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Rheological analysis of dairy products: Instrumentation and Applications to Functional Dairy Products Enriched with Plant-based Ingredients

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Abstract

Food rheology studies how food and beverages flow and deform. Milk and dairy products often contain multiple ingredients and structures that create a complex rheological response. This article aims to thoroughly review the rheological characteristics of various dairy products (milk, concentrated milk, fermented dairy gels, foams and cream, ice cream, butter, and low-fat dairy desserts), focusing on how the composition of dairy mixtures and processing parameters influence their rheological behaviour and texture changes. Additionally, the study discusses the most commonly used rheological measurements and instruments in the dairy industry. Results show that measurements like texture profile analysis and fundamental methods, such as small amplitude oscillatory shear (SAOS), large amplitude oscillatory shear (LAOS), and tribology, provide more accurate information than empirical methods like gelometers and penetrometers. However, the colloidal properties and clumping behaviour of dairy systems should be considered when choosing the appropriate rheological measurement technique. The study also highlights the trend of using hydrocolloids to improve the texture of dairy gels, especially low-fat dairy desserts, through casein-hydrocolloid linkages. Furthermore, it discusses how adding plant-based ingredients like coffee powder, flaxseed powder, and apple polyphenols in functional dairy products impacts their rheological properties, pointing to future improvements in product quality. Findings show that the interaction between dairy proteins and phenolic compounds significantly influences the texture and sensory qualities of functional dairy products enriched with plant extracts.

Keywords: Functional dairy; Milk; Rheology; Rheological measurements

1 Introduction

Rheology is the study of the flow and deformation of matter. This term is often used in food applications to describe the deformation, flow behaviour, decomposition, and morphological properties of food products when subjected to a force (Martínez-Padilla, 2024). The basic principles of stress, defined as the force applied per unit area, and strain, representing the deformation per unit length, constitute the fundamental elements of all rheological investigations. Specifically, in solid food systems, attention is primarily directed towards product deformation and structural modifications, whereas in liquid food systems, the principal focus is on viscosity (Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000). Rheological properties are impor-

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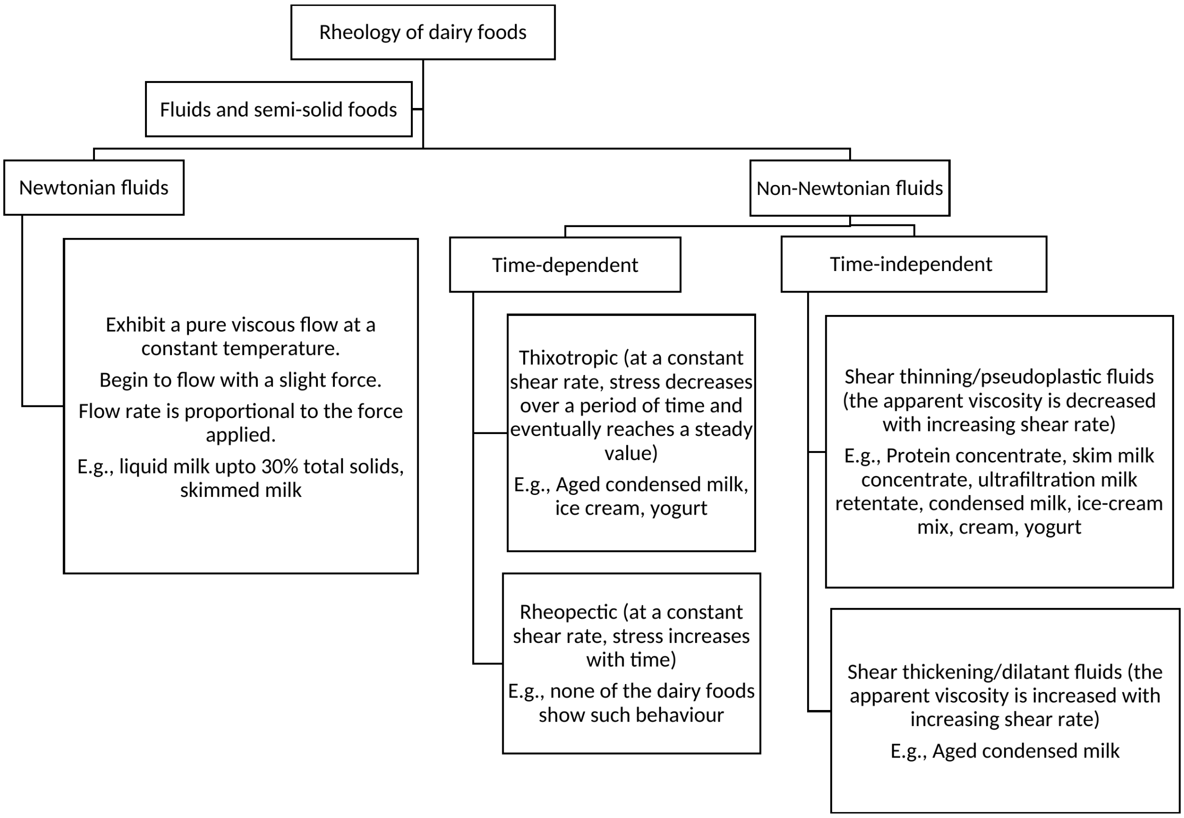

