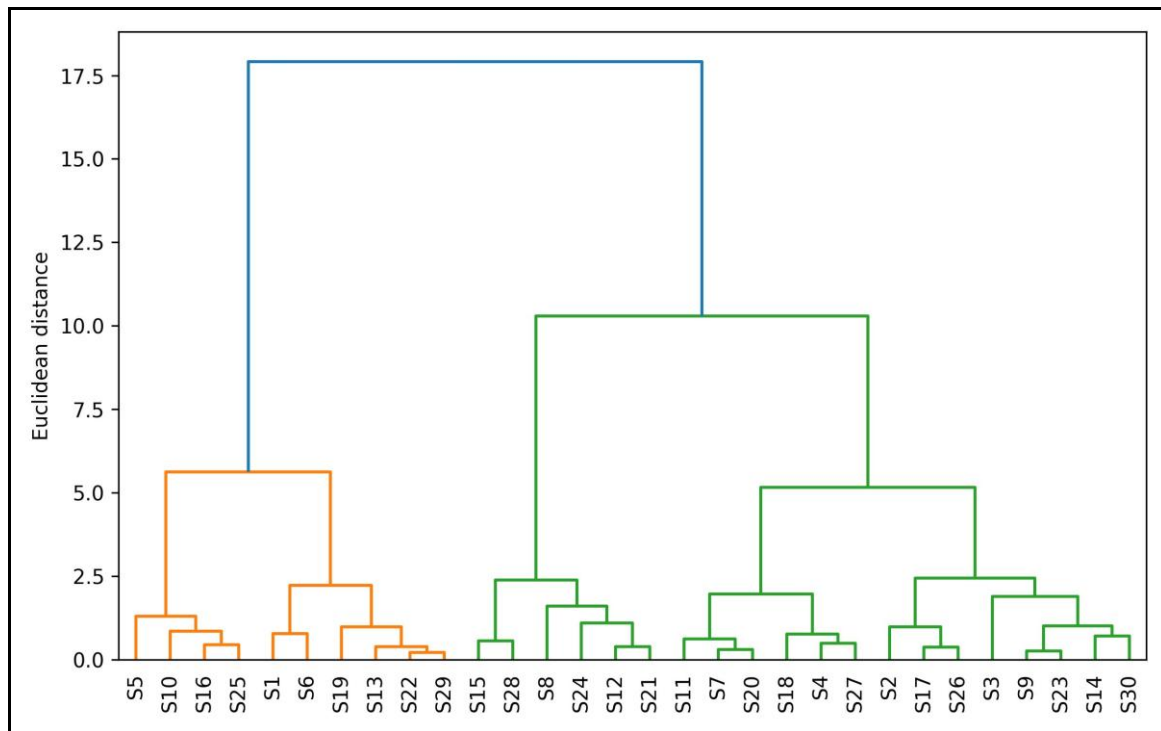


Figure 4. Hierarchical cluster analysis (HCA) dendrogram of raw cow milk samples based on physicochemical parameters and total sensory score (n=30).

At higher linkage distances, the samples separate into two main clusters, suggesting a broad differentiation between milk samples with higher compositional richness and sensory quality and those with comparatively lower values. Within these major clusters, several sub-clusters can be identified, reflecting more subtle variations in physicochemical composition, such as differences in fat, protein, and solids-not-fat content. Samples grouped within the same sub-cluster are characterized by similar sensory scores, indicating a strong coherence between analytical parameters and sensory perception.

Notably, samples associated with higher sensory scores tend to cluster together, confirming that sensory quality is closely linked to the overall physicochemical profile of the milk. Conversely, samples with lower sensory scores form separate clusters, highlighting the sensitivity of hierarchical clustering in distinguishing quality-related differences at the individual sample level. This pattern supports the findings observed in the correlation analysis and scatter plots, further reinforcing the conclusion that milk quality is governed by an integrated set of compositional factors rather than by isolated parameters.

Overall, the dendrogram from Figure 4 provides a robust multivariate validation of the relationships between physicochemical composition and sensory quality. The clustering results demonstrate the effectiveness of hierarchical analysis as a tool for classifying raw milk samples according to quality attributes and offer valuable insights for quality control, milk grading, and the identification of samples suitable for high-value dairy processing.

Conclusions. The present study provides a comprehensive evaluation of the physicochemical and sensory quality of raw cow milk collected from a single dairy farm in Romania under controlled production and sampling conditions. The standardized sampling design, combined with full traceability and uniform environmental parameters, enabled an accurate assessment of intrinsic milk quality attributes while minimizing external sources of variability.

The physicochemical analysis demonstrated that all milk samples fell within internationally accepted ranges for high-quality raw cow milk. Moderate natural

variability was observed in fat, protein, lactose, total solids, and solids-not-fat contents, reflecting individual biological differences among cows rather than quality deficiencies. Density, pH, titratable acidity, and freezing point values consistently confirmed the freshness, authenticity, and absence of water adulteration across all samples. These results collectively indicate excellent chemical stability and technological suitability of the analyzed milk.

Sensory evaluation further confirmed the high quality of the raw milk, with the majority of samples achieving very high total sensory scores. Clean appearance, uniform color, pleasant odor, and balanced taste were consistently reported, indicating proper farm hygiene, appropriate animal nutrition, and correct post-milking handling practices. Minor variations in sensory scores were attributed to natural compositional differences rather than sensory defects or spoilage.

Multivariate statistical analyses provided strong evidence of the close interdependence between physicochemical composition and sensory perception. Positive correlations between fat, protein, lactose, total solids, and sensory score highlighted the central role of compositional richness in determining consumer-relevant quality attributes. The negative associations observed with pH and freezing point further supported the internal consistency of the dataset and reinforced the reliability of the analytical results. Hierarchical cluster analysis successfully differentiated milk samples into distinct quality-related groups, offering a robust validation of the integrated quality assessment approach.

Overall, the findings of this study confirm that raw cow milk produced under controlled farm management conditions in Romania can achieve high nutritional value, excellent sensory quality, and strong technological potential. The integration of physicochemical, sensory, and multivariate analyses proved to be an effective strategy for holistic milk quality evaluation. These results provide valuable baseline data for quality monitoring programs, milk grading systems, and future comparative studies, and support the potential of Romanian dairy production to supply raw milk suitable for premium dairy products and high-value processing applications.

Conflict of Interest. The authors declare that there is no conflict of interest.

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