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Rheological Behavior of Milk From Different Species as a Function of Chemical Composition and Temperature: An Engineering Basis for Milk Processing

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ABSTRACT

This study aims to evaluate the rheological behavior of cow, goat, buffalo, and sheep milk over a wide temperature range (1°C–90°C), considering their chemical composition. The milk from the different species showed Newtonian behavior, and the Newton model was the most suitable ($R_{adj}^2 \geq 0.9979$; P (%) ≤ 2.6817; RQME ≤ 0.0333) to predict the rheological behavior of milk over the wide temperature range studied (1°C–90°C). Despite the statistically significant differences in the viscosity of goat and cow milk, the effect size is small in practical terms (on average, less than 4% difference), indicating that the necessary operating conditions are close to those found for a process designed for cow milk. In contrast, buffalo and sheep milk presented, on average, viscosity up to 24%–26% higher than cow and goat milk, which was attributed to the higher content of lipids, ash, and total solids, in addition to structural factors such as fat crystallization, protein interactions, and micellar structure. The Newtonian viscosity of milk from different species decreased with increasing temperature, and the Arrhenius equation described its thermal dependence well. These findings help better understand the rheological properties of milk from different species, supporting the development and improvement of dairy processes and products.

1 | Introduction

Milk is one of the most consumed foods worldwide, serving as a fundamental component of human nutrition in various forms, including fermented milk, cheese, butter, concentrated or dehydrated milk, cream, yogurt, and many other dairy products. While cow milk dominates global production (80.86%), buffalo (15.53%), sheep (1.03%), and goat milk (2.15%) are also essential, particularly in regions where climatic conditions and dietary habits favor their consumption (FAO 2025). The demand for goat, buffalo, and sheep milk has increased worldwide due to their nutritional benefits and potential for diversification of dairy products (Pappa et al. 2021; Faion et al. 2019; Bernardo et al. 2023; Firouz et al. 2023; Dias et al. 2022).

Milk composition varies significantly between breeds within a species, but also across different species (Pazzola et al. 2022; Stocco et al. 2024; Zanon et al. 2024), influencing its physicochemical and rheological properties. For instance, sheep milk has higher fat, protein, total solids, and casein content than cow, buffalo, and goat milk (Balthazar et al. 2017; Pietrzak-Fiećko and Kamelska-Sadowska 2020). Goat milk differs in fatty acid composition and casein concentration (Nguyen et al. 2018), while buffalo milk presents up to twice the fat content of cow milk, along with higher levels of saturated fatty acids and conjugated linoleic acid (Mejares et al. 2022). Such compositional differences directly impact milk rheology, processing conditions, and final product characteristics (Nguyen et al. 2018).

Although rheological studies over a wide temperature range have been conducted for raw milk, predominantly cow milk (Alcântara et al. 2012), research on goat, buffalo, and sheep milk remains scarce. Specifically for goat milk, only one study has investigated its rheological behavior, but within a relatively limited temperature range of 13°C to 58°C (Gabas et al. 2012). Moreover, most available studies on goat, buffalo, and sheep milk (Prajapati et al. 2017; Jayant et al. 2018; Saipriya et al. 2021) report viscosity data at only a single temperature, usually 20°C–30°C, which limits their applicability in designing industrial processes that operate across a broad temperature range. The lack of species-specific rheological data often leads to processing conditions being based on the properties of cow milk (Nguyen et al. 2018), which may not be optimal for other types of milk.

In addition to differences in chemical composition and physicochemical properties, the impact of heat treatment on milk components, especially proteins, can be different in goat, sheep, and buffalo milk compared to cow milk (Becskei et al. 2020; Mejares et al. 2022; Miloradovic et al. 2020). Some changes in the colloidal arrangement, microstructure, and whey protein denaturation can occur (Kilic-Akyilmaz et al. 2022). On the surface of the casein micelles, heated whey protein/casein (WP/CN) complexes produce unstable hydrophobic regions (Kilic-Akyilmaz et al. 2022; Mejares et al. 2022) and may influence the rheological behavior of milk of these different species at different process temperatures.

Given these gaps, this study aims to evaluate the rheological behavior of cow, goat, buffalo, and sheep milk over a wide temperature range (1°C–90°C), considering their chemical composition. Furthermore, mathematical modeling using Newtonian and non-Newtonian approaches (Ostwald-de-Waele, Herschel-Bulkley, and Bingham models) was applied to describe the flow behavior, providing a comprehensive understanding of the rheological behavior of milk from different species for improved processing and product development.

2 | Materials and Methods

2.1 | Milk Samples

Milk samples ($n = 3$ per species: cow, buffalo, goat, and sheep) were collected at Fazenda Santa Mônica, located in Jaborandi, São Paulo State, Brazil (20°41′16″ S, 48°24′46″ W; altitude 493 m). Samples were collected from the bulk tank milk after the morning milking, which followed a once-daily milking routine. Each species was represented by a single, commonly used dairy breed in Brazil: Girolando (cows), Mediterranean (buffaloes), Saanen (goats), and Lacaune (sheep). The farm operates under a semi-intensive production system, with animals raised on pasture and supplemented with concentrate feed.