Figure 1: Rheological classification of dairy products. Source: Khetra et al., 2018; Tabilo-Munizaga and Barbosa-Cánovas, 2005; Tunick, 2000

tant for the development of new functional dairy products and the optimisation of their quality attributes, as they are the determinants in unit operations, process control, product handling, and equipment design. In addition, rheological properties are essential in the sensory acceptance of the final product and its storage life. Rheological properties vary depending on the type of dairy product, especially moisture levels, fat, and protein content. However, almost all dairy products show intermediate behaviour of solids and liquids, which are considered fluids and semi-solids in rheology, and show viscoelastic behaviour (Khetra et al., 2018). The rheological classification of dairy products is illustrated in Figure 1.

Bovine milk is regarded as a colloidal suspension made up of approximately 87.7% water, 3.4% protein, 3.7% fat, 4.8% lactose, and 0.7% minerals (Mokoonlall et al., 2016). Concerning the rheology of mammalian milk, the type of casein plays an important role. Casein proteins constitute 80% (w/w) of the total milk proteins. The four main types of caseins in milk are αs1-, αs2-, β-, and κ-casein, with proportions of 38%, 10%, 36%, and 13%, respectively (Bayraktar, 2018; Mokoonlall et al., 2016). Caseins bind to divalent cations (primarily Ca^{2+} and Mg^{2+}) to form submicron-scale spherical colloids, called casein micelles, with an average diameter of 150 nm. According to existing models (Dalgleish, 1998), the interior of the casein micelle is relatively hydrophobic and mainly consists of α- and β-caseins, which are calcium-sensitive. When calcium ions are present in the media, they tend to precipitate. The surface of the casein micelles is made up of hydrophilic κ-casein, which is the main factor determining colloidal stability. Changes in the κ-casein layer can destabilise the casein micelles, leading to the formation of a colloid gel. This forms the basis for the practical processes of making yogurt and cheese (Bauland et al., 2022; Bayraktar, 2018). Due to the absence of phosphoseryl residues and the presence of a glycosidic moiety, κ-casein is soluble in calcium. Most of the calcium in micelles is associated with inorganic phosphates and exists in nanoclusters. The number of divalent cations linked to caseins depends on the ionic activity of their free form in the soluble phase. Overall, the mineral balance within the dairy matrix is crucial for the properties and stability of the colloids (Bauland et al., 2022; Bayraktar, 2018). The second major group of proteins, known as whey or serum proteins, includes α-lactalbumin, β-lactoglobulin, bovine serum albumin, and immunoglobulins. These are non-phosphorylated globular proteins that are insensitive to calcium ions. Additionally, they are soluble at pH 4.6 and denature at temperatures above 70^{o}C (Bayraktar, 2018; Graveland-Bikker & Anema, 2003). Whey proteins contribute to dairy rheology mainly by serving as structural agents that improve viscosity, firmness, and elasticity, particularly when heat-denatured, as they unfold and create disulfide bonds within casein micelles and promote hydrophobic interactions within gel networks in products like yogurt, cheese, and dairy desserts. In acidified dairy systems like yogurt, denatured whey increases the storage modulus and reduces syneresis by binding with casein on the surface of casein micelles, transforming the network structure to a firmer, more brittle gel (Graveland-Bikker & Anema, 2003). In cheese making, denatured whey protein concentrates serve as fillers to boost yield and improve the rigidity of the casein matrix (Perreault et al., 2017). According to Patocka et al. (2006), whey protein isolate can initially decrease the viscosity of yogurt drinks and buttermilk, but concentrations above 30% can result in a significant increase in viscosity and thixotropic behaviour.

