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Research Paper

Techno-functional and Compositional Analysis of Raw and Processed Milk: A Comparative Study

Basant Shubhankar[1*], Nityananda Shaw[1], Sameer Kumar Barik[2], Snehasis Kumar Mahakud[3], Bapun Choudhary[4], Bapun Mohanta[5], Rohit Mohanta[6], Bikash Mohanta[7], Subhrat Kumbhakar[8], Rudranarayan Sahu[9]

[1*]*Assistant Professor, PG Department of Chemistry, Kolhan University, Chaibasa, Jharkhand, India*
[1]*Assistant Professor, Department of Psychology, Tata College, KU, Chaibasa, Jharkhand*
[2-8]*Student, PG Department of Chemistry, Kolhan University, Chaibasa, Jharkhand, India*
[9]*Teaching Assistant, PG Department of Chemistry, Kolhan University, Chaibasa, Jharkhand, India*

ARTICLE DETAILS

Corresponding Author:
Basant Shubhankar

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ABSTRACT

This study offers a comparative physicochemical analysis of raw cow milk, raw buffalo milk, and reconstituted powdered milk to elucidate the influence of species-specific composition and processing technologies on milk quality. Seven critical parameters—pH, specific gravity, dynamic viscosity, β-carotene content (A_{450}), total solids, ash content, and titratable acidity—were evaluated using standardized analytical protocols. Buffalo milk demonstrated superior values in specific gravity (1.034 ± 0.001), viscosity (2.18 ± 0.01 mPa·s), total solids (17.51 ± 0.18%), ash content (0.89 ± 0.01%), and titratable acidity (0.165 ± 0.002%), highlighting its nutrient-dense matrix and industrial suitability for value-added dairy processing. Cow milk showed higher pH (6.72 ± 0.01) and β-carotene absorbance (A_{450} = 0.410 ± 0.004), indicating superior antioxidant capacity and digestibility, especially for pediatric and clinical nutrition. Powdered milk exhibited intermediate values but showed a marked reduction in A_{450} (0.342 ± 0.005), attributed to carotenoid degradation during spray drying. All intergroup differences were statistically significant ($p < 0.05$), and Pearson's correlation analysis revealed strong interrelationships among compositional parameters, particularly between solids, ash content, and acidity. These findings emphasize the techno-functional distinctions of each milk type, with buffalo milk suited for traditional dairy products, cow milk optimized for digestibility, and powdered milk favoured for long-term storage and emergency nutrition. The study provides critical insights for dairy formulation, nutritional planning, and industrial processing strategies.

1. Introduction

Milk is a naturally engineered emulsion that combines water with essential macronutrients and micronutrients, including fats, proteins, sugars, minerals, and vitamins. Designed to support the early stages of life, milk remains a critical dietary staple for humans of all ages. Within the Indian subcontinent, dairy farming is integral to both nutrition and economy, with cow (*Bos taurus*) and buffalo (*Bubalus bubalis*) milk serving as primary sources of dietary intake and raw material for the dairy industry (Khan et al., 2019). While both types of milk contribute similarly to human nutrition, their biochemical and physical properties diverge notably. Cow milk, with a fat content averaging between 3.5% and 4.5%, is lighter in consistency and contains finer fat globules. Its higher β-carotene concentration imparts a yellowish tint and enhances its digestibility, making it a preferred option for children and patients due to its low energy density and ease of absorption (Yadav & Sharma, 2021). On the other hand, buffalo milk is more concentrated—containing 6.5% to 8% fat and up to 5% protein—along with greater levels of calcium and phosphorus. These features result in a denser, more viscous fluid that is ideal for producing traditional dairy products like paneer, khoa, yogurt, and ghee (Thakur & Patel, 2020). Powdered milk, processed predominantly through spray drying, enhances milk's storage and transport efficiency by removing moisture.