On each collection day, 1 L of raw milk was obtained from each species, totaling 12 samples. After milking, the samples were immediately refrigerated at 4°C–7°C and stored in pre-cleaned and sterilized glass bottles. The samples were then transported under refrigeration and analyzed at the Laboratory of Physical Measurements at São Paulo State University—UNESP, São José do Rio Preto/SP, where they were stored at 5°C ± 1°C until analysis. All analyses were performed in triplicate within 48 h to preserve the original characteristics of raw milk.

2.2 | Chemical Characterization of Milk

The chemical composition (solids, proteins, lipids, ash, and carbohydrate contents) of milk samples was evaluated as follows: Total solids—gravimetric method in a constant temperature at 105°C ± 2°C until reaching constant weight (IAL 2008) (method 012/IV); protein—Kjeldahl method (AOAC INTERNATIONAL 2005) (method 991.20); lipid—Gerber method (AOAC INTERNATIONAL 2005) (method 2000.18); ash—muffle incineration (AOAC INTERNATIONAL 2005) (method 935.42); carbohydrates were calculated by difference.

2.3 | Rheological Characterization at Different Temperatures

Concentric cylindrical geometry (outer cylinder: 78.5 and 30.15 mm; inner cylinder: 42 and 28 mm) with a 5920 µm gap and the rotational rheometer (TA Instruments, New Castle, USA—model ARG2) was used to conduct steady shear rheological measurements under controlled stress and temperature; the latter controlled by a Peltier system. The system was handled by the software Rheology Advantage, and the steady-state flow was attained after shearing the samples for 2 min, which is the time required for the shear stress to stabilize at constant values for each shear rate. The shear rate ranged from 0.84 to 168.44 s^{-1} at 10 different temperatures (1°C, 10°C, 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, 80°C, and 90°C) using raw cow, goat, sheep, and buffalo milk samples.

Analyses were performed in triplicate ($n = 3$) for each collection day ($k = 3$), totaling nine evaluations per milk species. Each constant shear rate provided accurate shear stress information (Pa). The accuracy of the rheometer was previously evaluated according to Evangelista et al. (2020).

2.4 | Data Modeling

Modeling rheological behavior is a valuable tool and provides essential information for designing food process engineering operations and comprehending the dependence of the product on temperature (Ribeiro-Sanches et al. 2024; Guimarães et al. 2020; Evangelista et al. 2020). Thus, rheological models frequently reported in the literature, such as Newton's Law (Equation 1). Models by Ostwald-de Waele (Power Law) (Equation 2), Bingham (Equation 3), and Herschel-Bulkley

(Equation 4) were adjusted to data from shear stress and shear rate data of milk samples from different species using Microsoft Excel version 2016 software (Microsoft, Redmond, Washington, United States).

$$\sigma = \mu \cdot \gamma \quad (1)$$

$$\sigma = \kappa \cdot \gamma^{n} \quad (2)$$

$$\sigma = \sigma_0 + \kappa \cdot \gamma^{n} \quad (3)$$

$$\sigma = \sigma_0 + \mu_{pl} \cdot \gamma \quad (4)$$

In these equations, σ is the shear stress (Pa), μ is the Newtonian viscosity (Pa·s), μ_{pl} is the Bingham plastic viscosity (Pa·s), γ is the shear rate (s^{-1}), κ is the consistency index ($Pa \cdot s^{n}$), n is the flow behavior index (dimensionless), σ_0 is the residual stress (Pa). The coefficient of determination (R_{adj}^2), root mean square error (RQME), and relative mean error (P) were used to verify the consistency of the chosen model. The equation is considered satisfactory if the P values are less than 10%, R_{adj}^2 is close to 1, and the closer the RQME value approaches zero.

Considering that temperature plays an essential role in the rheological characteristics of any food products, once the best model was chosen and its consistency tested, the effect of temperature on the viscosity at a specific shear rate was expressed by the Arrhenius relationship, which involves the absolute temperature (*T*, in Kelvin), the universal gas constant ($R = 8.3145\,J\,mol^{-1}\,K^{-1}$) and the energy activation for viscosity (Ea), as shown in Equation (5). The polynomial models of the 2nd-degree equation shown in Equation (6) and the exponential equation (Equation 7) were also tested.

$$\mu = f(T) = A \cdot e^{\left(\frac{-Ea}{RT}\right)} \quad (5)$$

$$\mu = aT^2 - bT + c \quad (6)$$

where *a*, *b*, and *c*, constants

$$\mu = A \cdot e^{-bT} \quad (7)$$

where *A* and *b*, constants

The values of *Ea* and the constant *A* were determined from the experimental data. From the parameters *Ea* and *A*, the rheological data was described as a function of temperature.

3 | Results and Discussion

3.1 | Chemical Characterization

The chemical composition of the raw milk samples is presented in Table 1. Significant differences were observed between species, particularly in the contents of total solids, fat, protein, and ash—components that directly influence the physical behavior of milk, including its viscosity, especially under heating.