The rheological properties of milk and dairy products mainly depend on the composition of the milk mixture (proteins, fats, minerals, hydrocolloids, etc.), the reactions and interactions among the ingredients, and processing parameters such as temperature, pH, pressure, and mixing speed. For example, the flow behaviour of concentrated milk changes significantly with water removal through evaporation, which increases solid content and decreases the space between particles like fat globules, casein micelles, whey proteins, and other components (Karlsson et al., 2005). Therefore, it is vital to evaluate rheological changes in dairy products caused by these parameters to maintain quality characteristics, including sensory acceptability and product stability. Various methods are available for rheological characterisation of foods, and the choice depends primarily on the specific product and the practical analysis needs. However, reviews that extensively elaborate on the rheological properties of different dairy products remain limited. This study, therefore, aims to explore in detail key rheological properties of different dairy products and the principles behind them. It also discusses how rheological measurements are performed across various dairy products. Furthermore, the study examines the effect of incorporating various plant-based ingredients in the development of functional dairy products on their deformation and flow behaviour.

2 Literature Search and Selection Strategy

In the present review, a comprehensive literature search was performed covering the period from 1996 to 2025, utilizing three major international databases: ScienceDirect, Scopus, and Google Scholar. The search strategy incorporated specific keyword combinations, namely "milk" OR "dairy" AND "rheology", "rheology" OR "flow behaviour" AND "functional dairy", and "dairy" AND "rheological measurements" OR "instruments". The principal inclusion criteria required that studies be available in full-text format and published in English. The objective of this search was to identify the most pertinent and up-to-date scientific works providing detailed information on the rheological properties of diverse dairy matrices, the analytical instruments employed for rheological characterization, and the effects of processing parameters and compositional factors on product rheology, irrespective of publication type. Furthermore, studies deemed to offer considerable contributions to the scientific understanding of the topic were incorporated for detailed evaluation. Nonetheless, the review revealed a relative paucity of recent publications explicitly addressing rheological concepts and their practical applications within the field of dairy science.

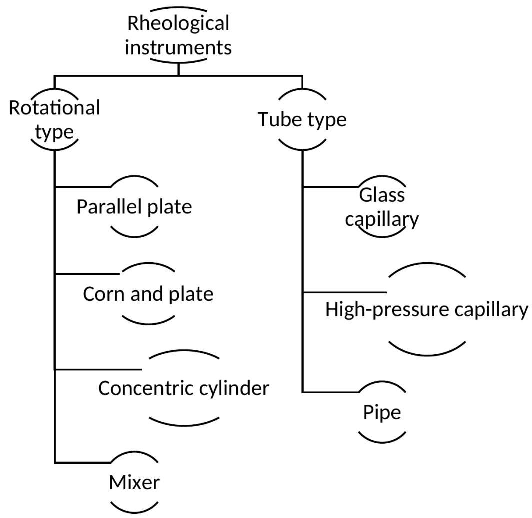

Figure 2: Classification of rheological instruments used for dairy products. Source: Adebowale, n.d.

