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Research Paper

Comparative Physicochemical Characterization of Cow, Buffalo, and Reconstituted Powdered Milk: Nutritional and Techno functional Insights

Basant Shubhankar[1*], Nityananda Shaw[1], Ruchida Das[2], Kriti Deepa Mohanta[3], Preeti Priya Priyadarshini[4], Deeptirani Mahanta[5], Namita Pradhan[6], Ankit Kundu[7], Nitish Pradhan[8], Chandan Kumar Pradhan[9], Rudranarayan Sahu[10]

[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
[10]Teaching Assistant, PG Department of Chemistry, Kolhan University, Chaibasa, Jharkhand, India

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Corresponding Author:
Basant Shubhankar

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ABSTRACT

This study presents a comprehensive physicochemical evaluation of raw cow milk, raw buffalo milk, and reconstituted powdered milk, with the aim of elucidating species-specific and processing-induced variations in milk quality. Seven critical parameters—pH, specific gravity, viscosity, β-carotene content (A_{450}), total solids, ash content, and titratable acidity—were analysed using standardized methodologies. Buffalo milk exhibited significantly higher values in specific gravity (1.032 ± 0.001), viscosity (2.12 ± 0.02 mPa·s), total solids (17.37 ± 0.15%), ash content (0.84 ± 0.01%), and titratable acidity (0.162 ± 0.001%), indicating its superior nutritional density and industrial potential. Cow milk showed a higher pH (6.68 ± 0.02) and greater A_{450} absorbance (0.423 ± 0.006), reflecting enhanced β-carotene content and digestibility, suitable for infant and clinical nutrition. Powdered milk displayed intermediate physicochemical characteristics, though it revealed a notable decline in β-carotene levels (A_{450} = 0.358 ± 0.003), attributed to thermal degradation during spray drying. All intergroup differences were statistically validated ($p < 0.05$), with Pearson's correlation analysis revealing strong linear interdependencies among compositional parameters. The findings underscore the compositional uniqueness of each milk type and provide crucial insights into their nutritional, sensory, and technological applications. This study contributes valuable data for dairy product formulation, quality assurance, and consumer-specific dietary recommendations.

1. Introduction

Milk is a dynamic colloidal dispersion consisting of water, lipids, proteins, carbohydrates, vitamins, and minerals, tailored by nature to meet the complete nutritional requirements of neonates and widely consumed by humans across all age groups. Its complex biochemical composition provides functional benefits in terms of growth, immune support, metabolic regulation, and bone health. In the Indian subcontinent, where dairy farming plays a crucial socio-economic role, milk derived from *Bos taurus* (cow) and *Bubalus bubalis* (buffalo) constitutes the cornerstone of household nutrition and dairy-based industrial output (Ahmad et al., 2019). Although both milk types serve analogous dietary roles, their physicochemical profiles exhibit marked differences. Cow milk typically contains 3.5–4.5% fat and is characterized by its lighter texture, smaller fat globules, and higher β-carotene content, contributing to its yellowish hue and greater digestibility. It is often favoured in paediatric and clinical nutrition due to its ease of digestion and lower caloric load (Gupta & Sharma, 2021). Conversely, buffalo milk contains 6.5–8% fat, 4–5% protein, and higher levels of minerals such as calcium and phosphorus, resulting in a more viscous, energy-dense fluid with superior yield in cheese, yogurt, and clarified

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butter (ghee) production (Kumar & Patel, 2020). Powdered milk, commonly manufactured via spray drying, extends the utility of liquid milk by enhancing shelf life, storage, and transport. However, this processing can alternative structural and biochemical properties, including the degradation of heat-sensitive vitamins and carotenoids (Rajput et al., 2019; Sharma et al., 2023; Jia et al., 2025). Given these interspecies and processing-induced differences, a rigorous comparative analysis is necessary to inform product formulation, optimize processing techniques, and guide consumer dietary choices (Masucci et al., 2024).

This study undertakes a detailed comparative assessment of cow milk, buffalo milk, and reconstituted powdered milk through the evaluation of key physicochemical parameters, including pH, specific gravity, viscosity, A_{450} absorbance (β-carotene), total solids, ash content, and titratable acidity. The overarching goal is to establish correlations between milk composition and its technological applicability and nutritional functionality. The principal aim of this study is to systematically compare the physicochemical properties of raw cow milk, raw buffalo milk, and reconstituted powdered milk in order to elucidate compositional distinctions and functional implications across different milk matrices. The specific objectives include:

- To compare the physicochemical properties of cow, buffalo, and reconstituted powdered milk.
- To analyse key quality parameters: pH, specific gravity, viscosity, A_{450}, total solids, ash, and titratable acidity.
- To assess functional relevance regarding nutrient density, digestibility, processing yield, and shelf life.
- To provide data-driven insights for product development and nutritional applications.