Regarding lipid content, sheep ($7.44\,g{,}\cdot 100\,g^{-1}$ of sample) and buffalo ($6.91\,g{,}\cdot 100\,g^{-1}$ of sample) milk had twice the amount of lipids compared to goat ($3.09\,g{,}\cdot 100\,g^{-1}$ of sample) and cow ($3.37\,g{,}\cdot 100\,g^{-1}$ of sample) milk. Compared to cow milk, sheep milk has a higher concentration of unsaturated fatty acids (Mohapatra et al. 2019), while buffalo milk contains more saturated fatty acids and linolenic acid (Mejares et al. 2022). The quantity and type of lipids may influence the viscosity of milk, especially when heated. In particular, higher concentrations of lipids could favor more significant interactions between fat globules, potentially resulting in greater viscosity.

Goat milk had the lowest protein content ($3.08\,g{,}\cdot 100\,g^{-1}$ of sample) compared to milk from other species. Cow and buffalo milk presented similar protein contents (approximately $3.01\,g{,}\cdot 100\,g^{-1}$ of sample), while sheep milk stood out with the highest content ($5.48\,g{,}\cdot 100\,g^{-1}$ of sample), approximately 77% higher than the others. In addition to being a significant source of whey proteins ($1.02\,g{,}\cdot 100\,g^{-1}$ of sample), in which β-lactoglobulin predominates, sheep milk also has the highest concentration of casein ($4.18\,g{,}\cdot 100\,g^{-1}$ of sample) (Mohapatra et al. 2019). Higher protein content, particularly casein, may contribute to increased milk viscosity due to greater micellar density and the potential formation of protein networks. Additionally, the thermal denaturation of whey proteins might intensify these interactions, which could help explain the observed differences in viscosity.

From a technological point of view, the high levels of lipids and proteins in sheep and buffalo milk make them helpful in producing various dairy products such as cheese, condensed milk, yogurt, ice cream, cream, and butter (de Carvalho et al. 2022; Dias et al. 2022; Felice et al. 2021).

The ash content, which reflects the total mineral concentration in milk, varied among the species. Sheep milk showed the highest value ($0.89\,g{,}\cdot 100\,g^{-1}$ of sample), followed by buffalo milk ($0.73\,g{,}\cdot 100\,g^{-1}$ of sample). Cow and goat milk exhibited similar ash

TABLE 1 | Chemical composition of milk from different species ($g \cdot 100\,g^{-1}$ of sample).

Component	Cow	Goat	Buffalo	Sheep	Valor *p*
Lipids	3.37 ± 0.02^{c}	3.09 ± 0.02^{d}	6.91 ± 0.03^{b}	7.44 ± 0.04^{a}	< 0.001
Proteins	3.11 ± 0.03^{b}	3.08 ± 0.02^{c}	3.11 ± 0.02^{b}	5.48 ± 0.03^{a}	< 0.001
Ashes	0.69 ± 0.01^{c}	0.69 ± 0.01^{c}	0.73 ± 0.01^{b}	0.89 ± 0.01^{a}	< 0.001
Carbohydrates	4.58 ± 0.03^{a}	4.46 ± 0.06^{b}	4.47 ± 0.06^{b}	4.13 ± 0.02^{c}	< 0.001
Solid content	11.74 ± 0.03^{c}	11.32 ± 0.05^{d}	15.21 ± 0.06^{b}	17.94 ± 0.03^{a}	< 0.001

Note: Different letters on the same line indicate a significant difference according to the Analysis of Variance (ANOVA) ($p < 0.05$) and Tukey's multiple comparison test ($\alpha = 0.05$).

contents (0.69 g,·100 g^{-1} of sample). Knowing the mineral profile is essential in thermal processes, since the distribution of minerals—especially calcium and phosphorus—between the aqueous and colloidal phases can be altered with heating (Kilic-Akyilmaz et al. 2022), influencing protein aggregation and, consequently, the viscosity of the system. Regarding carbohydrates, sheep milk presented the lowest value (4.13 g,·100 g^{-1} of sample), while cow milk recorded the highest value (4.58 g,·100 g^{-1} of sample).

Regarding total solids, sheep milk had the highest content (17.94 g,·100 g^{-1} of sample), being 52.81% higher than cow milk (11.74 g,·100 g^{-1} of sample), 58.48% higher than goat milk (11.32 g,·100 g^{-1} of sample), and 17.95% higher than buffalo milk (15.21 g,·100 g^{-1} of sample). Buffalo milk also had a higher total solids content compared to goat and cow milk, being 29.56% and 34.36% higher, respectively. Although cow milk had a higher solids content than goat milk, both were in the range of 11 g·100 g^{-1} of sample. Higher total solids may contribute to higher milk viscosity due to the higher molecular friction and electroviscous effects.

In addition, using these different raw materials can contribute to the diversification of the products and increase their yield due to the higher total solid content, potentially improving the economic returns for dairy industries. However, the industrial processing of mainly goat, buffalo, and sheep milk still lacks important information on how thermal processing can affect the rheological behavior of these different raw materials, limiting the proper and efficient design of appropriate industrial operations.