[1*]Corresponding Author can be contacted at bscpcb@gmail.com
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However, the heat involved in this conversion often compromises its biochemical profile, notably reducing sensitive compounds like vitamins and carotenoids (Singh et al., 2019; Iqbal et al., 2020; Liu et al., 2025). Owing to such compositional shifts—both between species and due to industrial processing—a thorough comparison is necessary to optimize food technology applications and inform consumer decisions (Esposito et al., 2024; Malik & Chauhan, 2025).

This investigation presents a comparative study of cow, buffalo, and rehydrated powdered milk, analyzing critical parameters such as pH, density (specific gravity), viscosity, β-carotene proxy (A_{450} absorbance), total solids, mineral residue (ash content), and titratable acidity. The aim is to uncover how compositional differences influence the nutritional quality and processing potential of each milk type. The central goal of this research is to conduct a comprehensive evaluation of the compositional and functional characteristics of fresh cow milk, fresh buffalo milk, and reconstituted milk powder. By identifying differences in their physicochemical makeup, the study aims to highlight their respective nutritional and technological applications. The specific objectives are as follows:

- To perform a comparative assessment of the compositional traits of cow milk, buffalo milk, and powdered milk after reconstitution.
- To investigate primary quality indicators such as hydrogen ion concentration (pH), density (specific gravity), fluid consistency (viscosity), absorbance at 450 nm (A_{450}), total solids content, inorganic residue (ash), and acidity levels.
- To evaluate each milk type's performance in terms of nutrient richness, digestibility, processing efficiency, and preservation potential.
- To generate evidence-based information that supports formulation strategies, industrial processing decisions, and dietary planning.

2. Materials and Analytical Protocols

2.1 Sample Collection and Preparation

For this study, three categories of milk were sourced for detailed physicochemical evaluation.

- **Set A (C1, C2, C3)** represented fresh cow milk, collected from nearby dairy suppliers operating within a 5 km perimeter, under sanitary milking standards.
- **Set B (B1, B2, B3)** included raw buffalo milk sourced from certified Murrah breed farms recognized for their breed purity and hygiene compliance.
- **Set C (P1, P2, P3)** consisted of industrially processed full-cream milk powder, rehydrated in distilled water at a standard dilution ratio of 1:7 (w/v), as per label guidelines, to mimic the consistency of liquid milk.

Fresh liquid milk samples were immediately placed in insulated carriers containing frozen gel packs, maintaining a controlled temperature range of 4 ± 1 °C to inhibit microbial activity and enzymatic alterations. All tests were initiated within 24 hours of arrival to ensure chemical stability and representative results.
Powdered milk samples were stored in airtight, moisture-free containers at ambient temperature and reconstituted just before analysis to avoid degradation or changes due to prolonged exposure to air or humidity. This ensured consistency in evaluation and comparability across all sample groups.

2.2 Analytical Techniques and Statistical Evaluation

All compositional assessments were carried out in triplicate under standardized laboratory conditions to ensure precision and repeatability of measurements. Each parameter—namely pH, density (specific gravity), dynamic viscosity, absorbance at 450 nm (A_{450}), total solid content, mineral residue (ash), and titratable acidity—was reported as the arithmetic mean accompanied by the standard deviation (mean ± SD). To evaluate differences across the three milk types (cow, buffalo, and reconstituted powdered milk), comparative statistics were applied using the independent samples Student's t-test, with a confidence threshold set at 95% ($\alpha = 0.05$). The resulting p-values were used to determine the level of statistical significance for each trait (Sidhu & Bar, 2022). Furthermore, Pearson's correlation coefficient (r) was computed within each milk group to explore linear relationships between parameter pairs—for example, pH vs. A_{450} or viscosity vs. total solids—thus revealing underlying associations among compositional traits. Strict calibration of analytical instruments and monitoring of ambient conditions (temperature, humidity) were ensured prior to and during the testing phase to preserve data integrity and analytical reliability.