3 Rheological instruments and their applications in dairy products

In the food industry, common equipment used to study the rheological attributes of fluids and semi-solid foods, such as dairy, can be divided into two groups: rotating type and tube type (Figure 2). Rotation systems are typically used to study the time-dependent behaviour of foods as they allow samples to be subjected to alternative cuts and periods. In addition, rotation systems operate in a stable angular speed or oscillating mode. Tube-type rheometers work according to a pressure difference that creates a flow and allows only one pass through the apparatus over time (Adebowale, n.d.; Martínez-Padilla, 2024; Steffe, 1996). Solid foods are often tested with compression, tension or torque. The cone and plate system is simple but can only be used at a moderate shear rate (small cone angle). High-pressure capillaries are suitable for fluids operated at higher cutting speeds but require significant end pressure correction. For fluids with larger particles, pipe and mixer-type viscometers are ideal. Gravity-operated glass capillaries can only be used with Newtonian fluids (e.g., liquid milk), as the cutting speed shear varies with the discharge (Adebowale, n.d.).

The rheometers used to measure the viscosity of fluids (its internal resistance to flow) are called viscometers. A viscometer measures a fluid's viscosity by enumerating the force requisite to move an object through it or the time it takes to flow through a defined path (Tabilo-Munizaga & Barbosa-Cánovas, 2005). Measurements are carried out under different working conditions: steady flow, laminar flow and uniform temperature. In addition, the equipment specifications should consider air bearing, automatic gap set, gap resolution, temperature control, normal force range, minimum and maximum torque and angular velocity. The most commonly used types in the food industry are capillary viscometers, falling-ball viscometers, and rotational and oscillatory rheometers. In modern dairy processing plants, inline viscometers are used often to integrate real-time data directly into production pipelines without interrupting processes. For example, rheonics sensors operate with vibrational technology which makes them resistant to plant vibrations and easy to clean. In powder milk production, installing inline viscometers in the high-pressure line facilitates monitoring milk concentrate before it enters a spray dryer, ensuring the concentrate achieves optimal viscosity (O'Shea et al., 2019). Recent studies indicate that Coriolis flowmeters are widely used to accurately measure the dynamic viscosity of both Newtonian and non-Newtonian dairy streams in the production line (Bista et al., 2019). These inline viscometers have helped in mitigating process issues like fouling, nozzle or evaporator blockages, and augmenting process control and decreasing production waste in dairy powder manufacturing (Bista et al., 2019; O'Shea et al., 2019). The viscome-