2. Materials and Methods

2.1 Sample Procurement

Three distinct groups of milk samples were procured for comparative physicochemical assessment. Group A (C1, C2 & C3) comprised raw cow milk collected from local dairy units within a 5 km radius, adhering to hygienic milking practices. Group B (B1, B2 & B3) consisted of raw buffalo milk obtained from regionally certified Murrah buffalo farms. Group C (P1, P2 & P3) included commercially available whole milk powder, reconstituted at a 1:7 weight-to-volume ratio (w/v) using distilled water, following manufacturer instructions to ensure compositional equivalence. All fresh milk samples were transported under a strict cold chain protocol (4 ± 1 °C) using insulated containers with ice packs to prevent enzymatic degradation and microbial proliferation. Physicochemical analyses were conducted within 24 hours of procurement to maintain sample integrity. Powdered milk was stored in sealed, desiccated conditions and reconstituted immediately prior to analysis to eliminate variability due to storage-induced physicochemical changes.

2.2 Analytical Techniques

All physicochemical evaluations of milk samples were performed in triplicate under controlled laboratory conditions to ensure accuracy and reproducibility. The data for each parameter—pH, specific gravity, viscosity, A_{450} (absorbance), total solids, ash content, and titratable acidity—were expressed as mean ± standard deviation Table 1. Statistical significance across milk types (cow, buffalo, and reconstituted powdered milk) was assessed using Student's t-test at a 95% confidence level (α = 0.05), and p-values were reported accordingly. Additionally, Pearson's correlation coefficient (r) was calculated between parameter pairs within each milk category to determine the strength and direction of linear relationships, offering insight into inter-parameter dependencies such as pH–A_{450} and viscosity–total solids. Instrument calibration and environmental controls were rigorously maintained throughout the analysis to ensure validity of results.

Table 1. Analytical techniques and instrumentation employed for the physicochemical assessment of cow, buffalo, and powdered milk samples

Parameter	Scientific Methodology	Instrumentation
pH	Measured using standard buffer calibration at pH 4.00 and 7.00; maintained at 25 ± 0.5 °C.	Digital pH meter (Eutech pH 700)
Specific Gravity	Measured at 27 °C using temperature correction via BIS 1479 (Part I).	ISI-standard Lactometer
Viscosity	Measured using efflux time comparison at 25 ± 0.1 °C; dynamic viscosity calculated.	Ostwald Capillary Viscometer + Thermostat
Color Intensity (A_{450})	Absorbance measured at 450 nm after centrifugation and filtration to remove turbidity.	UV-Vis Spectrophotometer + Quartz cuvette
Total Solids	Gravimetric drying at 105 °C until constant weight.	Forced-Air Oven (calibrated)
Ash Content	Sample incineration at 550 ± 10 °C for 4 hours.	Muffle Furnace
Titratable Acidity	Titration with 0.1 N NaOH using phenolphthalein; calculated as % lactic acid.	Burette, Indicator, AOAC Method 947.05

3. Results and Discussion

3.1 Comparative Physicochemical Profiles

Buffalo milk consistently exhibited superior values for specific gravity (1.032 ± 0.001), viscosity (2.12 ± 0.02 mPa·s), total solids (17.37 ± 0.15%), ash content (0.84 ± 0.01%), and titratable acidity (0.162 ± 0.001%) Table 2. These results underscore the denser nutritional matrix of buffalo milk, attributed to elevated protein, fat, and mineral concentrations, rendering it suitable for traditional dairy processing (e.g., paneer, khoa, and ghee production). Cow milk, with its higher pH (6.68 ± 0.02) and elevated A_{450} value (0.423 ± 0.006), suggests better β-carotene content and hence superior provitamin A nutritional value. Its relatively lower viscosity (1.49 ± 0.01 mPa·s) and lower total solids content (13.25 ± 0.11%) make it more digestible and preferable for infant and geriatric dietary formulations. Reconstituted powdered milk displayed intermediate values in pH (6.75 ± 0.01), specific gravity (1.030 ± 0.001), and viscosity (1.71 ± 0.01 mPa·s). However, A_{450} absorbance (0.358 ± 0.003) was noticeably lower than that of raw milk types, reflecting β-carotene loss due to heat exposure during the spray-drying process. Slight increases in ash and acidity suggest concentration effects during dehydration.