3.2 | Rheological Characterization and Mathematical Modeling

The flow behavior between shear stress and strain rate for milk from different species at all the temperatures studied is shown in Figure 1. In all cases, it is possible to notice a linear relationship between shear stresses and shear rates, evidencing a Newtonian behavior at all the temperatures studied.

The experimental data were adjusted to the Newton (Equation 1), Ostwald-de Waele (Equation 2), Herschel-Bulkley (Equation 3), and Bingham (Equation 4) models, and they presented quality of fit, with adjusted determination coefficients higher than 0.9979, which is an indication of the accuracy of the models' fit (Table S1). However, this parameter alone is not sufficient to choose the best model. Despite the high coefficient of determination (R_{adj}^2) obtained by all models, the lowest values of relative mean error (P) and root mean square error (RQME) were received by the Newton model. The parameters of the Ostwald-de Waele, Herschel-Bulkley, and Bingham models are available in the Supporting Information (Tables S2–S5).

The Ostwald-de Waele model fitted the milk sample data at all temperatures, and the n-value parameter was very close to 1, which means that the Ostwald-de Waele model matches the Newton model. A similar situation occurred for the Herschel-Bulkley and Bingham models, for all dairy species, at all temperatures, where the value of σ_0 is very close to or practically zero, and the n value was approximately 1, making both equations identical to the Newton model. This information corroborates that the Newton model is the most appropriate for predicting the rheological behavior of milk from different species in the temperature range studied (1°C–90°C).

Gabas et al. (2012) studied the rheological behavior of goat milk as a function of temperature (0°C to 58°C) and solids concentration (10.5% to 50.0%). The authors reported different rheological behaviors based on temperature and total solids (TSS) concentration. Goat milk displayed Newtonian behavior at temperatures of 3°C–58°C and 10.5%–22.0% TS, pseudoplastic behavior without yield stress for solid contents of 25.0%–39.4% and 44.3%–50.0% at temperatures of 3°C–58°C and 30°C–58°C, respectively, and pseudoplastic behavior with yield stress for solid contents of 44.3%–50.0% at temperatures of 0°C–23°C.

The rheological behavior of dairy products can be pretty diverse since several factors like temperature, composition (proteins, lipids, total solids, and minerals in milk), age, microstructure, processing conditions (heat treatment, pH value, concentration, etc.) influence the rheological behaviors of milk and dairy products and these are essential factors usually involved in the processing of milk and milk products (Saipriya et al. 2021).

The average viscosity (μ, mPa s) of milk from different species at different process temperatures, obtained by fitting the Newton model, decreased as the temperature increased (Table 2). The increase in temperature causes the molecules to become more agitated, lessening intermolecular contact and promoting fluid movement (Evangelista et al. 2020), decreasing viscosity.

In addition to the effect of temperature, the viscosity of milk from different species was different, considering the same process temperature. In general, sheep and buffalo milk always showed higher viscosity when compared to cow and goat milk at all the temperatures studied. This phenomenon is presumably connected to the higher concentration of lipids, proteins, and ash found in the milk of these species, which causes more molecular friction and electroviscous effects (Evangelista et al. 2020), resulting in a higher viscosity. Viscosity data were first analyzed by temperature range to identify specific behaviors. Subsequently, an overall comparative analysis was performed based on average values across the entire temperature range.

At low temperatures (1°C and 10°C), goat milk showed viscosity values of 3.68 ± 0.04 mPa s at 1°C and 2.98 ± 0.04 mPa s at 10°C, which were significantly higher than cow milk by 4.48% to 11.36%. Buffalo milk demonstrated even greater viscosity, reaching 4.15 ± 0.01 mPa s at 1°C and 3.21 ± 0.02 mPa s at 10°C, surpassing cow milk by 17.76% to 20.17% and goat milk by 7.92% to 12.71%. Most remarkably, sheep milk recorded the highest viscosity values (4.28 ± 0.02 mPa s at 1°C and 3.58 ± 0.03 mPa s at 10°C), showing differences of 21.56% to 33.81% compared to cow milk, 16.35% to 20.16% relative to goat milk, and 3.23% to 11.35% higher than buffalo milk.