ter data are further used in mathematical models to improve the analysis. The most commonly used models are the power-law, Herschel-Bulkley, and Casson models. However, the rheological behaviour of dispersed systems may vary depending on the measurement technique. For instance, the results of rotation viscometers are affected by the phenomenon of clumping, while the oscillation techniques are less affected by clumping (Biglarian et al., 2022; Martínez-Padilla, 2024; Tabilo-Munizaga & Barbosa-Cánovas, 2005).
Rheological measurements of dairy products can be classified into empirical, imitation and fundamental tests. Empirical tests include evaluating the product using simple instruments such as ball compressors, penetrometers and curved tension meters that provide single-point information. Due to the difficulty of comparing results with arbitrary experimental conditions and rigorous experiments, such instruments are considered low in precision (Martínez-Padilla, 2024; Tunick, 2000). However, the results obtained from empirical instruments provide important information about quality control, sensory properties and may even be official standards or identity indexes. Adams consistometer (yogurt mixture), bloom gelometer (gelatin-based dairy), Bostwick consistometer (baby foods), Hilker-Guthrie plummet (cultured cream), Van Dorran pressure tester (butter) and penetrometer (butter) are the most commonly used empirical rheological instruments in the dairy industry (Adebowale, n.d.).
Imitative tests include texture profile analysis (TPA), which is based on double compression tests that use a universal machine to simulate the chewing of food with large destructive cutters and provides extensive data (e.g., fracturability, hardness, springiness, adhesiveness, and cohesiveness). TPA machines have been designed considering the human mouth from an engineering perspective. The widely used universal testing machines for TPA were developed by improving texturometers in the early 1960s, which compressed bite-sized samples to generate force-time curves (Tunick, 2000). In TPA, two cycles of deformation are applied to the sample of the studied material, with a certain resting time, and a TPA curve is created by plotting force versus time (Paredes et al., 2022). TPA gives a general indication of the sample's texture, useful for comparisons. For example, differences in mozzarella cheese texture can be compared using TPA based on various culture types, homogenisation levels, or levels of proteolysis (Tunick, 2000). More valuable analysis can be achieved by correlating TPA curves with typical sensory evaluation results. However, TPA does not provide true rheological measurements like fundamental instruments do. Additionally, TPA results can vary depending on the testing conditions used by the analysts (Paredes et al., 2022; Tunick, 2000).
Fundamental tests include compression, dynamic, and transient tests and generate mathematical explanations of rheological behaviour. Basic tests are considered more precise because the measurements are independent of the instrument and produce identical results (Steffe, 1996; Tunick, 2000). The most basic form of rheological testing is uniaxial compression, in which a downward stress is applied to the sample, and the resulting deformation is quantified as engineering strain. Dynamic tests are performed under small amplitude oscillatory shear conditions or large amplitude oscillatory shear conditions to generate information such as the elastic modulus (G′), viscous modulus (G″), complex viscosity (η^*), and yield point (σy) dynamically. Transient tests include stress relaxation tests and creep recovery tests. In the stress relaxation test, the relaxation modulus (stress-to-strain ratio) is measured after applying a sudden and constant strain of approximately 0.1%. In the creep recovery test, a rapid and persistent stress is applied (creep) and removed (relaxation), and the subsequent strain is measured over time. For example, in a creep recovery test, a hard cheese strains less than a soft cheese and recovers well due to its higher rigidity and elasticity (Tunick, 2000). Destructive methods (large deformations), such as constant shear rate and strain sweep tests, and non-destructive methods (small deformations), such as oscillatory measurements, are used to characterize the rheological properties of acid gels in the industry (Bayraktar, 2018). Small amplitude oscillatory shear (SAOS), large amplitude oscillatory shear (LAOS), and torsion analysis are currently the most applied representative fundamental tests, especially in cheese manufacturing plants (Park, 2007; Tunick, 2000).

In addition, the stress-strain test that helps to study the behaviour of food gels can be divided into two groups: small-strain tests and large-strain tests. Small-strain tests use only a minor deformation to disrupt the sample and are mainly used in fundamental tests. Oscillatory test, stress relaxation test, and yield stress determination are examples of small-strain tests. Large-strain tests cause deformations up to a point of permanent structural damage of the sample and generate information that is correlated with sensory evaluation. The puncture test, the uniaxial compression test, the torsion analysis, and the folding test are examples of large-strain tests (Tabilo-Munizaga & Barbosa-Cánovas, 2005).

3.1 Small Amplitude Oscillatory Shear (SAOS)

SAOS is performed within the linear viscoelastic range to maintain the specimen structure undamaged. The sample is positioned between two parallel plates and exposed to sinusoidal oscillation, with G$'$, G$''$, and η^* values measured dynamically without being influenced by the stress or strain magnitude. SAOS can detect changes in the microstructure of foods and the involvement of biomaterials during processing without compromising the texture of the sample. It can also identify potential structural or phase changes, such as protein denaturation, occurring within the food matrix, revealing the kinetics of the process. In SAOS experiments, rotational rheometers employ various geometries, such as parallel plate, cone plate, and concentric cylinder, depending on the sample's nature (Ahmed, 2018). However, when the food is not homogeneous or when wall slip occurs, vibration measurements within the linear range may introduce several errors. Large velocity gradients typically arise in a thin region adjacent to the wall or in time-dependent material behaviour. This can be mitigated by pre-shearing the sample with steady rotation before conducting SAOS or by employing serrated or rough surfaces to address wall slip in products like cheddar cheese (Steffe, 1996).