Table 1. Summary of Analytical Methodology and Instrumentation Used for Physicochemical Characterization of Milk **Samples**

PhysicochemicalParameter	Analytical Methodology	Instrumentation
pH	Calibrated with standard buffers (pH 4.00 and 7.00); measurements at 25 ± 0.5 °C.	Digital pH Meter (Eutech pH 700)
Specific Gravity	Measured at 27 °C using BIS 1479 (Part I) with temperature correction applied.	ISI-Standard Lactometer
Viscosity	Determined via efflux time; dynamic viscosity calculated at 25 ± 0.1 °C.	Ostwald Capillary Viscometer + Thermostatic Bath
Color Intensity (A_{450})	Measured absorbance at 450 nm post-centrifugation and filtration.	UV-Visible Spectrophotometer + Quartz Cuvettes

Total Solids	Determined by gravimetric drying at 105 °C until weight constancy.	Calibrated Forced-Air Oven
Ash Content	Measured via dry ashing at 550 ± 10 °C for 4 hours.	Muffle Furnace
Titratable Acidity	Titration with 0.1 N NaOH using phenolphthalein indicator; expressed as % lactic acid.	Burette, Indicator; AOAC Method 947.05

3. Results and Discussion

3.1 Comparative Physicochemical Profiles of Milk Samples

Buffalo milk exhibited significantly elevated values for specific gravity (1.034 ± 0.001), dynamic viscosity (2.18 ± 0.01 mPa·s), total solids (17.51 ± 0.18%), ash content (0.89 ± 0.01%), and titratable acidity (0.165 ± 0.002%) Table 2. These parameters reflect a denser biochemical composition, predominantly due to its higher concentrations of proteins, lipids, and mineral constituents. Such a robust physicochemical matrix underpins its suitability for the manufacture of high-yield traditional dairy products such as paneer, khoa, and ghee.

Cow milk demonstrated the highest pH value (6.72 ± 0.01) and β-carotene absorbance (A_{450} = 0.410 ± 0.004), indicating superior antioxidant and provitamin A content. Its comparatively lower viscosity (1.58 ± 0.03 mPa·s) and reduced total solids (12.85 ± 0.12%) suggest improved digestibility and make it especially appropriate for pediatric and geriatric nutrition. Reconstituted powdered milk showed intermediate characteristics across most parameters, with pH (6.78 ± 0.02), specific gravity (1.028 ± 0.001), and viscosity (1.68 ± 0.02 mPa·s) falling between those of buffalo and cow milk. The reduced A_{450} value (0.342 ± 0.005) reflects partial degradation of β-carotene during thermal processing (e.g., spray drying). Marginally elevated ash (6.15 ± 0.12%) and titratable acidity (0.153 ± 0.001%) likely result from solute concentration effects during dehydration and reconstitution.

Table 2. Mean ± SD values of key physicochemical attributes for cow, buffalo, and powdered milk, illustrating statistically significant interspecies and processing-related differences.

Parameter	Cow Milk	Buffalo Milk	Powdered Milk
pH	6.72 ± 0.01	6.61 ± 0.02	6.78 ± 0.02
Specific Gravity	1.030 ± 0.002	1.034 ± 0.001	1.028 ± 0.001
Viscosity (mPa·s)	1.58 ± 0.03	2.18 ± 0.01	1.68 ± 0.02
A_{450} (Absorbance)	0.410 ± 0.004	0.120 ± 0.002	0.342 ± 0.005
Total Solids (%)	12.85 ± 0.12	17.51 ± 0.18	95.92 ± 0.30
Ash Content (%)	0.75 ± 0.02	0.89 ± 0.01	6.15 ± 0.12
Titratable Acidity (% LA)	0.147 ± 0.002	0.165 ± 0.002	0.153 ± 0.001

3.2 Statistical Differentiation and Interpretative Insights

The inferential statistical analysis of physicochemical parameters among cow milk, buffalo milk, and reconstituted powdered milk revealed statistically significant ($p < 0.05$) to highly significant ($p < 0.001$) intergroup differences Table 3. The most pronounced distinctions were observed in viscosity ($p = 0.00032$), total solids content ($p = 0.00019$), and β-carotene absorbance at 450 nm (A_{450}; $p = 0.00314$), underscoring fundamental disparities in structural composition, nutrient concentration, and functional characteristics of the different milk types. Particularly, the highly significant variation in ash content ($p = 0.00056$) and titratable acidity ($p = 0.00793$) highlights the critical role of mineral load and acid–base buffering capacity in influencing both nutritional quality and technological performance. These parameters are pivotal in determining milk's stability during processing, fermentation potential, and compatibility with value-added dairy formulations.