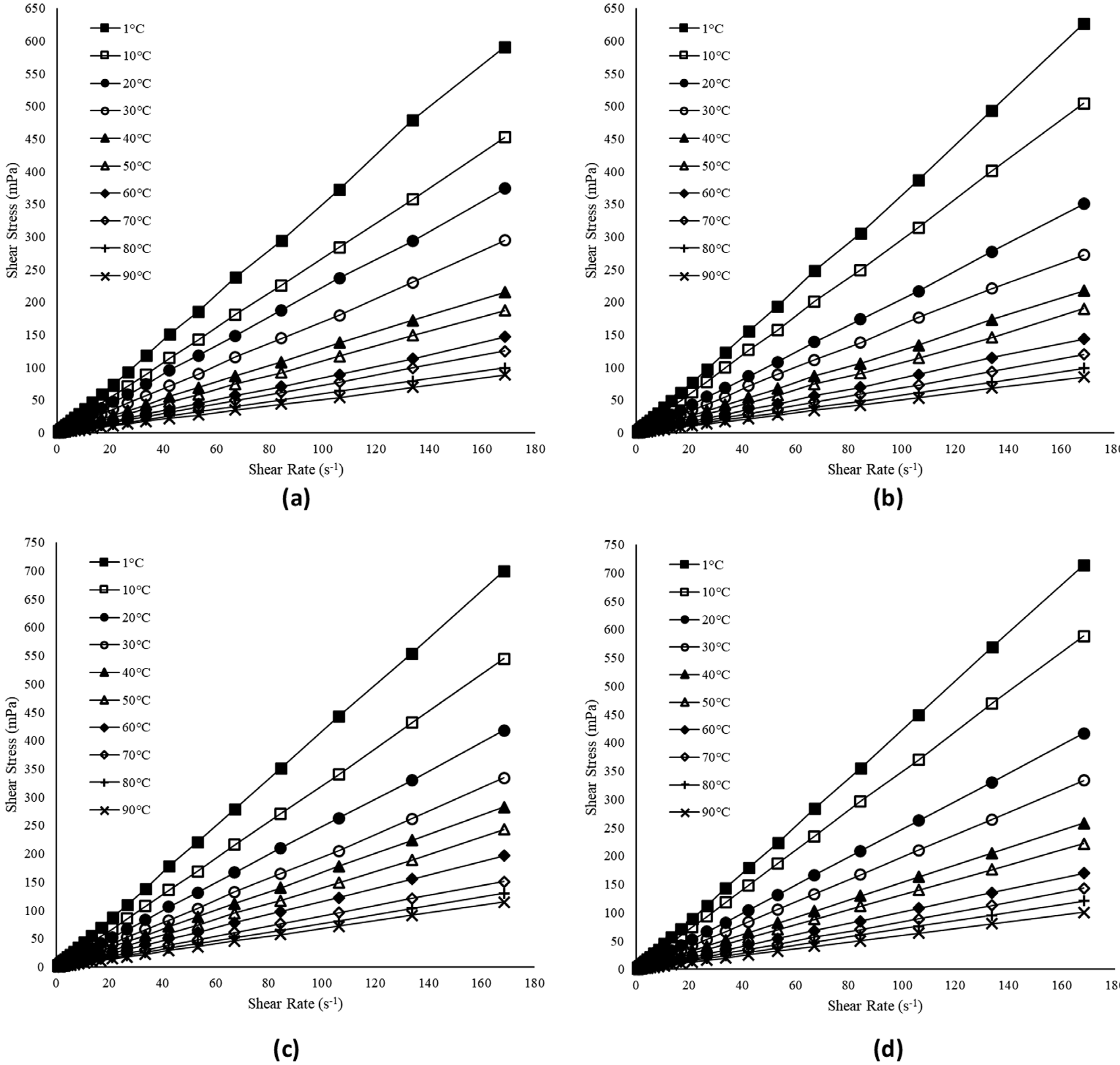

FIGURE 1 | Rheological behavior of (a) cow, (b) goat, (c) buffalo, and (d) sheep milk at different temperatures.

The higher viscosity of sheep and buffalo milk at lower temperatures can be attributed to their compositional characteristics, particularly their higher fat and protein content. Sheep and buffalo milk contain good proportions of saturated fatty acids (Mejares et al. 2022), which tend to crystallize at low temperatures, increasing flow resistance. Additionally, their elevated casein content and larger micelle diameters promote more intense protein–protein interactions (Roy et al. 2020; Park 2007; Nguyen et al. 2018). Reduced molecular mobility and increased colloidal stability under cold conditions contribute to a more structured rheological behavior and, consequently, higher viscosities.

Between 20°C and 30°C, sheep milk maintained the highest viscosity, ranging from 2.54 to 2.07 mPa s. These values were 14.94%–20.43% higher than those of cow milk (2.21–1.72 mPa s) and 23.23%–26.60% higher than goat milk (2.06–1.63 mPa s). Buffalo milk ranked second, with intermediate viscosity values (2.47–1.96 mPa s), exceeding cow milk by 11.78%–13.81% and goat milk by 19.65%–19.85%. Cow milk showed slightly higher viscosity than goat milk, though this difference was less than 7%. These variations likely reflect differences in casein micelle composition: goat milk is rich in β-casein, while cow milk contains more αS1-casein, resulting in distinct structural behaviors (Park et al. 2007).

These differences in viscosity among milk types are particularly relevant for unit operations such as ultrafiltration and cheese making. Higher viscosities, especially in sheep and buffalo milk, may lead to lower permeate flux, more significant membrane fouling, and increased energy demand during cross-flow filtration (Faion et al. 2019), ultimately

TABLE 2 | Mean viscosity (μ, mPa s) of milk from different species at different temperatures (°C).