3.2 Large Amplitude Oscillatory Shear (LAOS)

In non-linear environments, food products exhibit stress responses that deviate from the sinusoidal waveform, and the G$'$ and the G$''$ become functions of strain amplitude (γ). In experiments, a non-linear range is achieved by applying excessive strains of 1%. Non-linear range experiments are practically required to study the behaviour of foods when exposed to greater deformation, for example, swallowing or mastication (Steffe, 1996). LAOS rheological measurements of foods are more complex than SAOS. The data obtained from LAOS measurements are analysed by Fourier transform rheology (FTR), the Chebyshev polynomial expansion, and the Lissajous diagrams, which are relatively difficult to interpret. Amongst these techniques, FTR is the most powerful tool to analyse even weak non-linearity in the stress response. Moreover, in FTR, higher harmonic intensities and phases in the power spectrum can deliver crucial information about the analysed samples. Nevertheless, the interpretation may be complicated due to several higher harmonics (Ahmed, 2018).

3.3 Torsion Analysis

In the torsion analysis, the shear stress is applied to the sample in a rotary manner. Torsion analysis is a convenient method that does not change the geometry of the sample. Shear stress and strain are considered as real values up to a twist angle of about 45^o and friction between samples and fixtures is neglected. However, the torsion test requires fixing the sample to the machine. The sample preparation is usually more complex than uniaxial compression (Tabilo-Munizaga & Barbosa-Cánovas, 2005).

3.4 Tribology

Tribology involves the study of friction between two interfaces that undergo wear, tear, and lubrication, for instance, the oral processing of foods. Rheology and tribology have been combined to investigate the physical origins of mouthfeel and the dynamics of mouth lubrication, including the role of saliva in soft-food systems such as yogurt and cream (Ahmed, 2018; Zhang et al., 2025). For the measurements, a typical tribo-rheometric accessory is attached to a standard rheometer to take the coefficient of friction values between two solid surfaces under desiccated or lubricated conditions. The basic equation for tribology is given in Eq.1 (Ahmed, 2018).

$$F_R = \mu \times F_L \qquad (1)$$

Here, FR is the frictional force, μ is the friction coefficient, and FL is the surface load. The most important measurement is the friction coefficient, which quantitatively describes the nature of the surface interactions.

Tribology can be used successfully to detect melamine in adulterated milk. For example, when a pair of frictional components, consisting of nitrile butadiene rubber balls and silicone rubber substrates, is used, the μ value for the adulterated milk is higher than that of the control sample (Liu et al., 2018). An overview of rheological measurements that are important in food science and the food industry is presented in Table 1.