The observed trends align closely with prior investigations (Singh et al., 2019; Esposito et al., 2024), reaffirming that milk's physicochemical behavior is shaped not only by species-specific compositional biochemistry but also by post-harvest processing methodologies such as thermal dehydration and reconstitution. These insights validate the distinct techno-functional identities of each milk category—buffalo milk for its dense macronutrient and mineral profile favoring high-yield processing; cow milk for its enhanced digestibility and provitamin A richness; and powdered milk for its logistical efficiency, albeit with partial nutritional compromise.

Table 3. Statistical comparison (p-values) between cow and buffalo milk for key physicochemical parameters, indicating the level of significance in compositional variation.

Parameter	p-value	Statistical Significance
pH	0.04251	Significant ($p < 0.05$)
Specific Gravity	0.02167	Significant ($p < 0.05$)
Viscosity (mPa·s)	0.00032	Highly Significant ($p < 0.001$)
A_{450} (Absorbance)	0.00314	Highly Significant ($p < 0.01$)
Total Solids (%)	0.00019	Highly Significant ($p < 0.001$)
Ash Content (%)	0.00056	Highly Significant ($p < 0.001$)
Titratable Acidity (% LA)	0.00793	Significant ($p < 0.01$)

3.3 Functional Relevance of Milk Types

The techno-functional performance of milk is intricately governed by its physicochemical and compositional attributes, which influence its nutritional efficacy, processing adaptability, and consumer appeal. Based on the comparative data, distinct functional roles emerge for buffalo milk, cow milk, and reconstituted powdered milk Table 4. Buffalo milk exhibits very high nutrient density, attributable to its elevated concentrations of total solids, proteins (casein), and milk fat. These compositional strengths translate into exceptional processing yield, making it ideal for traditional high-solids dairy products such as paneer, khoa, and ghee. However, its higher viscosity and relatively low β-carotene content contribute to a dull white appearance and moderate digestibility, potentially limiting its use in pediatric and clinical nutrition scenarios.

Cow milk, with moderate nutrient density and lower total solids, demonstrates superior gastrointestinal tolerability. Its naturally high β-carotene concentration imparts a bright yellow hue and contributes to antioxidant functionality, enhancing its suitability for pediatric, geriatric, and therapeutic applications. Although its processing yield is moderate, its sensory appeal and bioavailability make it an optimal choice for direct consumption and clinical nutrition formulations (Joshi & Verma, 2020). Reconstituted powdered milk, while subject to partial degradation of heat-sensitive micronutrients during spray drying, maintains high nutrient density on a dry matter basis. It offers substantial logistical advantages—particularly extended shelf life, transport convenience, and ease of storage—which are critical for industrial applications, institutional catering, and food security initiatives. Its digestibility and functional output, however, are contingent on rehydration efficiency and processing control, which may introduce variability in end-use performance.

These differentiated techno-functional profiles justify a matrix-specific application strategy: buffalo milk for value-added dairy production, cow milk for digestibility-centric and therapeutic use, and powdered milk for scalable, shelf-stable distribution systems (Rao & Dey, 2023).

Table 4. Comparative evaluation of milk types based on techno-functional attributes affecting nutritional quality, industrial utility, and consumer preferences.