Temperature	Cow	Goat	Buffalo	Sheep	p^1
1	$3.525 \pm 0.023^{d,A}$	$3.683 \pm 0.045^{c,A}$	$4.151 \pm 0.017^{b,A}$	$4.285 \pm 0.028^{a,A}$	< 0.001
10	$2.677 \pm 0.027^{d,B}$	$2.981 \pm 0.042^{c,B}$	$3.217 \pm 0.021^{b,B}$	$3.582 \pm 0.037^{a,B}$	< 0.001
20	$2.215 \pm 0.005^{c,C}$	$2.066 \pm 0.024^{d,C}$	$2.476 \pm 0.014^{b,C}$	$2.546 \pm 0.015^{a,C}$	< 0.001
30	$1.723 \pm 0.010^{c,D}$	$1.639 \pm 0.007^{d,D}$	$1.961 \pm 0.020^{b,D}$	$2.075 \pm 0.023^{a,D}$	< 0.001
40	$1.284 \pm 0.004^{c,E}$	$1.282 \pm 0.004^{c,E}$	$1.672 \pm 0.014^{a,E}$	$1.625 \pm 0.007^{b,E}$	< 0.001
50	$1.108 \pm 0.017^{b,F}$	$1.102 \pm 0.004^{b,F}$	$1.419 \pm 0.014^{a,F}$	$1.411 \pm 0.002^{a,F}$	< 0.001
60	$0.853 \pm 0.001^{c,G}$	$0.847 \pm 0.009^{c,G}$	$1.160 \pm 0.009^{a,G}$	$1.106 \pm 0.004^{b,G}$	< 0.001
70	$0.737 \pm 0.005^{c,H}$	$0.702 \pm 0.001^{d,H}$	$0.900 \pm 0.007^{b,H}$	$0.972 \pm 0.001^{a,H}$	< 0.001
80	$0.593 \pm 0.002^{c,I}$	$0.580 \pm 0.005^{d,I}$	$0.769 \pm 0.002^{a,I}$	$0.753 \pm 0.004^{b,I}$	< 0.001
90	$0.519 \pm 0.002^{c,J}$	$0.506 \pm 0.004^{d,J}$	$0.679 \pm 0.003^{a,J}$	$0.642 \pm 0.002^{b,J}$	< 0.001
p-value^2	< 0.001	< 0.001	< 0.001	< 0.001	

Note: Different lower case letters in the same row and different upper case letters in the same column indicate significant difference according to Analysis of Variance (ANOVA) ($P < 0.05$) and Tukey's multiple comparison test ($\alpha = 0.05$).

affecting both process efficiency and product yield in dairy applications.

In the 40°C–60°C temperature range, cow and goat milk exhibited statistically similar viscosity values, ranging from 1.28 to 0.84 mPa s. Under these conditions, both buffalo (1.67–1.16 mPa s) and sheep milk (1.62–1.10 mPa s) maintained significantly higher viscosities, with buffalo milk exceeding cow and goat milk by 28.07%–36.95%, while sheep milk showed 26.56%–30.58% higher values compared to these species.

Above 60°C, buffalo milk consistently demonstrated greater viscosity (1.16–0.67 mPa s) than sheep milk (1.10–0.64 mPa s), except at 70°C, although these interspecies differences remained below 8%. This thermal behavior contrasts sharply with low-temperature viscosity patterns. The viscosity of cow and goat milk ranged from 0.85–0.51 mPa s and 0.84–0.50 mPa s, respectively. More substantial differences were observed between buffalo milk and cow (22.12%–35.99%) or goat milk (28.21%–36.95%). Similarly, sheep milk showed significant viscosity differentials versus cow (23.70%–31.89%) and goat milk (26.88%–38.46%)—variations with essential implications for dairy processing technologies.

The higher viscosity of buffalo milk above 60°C probably results from differences in physicochemical characteristics between the milk and how these characteristics respond to heating. In this temperature range, three factors become particularly important for viscosity: (1) the denaturation of whey proteins, (2) the subsequent complexation of these proteins with casein micelles, and (3) the physical state of the lipids. Studies such as that of Saipriya et al. (2021) corroborate this thermal influence, demonstrating that processing (e.g., pasteurization at 63°C for 30 min or 72°C for 16 s) significantly increases the viscosity of goat's milk compared to raw milk. Similar changes may occur in buffalo milk, since the denaturation of whey proteins may favor different interactions with casein micelles, further increasing viscosity. In addition to the influence of temperature, structural differences in casein micelles and the proportion of the four main caseins (α_{s1}, α_{s2}, β, and κ) between species (Nguyen et al. 2018) may also explain the distinct viscosity responses to heating observed between different types of milk.

Although there were variations at specific temperature intervals, the overall trend—based on the average viscosity differences across the entire temperature range—shows that buffalo milk was, on average, 24.04% more viscous than cow milk and 25.12% more viscous than goat milk. Similarly, sheep milk exhibited an average viscosity 25.69% higher than cow milk and 26.69% higher than goat milk. Comparing sheep and buffalo milk, the average percentage difference was only 4.68%. On the other hand, the average difference between cow and goat milk was only 3.83%, indicating very similar viscosity characteristics throughout the temperature range evaluated.