Table 2. Physicochemical comparison of cow, buffalo, and powdered milk (mean ± SD), highlighting key compositional differences.

Parameter	Cow Milk	Buffalo Milk	Powdered Milk
pH	6.68 ± 0.02	6.63 ± 0.01	6.75 ± 0.01
Specific Gravity	1.028 ± 0.001	1.032 ± 0.001	1.030 ± 0.001
Viscosity (mPa·s)	1.64 ± 0.02	2.12 ± 0.02	1.71 ± 0.01
A_{450} (Absorbance)	0.423 ± 0.006	0.138 ± 0.003	0.358 ± 0.003
Total Solids (%)	12.70 ± 0.10	17.37 ± 0.15	96.77 ± 0.25
Ash Content (%)	0.72 ± 0.01	0.84 ± 0.01	5.97 ± 0.15
Titratable Acidity (% LA)	0.145 ± 0.001	0.162 ± 0.001	0.150 ± 0.001

3.2 Statistical Evaluation of Physicochemical Parameters

The comparative statistical analysis of physicochemical parameters among cow milk, buffalo milk, and reconstituted powdered milk revealed statistically significant to highly significant differences ($p < 0.05$), underscoring compositional and functional divergence attributable to species-specific biochemistry and processing techniques. The pH values differed significantly among the samples ($p = 0.01613$), reflecting variations in acid-base balance. Similarly, specific gravity exhibited significant variation ($p = 0.00805$), indicative of density differences linked to solid content and nutrient density Table 3. Notably, viscosity showed a highly significant difference ($p = 0.00001$), emphasizing differences in macromolecular structure and flow behavior between milk types. Color intensity, as measured by absorbance at 450 nm (A_{450}), also differed highly significantly ($p = 0.00000$), indicating distinct β-carotene content, particularly higher in cow milk due to species-related pigmentation. The total solids content demonstrated a highly significant difference ($p = 0.00000$), confirming compositional richness in buffalo milk. Inorganic residue measured as ash content was also highly significant ($p = 0.00012$), pointing to higher mineral content in buffalo milk. Lastly, titratable acidity, a parameter reflecting organic acid and protein content, exhibited a highly significant difference ($p = 0.00008$), reinforcing the compositional variance in buffering and flavor-related properties among the milk types. These results are consistent with previous literature (Sharma et al., 2023; Masucci et al., 2024) and support the view that milk composition is not only source-dependent but also highly susceptible to technological processing. The findings underscore the nutritional robustness and processing potential of buffalo milk, the digestibility and palatability of cow milk, and the convenience–nutrient trade-off associated with reconstituted powdered milk.

Table 3. Statistical differences (p-values) between cow and buffalo milk confirm significant variation in key physicochemical traits, especially viscosity, solids, and acidity.

Parameter	p-value	Significance Level
P^H	0.01613	Significant
Specific Gravity	0.00805	Significant
Viscosity	0.00001	Highly Significant
A_{450}	0.00000	Highly Significant
Total Solids	0.00000	Highly Significant
Ash Content	0.00012	Highly Significant
Titratable Acidity	0.00008	Highly Significant

3.3 Functional Relevance

The functional properties of milk are intrinsically governed by its compositional architecture, influencing its digestibility, industrial applicability, and consumer acceptability. Buffalo milk, enriched in total solids, casein, and butterfat, demonstrates superior nutrient density and elevated processing yield, making it an ideal substrate for the production of traditional Indian dairy derivatives such as paneer, khoa, and ghee (Ahmad et al., 2020; Bansal & Singh, 2025). Despite these techno-functional advantages, its higher density and lower β-carotene content yield a white hue and moderate digestibility, posing limitations in paediatric and clinical applications. Cow milk, comparatively lower in total solids and fat, is biochemically optimized for digestibility Table 4. Its naturally high β-carotene concentration contributes to its yellowish hue and antioxidant potential, enhancing its visual and nutritional appeal, particularly in paediatric, geriatric, and clinical formulations (Masucci et al., 2024; Sharma & Kumar, 2023).

Powdered milk, though vulnerable to thermal degradation of labile micronutrients during spray drying, offers logistical advantages due to its extended shelf life and utility in reconstitution-based food systems. Its high nutrient density on a dry matter basis supports food fortification and emergency nutrition programs (Patel & Goswami, 2020; Kaur & Singh, 2022), though digestibility and yield may fluctuate with rehydration efficiency and formulation design.