3.5 Rheology of dairy products

Milk is a complex food emulsion where fat droplets are dispersed in an aqueous continuous phase (oil-in-water emulsion) (Lal et al., 2006). In food rheology, milk is considered a Newtonian fluid with a relative viscosity of 1.5-2.0 cP at 20°C. Buffalo, goat, and sheep milk have slightly higher viscosity values (2 to 2.5 cP); however, these values can vary depending on factors such as animal breed, milk age, and processing parameters-temperature, pressure, and pH (Khetra et al., 2018; Park, 2007). For instance, Janahar et al. (2021) indicated that high-pressure processing at 400 MPa, ∼40°C for 3 min can cause a significant increase in the viscosity of milk (from 2.68 cP to 3.08 cP) attributed to the disintegration of casein micelles into smaller particles, leading to increased hydration of casein micelles, which in turn results in increased milk viscosity. Additionally, high-pressure processing reduced creaming during refrigerated storage by reducing fat particle size, increasing fat velocity, and stabilizing the milk. Authors further demonstrated that thermal treatment at 72°C for 15 s produced samples with a viscosity of 2.75 cP, which was not significantly different from that of the untreated milk. The rheological characteristics of acid-gel-based dairy products, such as cheese, are highly influenced by processing parameters, including homogenisation pressure and fermentation temperature. Brighenti et al. (2018) showed that the firmness, cohesion, solubility, stickiness, and spreadability of cream cheese were negatively affected by a higher fermentation temperature (26°C). More particularly, at higher fermentation temperatures, acid gels exhibited lower apparent viscosity after heating and shearing due to structural weakness, making them more prone to breakdown. Furthermore, acid gels subjected to high homogenisation pressure (25 MPa) and high fermentation temperature formed weaker gels than those treated with high homogenisation pressure and low fermentation temperature, due to insufficient bulk-phase casein for forming cross-linkages. In another study, Hussain et al. (2025) reported that coagulation temperature is a key factor in regulating the rheological properties and quality of paneer. They observed extensive interactions between β-lactoglobulin and κ-casein at higher coagulation temperatures (90°C). Both G′ and G″ values of paneer increased, leading to the formation of dense protein networks with a less porous structure.

Variations in rheological properties depending on the type of animal milk can be observed in other dairy products. For example, goat milk has a lower casein/total nitrogen ratio (75%) than cow's milk (78%), affecting the quality attributes of acidified milk gels such as yogurt and cheese (Park, 2007). Acidified milk gels are solid-in-liquid colloids where the solid phase forms a network-like arrangement that halts the liquid phase. These diluted systems exhibit non-steady-state flow. Gelation occurs through chemical cross-linking via covalent reactions or physical cross-linking through interactions mainly between twisted biopolymers (e.g., carrageenans, pectins, and gelatin) and thermally denatured globular milk proteins (Costa et al., 2015; Tabilo-Munizaga & Barbosa-Cánovas, 2005). During lactic acid fermentation, milk proteins aggregate at the isoelectric point (pH 4.6) due to disruption and loss of the integrity of the casein micelles, forming a continuous particle gel containing strands within the range of 100 to 1000 μm and encompassing the serum. This viscoelastic microgel suspension exhibits a partially thixotropic characteristic depending on the mechanical stress applied (Mokoonlall et al., 2016).

Terzioğlu et al. (2023) examined how different types of animal milk-cow, buffalo, goat, camel, and sheep-affect the rheological properties of yogurt. Sheep yogurt showed the highest levels of firmness, consistency, and cohesiveness, while goat yogurt had the lowest. Additionally, sheep and buffalo yogurts recorded the highest yield stress values (6.0 and 5.8), whereas goat yogurt had the lowest (0.8). The highest consistency index was found in sheep yogurt (6.3), with the lowest in goat yogurt (4.2). Goat milk yogurt is more susceptible to structural rearrangements and fractures due to factors such as lower αS1-casein levels, higher solubility of β-casein, lower sedimentation rate of casein micelles, and increased calcium and phosphorus content compared to other milk types (Miocinovic et al., 2016; Terzioğlu et al., 2023). Recent studies have employed various methods-including the addition of skim milk powder, whey protein isolate, and milk protein isolate (MPI)-to improve the body and texture of goat milk yogurt (Costa et al., 2015). Miocinovic et al. (2016) found that fortifying goat milk with MPI (80% protein) could enhance the G′, G″, and δ values by restoring the strength and connectivity of bonds in the acid gel network with increased protein levels. Lal et al. (2006) reported that adding inulin or maltodextrin can improve yield stress, firmness, cohesiveness, and apparent viscosity of low-fat goat milk yogurt. Furthermore, including these at 5% levels resulted in pseudoplastic behaviour, while whey protein isolate caused dilatant behaviour (Lal et al., 2006). According to Jørgensen et al. (2015), adding denatured whey protein concentrate from native whey protein concentrate at low (25%) or medium (35%) levels can produce satisfactory rheological properties-such as lower firmness, lower G′, a less coarse/granular structure, and a smoother texture. Compared to cow's milk, goat milk has limited cheesemaking capabilities because of its lower casein-to-total nitrogen ratio. Variations in αS1-casein levels, heavily influenced by genetic polymorphism, result in reduced cheese yields and a more fragile rennet curd (Park, 2007). This weak coagulation results in more cheese particles being lost in the milk, decreased cheese yield, and compromised texture. The renneting process in goat milk is characterised by a shorter coagulation time and a faster hardening rate. Sheep milk produces significantly higher cheese yields per unit because of its higher fat, protein, and total solids content compared to cow or goat milk. Its casein structure, rich in calcium, combined with a higher β/αS-casein ratio, makes sheep milk more responsive to rennet, leading to faster coagulation. However, because of the greater casein and colloidal calcium content, sheep milk exhibits a lower syneresis rate (Haenlein & Wendorff, 2006; Park, 2007).