Trait	Buffalo Milk	Cow Milk	Powdered Milk
Nutrient Density	Very High	Moderate	High (concentrated form)
Digestibility	Moderate to Low	Very High	Moderate
Processing Yield	Excellent	Moderate	High (industrial use)
Shelf Life	Short	Moderate	Very Long
Visual Appeal	Dull (milky white)	Bright (creamy yellow)	Neutral (off-white)

3.4 Correlation Analysis of Physicochemical Parameters: A Pearson's r Statistical Interpretation

Pearson's correlation coefficient (r) was employed to evaluate the linear relationships among key physicochemical attributes of cow milk, buffalo milk, and reconstituted powdered milk. The strength and direction of inter-parameter associations within each milk type provide mechanistic insights into compositional interdependence and processing effects.

3.5 Cow Milk

This matrix illustrates the linear associations among physicochemical parameters of cow milk. Strong negative correlations were observed between pH and several parameters including A_{450} ($r = -0.875$), total solids ($r = -0.912$), ash content ($r = -0.890$), and acidity ($r = -0.852$), suggesting that as pH increases, nutrient concentration and acidity tend to decrease Figure 1. A strong positive correlation was found between total solids and ash content ($r = 0.987$), and between ash content and titratable acidity ($r = 0.972$), indicating the co-accumulation of mineral content and buffering capacity. The A_{450} values correlated positively with total solids ($r = 0.974$), reflecting the role of β-carotene in the solid phase of milk.

3.6 Buffalo Milk

In buffalo milk, parameters exhibited predominantly strong positive correlations Figure 2. Notably, pH correlated positively with viscosity ($r = 0.702$), A_{450} ($r = 0.865$), and total solids ($r = 0.888$), reflecting the influence of alkaline environment on compositional density and color expression. Total solids correlated highly with ash content ($r = 0.962$) and acidity ($r = 0.891$), signifying the tight linkage between nutrient load and acid-base buffering.

3.7 Reconstituted Powdered Milk

In powdered milk, several inverse correlations emerged due to processing-induced modifications Figure 3. A_{450} showed strong negative correlations with pH ($r = -0.812$), viscosity ($r = -0.789$), and total solids ($r = -0.845$), likely reflecting thermal degradation of β-carotene during spray drying. Specific gravity was negatively correlated with ash content ($r = -0.832$), suggesting solute redistribution upon reconstitution. Ash content and acidity retained a strong positive correlation ($r = 0.914$), confirming the buffering role of mineral constituents' post-rehydration.

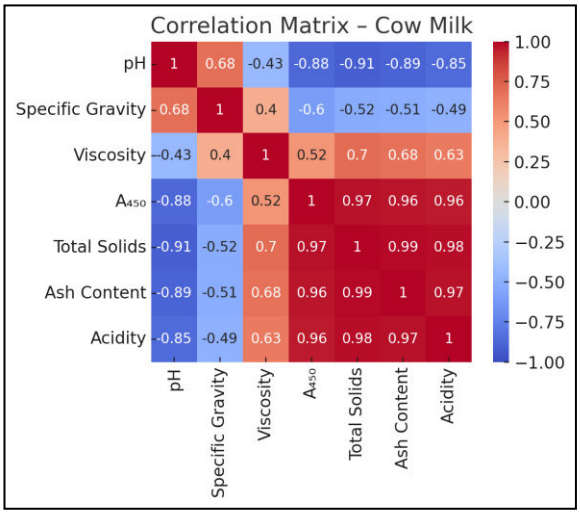

Fig 1. Pearson correlation matrix for physicochemical parameters of cow milk.