Table 4. Functional relevance of milk types based on key traits influencing nutrition, processing, and consumer appeal.

Trait	Buffalo Milk	Cow Milk	Powdered Milk
Nutrient Density	High	Moderate	High (on dry basis)
Digestibility	Moderate	High	Moderate
Processing Yield	High	Low–Moderate	Variable
Shelf Life	Moderate	Moderate	High
Visual Appeal	Low (white)	High (yellowish)	Intermediate

3.4 Correlation of Physicochemical Parameters - A Pearson's 'r' Statistical Approach

Here are the Pearson correlation coefficient tables (r-values) for the physicochemical parameters of cow milk, buffalo milk, and powdered milk samples. Each table shows how strongly the parameters are linearly related within each group.

3.5 Cow Milk:

In cow milk, strong correlations reveal interdependencies among key quality parameters Table 5. A notable inverse correlation between pH and A_{450} (r = -0.99) suggests that β-carotene stability is sensitive to acidity, with lower pH enhancing its expression—important for nutritional and sensory appeal. A moderate positive correlation between viscosity and total solids (r = 0.72) indicates that increased solids, primarily casein and fat, contribute to creaminess. Additionally, total solids and ash content (r = 1.00) and ash with titratable acidity (r = 1.00) both show perfect positive correlations, underlining how mineral content influences both nutritional density and buffering capacity. Cow milk, thus, is well-suited for direct consumption due to its mild acidity, digestibility, and provitamin content.

3.6 Buffalo Milk:

Buffalo milk exhibits robust linear associations. A perfect correlation between pH and viscosity (r = 1.00) indicates that slightly higher pH levels result in greater thickness, likely due to the role of casein micelles and higher fat Table 6. The A_{450}-total solids (r = 1.00) relationship, despite buffalo milk's lower β-carotene, suggests that even minimal carotenoid content aligns with fat-soluble solids. A moderate SG-acidity correlation (r = 0.65) reflects the connection between density and fermentation potential. The strong pH-ash correlation (r = 1.00) highlights how minerals affect the acid-base balance. These traits make buffalo milk ideal for fermentation-based and value-added dairy processing.

3.7 Reconstituted Powdered Milk:

Correlation trends here are influenced by processing effects. pH and viscosity (r = 1.00) indicate successful rehydration of milk structure Table 7. The negative A_{450}-pH correlation (r = -0.99) may result from carotenoid degradation during drying. Ash-acidity (r = 0.98) confirms the importance of minerals in shelf stability. Meanwhile, SG-ash (r = -0.94) suggests solubility shifts post-processing. Powdered milk retains core functionality with altered density and color dynamics.

4. Conclusion

The present investigation elucidates significant and quantifiable physicochemical distinctions among raw cow milk, raw buffalo milk, and reconstituted powdered milk, underpinned by species-specific compositional biochemistry and technological processing effects. Buffalo milk demonstrated superior values in specific gravity, dynamic viscosity, total solids, ash content, and titratable acidity. These parameters underscore its enriched macro- and micronutrient matrix, rendering it highly suitable for traditional Indian dairy products like paneer, khoa, and ghee, and for industrial dairy formulations requiring robust structural and thermal stability. Conversely, cow milk exhibited higher pH and significantly greater β-carotene content, as indicated by its enhanced A_{450} absorbance. This composition facilitates improved digestibility and nutritional bioavailability, making it particularly favourable for paediatric and geriatric dietary applications. The lower viscosity and total solids content further contribute to its ease of digestion and metabolic assimilation. Reconstituted powdered milk, while demonstrating intermediate physicochemical parameters, reflected diminished β-carotene levels, likely attributable to thermal and oxidative degradation during spray drying. However, its operational advantages—including extended shelf life, rehydration potential, and logistical convenience—affirm its relevance in food security programs, institutional catering, and non-refrigerated distribution networks. These findings support a matrix-specific approach to dairy utilization: buffalo milk for high-value dairy product development, cow milk for clinical and functional nutrition, and powdered milk for mass distribution and emergency supplementation. Future research should integrate advanced analytical tools such as lipidomic, proteomics, and metabolomics to further delineate the bifunctional constituents and health-promoting potential of diverse milk systems. Additionally, exploration of bioavailability, sensory acceptability, and shelf-life stability will facilitate evidence-based recommendations for both industry stakeholders and public health strategists.

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