Understanding how milk viscosity varies with temperature and species is essential for optimizing dairy processing. Higher viscosity, especially in buffalo and sheep milk at low temperatures, may increase pressure drop and energy requirements for pumping (Flauzino et al. 2010). Recognizing these variations allows for strategic process adjustments, such as temperature control and pumping power optimization. Viscosity also influences the efficiency of heat exchangers (Gonçalves et al. 2017) during pasteurization and sterilization by affecting flow and heat transfer. Buffalo and sheep milk may thus require process modifications to ensure uniform heating and prevent localized overheating. Additionally, viscosity is a determining factor in droplet size during spray drying (Mercan et al. 2018), directly impacting drying efficiency and the properties of milk powder. These findings highlight the practical significance of our study for industrial dairy processing.

Using the experimental data fitted by Newton's Law, the Arrhenius, second-degree polynomial, and exponential models (Equations 5–7) were tested to determine the best representation of the relationship between viscosity and temperature.

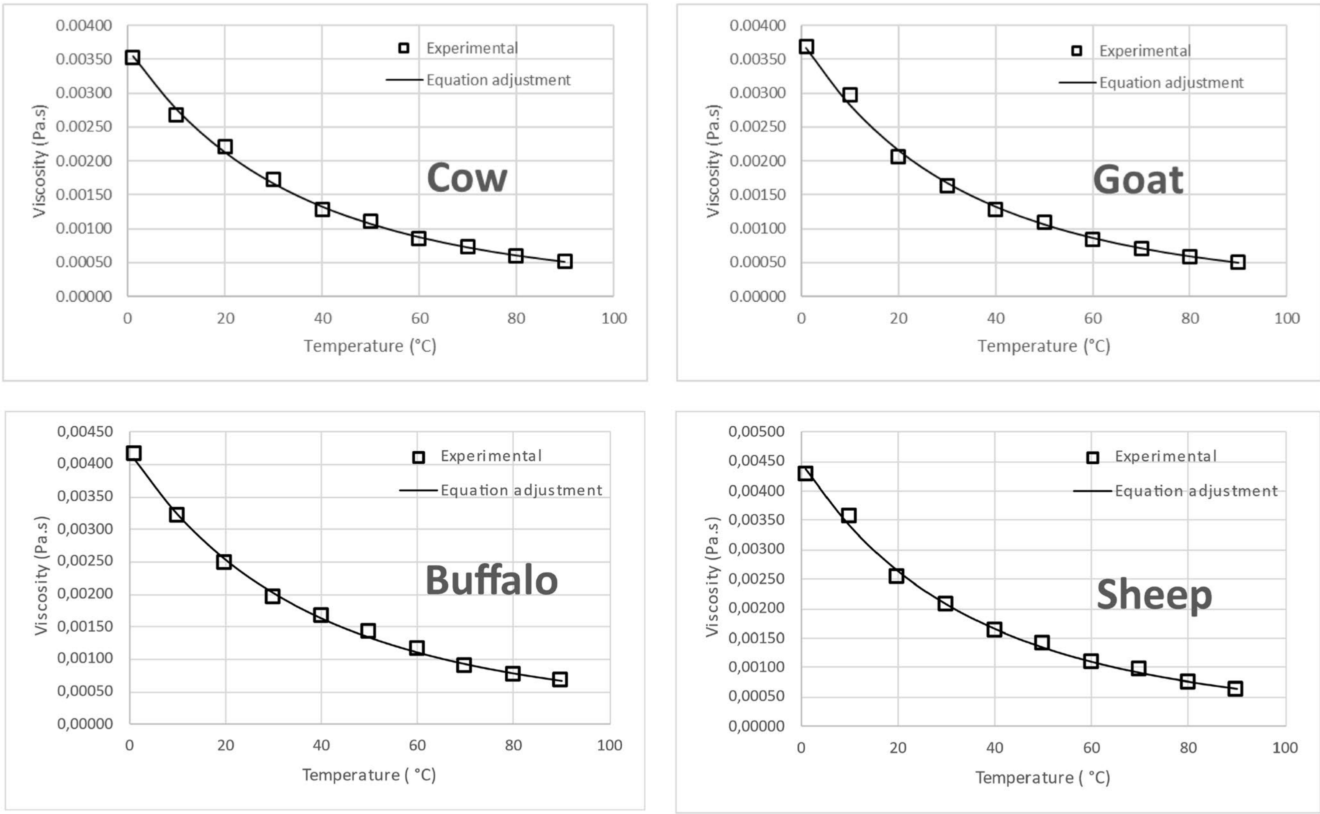

FIGURE 2 | Cow, goat, buffalo, and sheep milk viscosity is predicted by the Arrhenius equation as a function of temperature. The squares are the experimental values, and the solid line are the values obtained by the adjusted equation.