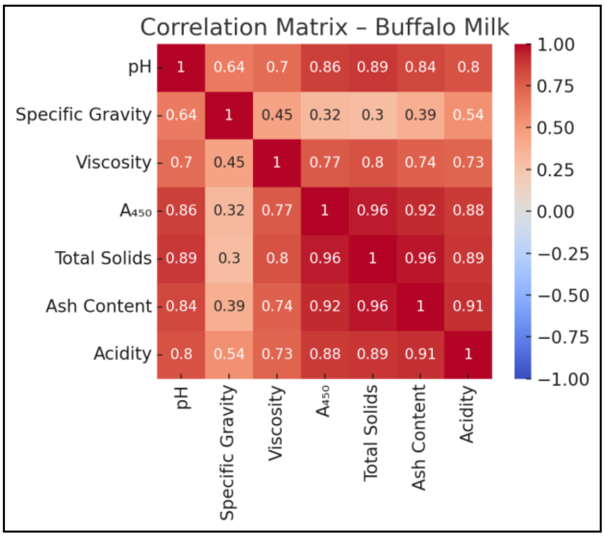

Fig 2. Pearson correlation matrix for physicochemical parameters of buffalo milk.

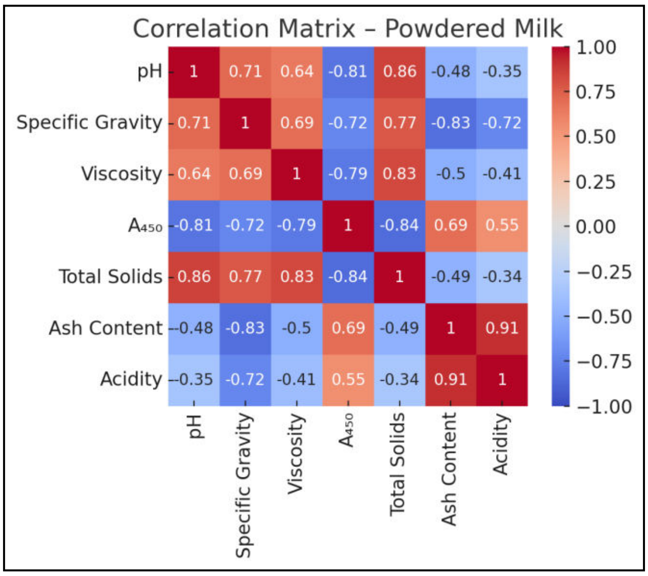

Fig 3. Pearson correlation matrix for physicochemical parameters of powdered milk.

4. Conclusion

This study delineates distinct and statistically robust physicochemical variations among raw cow milk, raw buffalo milk, and reconstituted powdered milk, arising from intrinsic species-specific biochemical composition and extrinsic processing influences. Buffalo milk exhibited elevated values for specific gravity, dynamic viscosity, total solids, ash content, and titratable acidity, indicative of its nutrient-dense matrix enriched in proteins, fats, and minerals. These attributes render it highly compatible with the production of traditional Indian dairy derivatives (e.g., paneer, khoa, ghee) and industrial applications requiring thermal resilience and structural integrity. In contrast, cow milk was characterized by higher pH and significantly greater β-carotene content, as reflected by its superior A_{450} absorbance. These compositional traits enhance its digestibility, antioxidant potential, and provitamin A availability, supporting its preferential use in pediatric, geriatric, and clinical nutrition. The lower viscosity and reduced total solids further favor ease of gastrointestinal assimilation and metabolic processing. Reconstituted powdered milk exhibited intermediate physicochemical profiles but showed attenuated β-carotene content, likely resulting from heat-induced oxidative degradation during spray drying. Nonetheless, its practical advantages—including prolonged shelf stability, transport efficiency, and reconstitution flexibility—reinforce its strategic value in emergency nutrition, institutional feeding, and non-cold-chain supply systems.Collectively, these findings advocate for a compositional matrix-driven approach to dairy valorization: buffalo milk for structurally demanding dairy processing, cow milk for clinical and functional formulations, and powdered milk for scalable, storage-stable deployment. To advance these insights, future studies should integrate high-resolution analytical platforms such as lipidomics, proteomics, and metabolomics to unravel the functional bioactives, health-promoting moieties, and post-processing transformations. Parallel investigations into bioavailability, organoleptic properties, and long-term storage dynamics will further inform formulation strategies, regulatory standards, and public health-oriented dairy interventions.

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