The Arrhenius model best fits all milk from different species (Equations 8–11; Figure 2). This was supported by the highest adjusted ${R_{adj}}^2$ values, along with the lowest p-values and RQME (Table S6), reinforcing the suitability of the Arrhenius approach for modeling viscosity behavior in dairy systems.

$$\textbf{Cow}\ \mu = 1.33 \cdot 10^{-6} \cdot e^{\left(\frac{-17990}{8.3145 \cdot T}\right)} \tag{8}$$

$$\textbf{Goat}\ \mu = 1.01 \cdot 10^{-6} \cdot e^{\left(\frac{-18685}{8.3145 \cdot T}\right)} \tag{9}$$

$$\textbf{Buffalo}\ \mu = 2,64 \cdot 10^{-6} \cdot e^{\left(\frac{-16749}{8,3145 \cdot T}\right)} \tag{10}$$

$$\textbf{Sheep}\ \mu = 1,91 \cdot 10^{-6} \cdot e^{\left(\frac{-17628}{8,3145 \cdot T}\right)} \tag{11}$$

The activation energy (*Ea*), calculated using the Arrhenius model, reflects the sensitivity of a fluid viscosity to temperature variations (Martins et al. 2020). Among the samples analyzed, goat milk showed the highest *Ea* (18.68 kJ mol^{-1}), indicating greater thermal sensitivity—that is, its viscosity varies more sharply with increasing temperature. Cow (17.99 kJ mol^{-1}) and sheep (17.62 kJ mol^{-1}) milk exhibited intermediate values with similar behavior. In contrast, buffalo milk had the lowest Ea (16.74 kJ mol^{-1}), suggesting a viscosity less affected by temperature and thus more stable under heating conditions. It may help explain why its viscosity remained higher at temperatures above 40°C, even though it contains fewer total solids than sheep milk.

Interestingly, the variations in *Ea* among species likely stem from compositional and structural differences, particularly in fat globule size, protein aggregation, and mineral content, which affect intermolecular interactions and flow resistance. For instance, higher casein micelle content and lipid phase volume can increase energy dissipation during flow, thereby influencing *Ea*.

Although data on activation energy for milk viscosity remains scarce, related studies provide important insight. Gonçalves et al. (2017) reported *Ea* values of 15.25 to 20.99 kJ mol^{-1} for fermented dairy products (e.g., yogurt and beverages) under low-temperature shear. Similarly, Braga et al. (2021) found that fat content affects *Ea* in yogurts: skimmed samples, with less fat, had higher *Ea* and were more sensitive to temperature changes. These findings align with our results, reinforcing the role of milk composition in thermal rheological behavior.

Beyond dairy, Deswal et al. (2014) demonstrated that in plant-based oat milk, increasing soluble solids substantially raised *Ea* from 7.43 to 303.64 kJ mol^{-1}, confirming that solute concentration is a key driver of temperature-dependent viscosity behavior across liquid food matrices.

From an engineering standpoint, modeling milk viscosity with the Arrhenius equation provides a reliable predictive tool for designing and optimizing processes involving momentum, heat, and mass transfer. Knowledge of *Ea* and viscosity behavior allows for better predicting flow resistance in pipelines and heat exchangers, impacting parameters such as flow rate, heating time, and energy requirements (Evangelista et al. 2020). Although no major modifications in industrial equipment may be necessary for pumping milk from different species, viscosity variations must still be accounted for to avoid underestimating the energy required for pumping, mixing, or overcoming pressure losses in complex processing lines. Accurate rheological modeling ensures precise control over processing conditions, improving product quality and energy efficiency.

4 | Conclusions

Newton's law of viscosity was the most appropriate to describe the relationship between shear stress and shear rate for cow, goat, sheep, and buffalo milk over a wide temperature range (1°C–90°C), classifying them as Newtonian fluids. Despite the significant differences in the viscosity of goat and cow milk, the effect size is small in practical terms (on average, less than 4% difference), indicating that the necessary operating conditions are close to those found for a process designed for cow milk. In contrast, buffalo and sheep milk are more viscous (24%–26% on average) than cow and goat milk, which was attributed to the higher content of lipids, ash, and total solids, as well as structural factors such as fat crystallization, protein interactions, and micellar structure. These rheological differences may indicate the need for adjustments in unit operations, such as pumping and heat exchangers, to optimize the processing of this milk on an industrial scale.

The Newtonian viscosity of milk from different species decreased with increasing temperature, and the Arrhenius equation could adequately describe its thermal dependence. The activation energy indicated that goat milk is the most sensitive to temperature variations, while buffalo milk showed the least sensitivity. The results of this study provide relevant information for dairy process engineering, assisting in the sizing of equipment and the optimization of processing conditions. Future research should explore the impact of the concentration process on the chemical composition and rheological behavior of milk from these different species, especially for the formulation of concentrated dairy products.

Author Contributions

All authors contributed substantially to this study. H.C.S. conducted the research and wrote the manuscript. A.S.S. and B.H.P.G. contributed to the experiments and the first draft of the manuscript. A.L.B.-M. and M.A.R.-S. contributed to the mathematics model and assisted in writing and data analysis. A.L.B.P. and J.T.-R. both were the project administrators, provided expertise regarding the chemical analysis and rheological experiments. A.L.B.P. reviewed and edited the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Fitting data to the rheological models. **Table S2:** Comparison of rheological models for cow milk. **Table S3:** Comparison of rheological models for goat milk. **Table S4:** Comparison of rheological models for buffalo milk. **Table S5:** Comparison of rheological models for sheep milk. **Table S6:** Statistical parameters of the equations that relate Viscosity and Temperature, with the data obtained by the Newton model.