Additionally, the rheology of dairy products is mainly influenced by their complex composition, including water, fat, proteins, and minerals. For instance, proteins such as casein micelles and minerals like calcium significantly impact the texture and thickening behaviour of gel-like dairy products. Recent literature emphasizes a critical link between particle size distribution and the fundamental viscoelastic behaviour of diverse food systems, including dairy. Parallel to the observed decrease in Herschel–Bulkley model parameters-both yield stress and consistency coefficient- with decreasing particle size in plant-based suspensions (Pekmez et al., 2025), modern dairy research exhibits a similar sensitivity during mechanical breakdown and gelation. For instance, Hu et al. (2026) demonstrated that the oral perception of dairy emulsions and soft gels (e.g., yogurt) is heavily driven by the structural viscosity, showing that large particle sizes and the excessive aggregation of particles can exceed a critical mechanical threshold, which triggers the consumer perception of "graininess". Another recent study on cheese rheology by Pace et al. (2024) addressed the importance of manipulating network particles to optimise large-strain elastic behaviour and demonstrated numerical markers for firmness, stickiness, and consumer bite-down perception. Collectively, these findings highlight that structural modifications, such as particle size optimisation, allow manufacturers to better control mouthfeel and industrial handling through the precise tuning of rheological parameters. Processing parameters also play a crucial role in determining dairy product rheology. For example, in yogurt manufacturing, pasteurizing milk at 95°C for 5 minutes or at 85°C for 30 minutes is necessary to denature β-lactoglobulin and α-lactalbumin effectively (Zhang et al., 2025). The dairy industry employs various methods to achieve the desired consistency and flow characteristics in different products. For example, to produce viscous yogurt with good water retention, milk dry matter content is increased by adding milk powder and concentrating milk through evaporation or membrane filtration (Jørgensen et al., 2015). As reported in the existing literature, key rheological changes in various dairy products-depending on processing conditions and ingredients-are summarized in Table 2.

3.6 Rheology of Functional Dairy Products Enriched with Plant-based Ingredients

Foods that provide health benefits or therapeutic effects through regular consumption are called functional foods. In recent decades, consumer demand for dairy products comprising functional components, such as probiotics and plant-based components, has increased. The rheology of dairy with functional components is complex, as the combination of protein, fat, and added ingredients interacts with each other, creating modified viscoelastic properties, water-holding capacity, and texture that can be controlled to meet particular needs of the product (Lamsar & Abhilasha, 2023). For example, literature indicates that incorporating functional ingredients such as flaxseed, wheat bran, jujube mucilage, or date fibre into yogurt enhances the hardness and viscosity while reducing syneresis, primarily due to increased protein and solid content, resulting in improved moisture absorption and stronger protein network formation (Basiri et al., 2022). However, certain challenges must be focused on when incorporating functional ingredients into dairy products (Chandimala et al., 2024; Lamsar & Abhilasha, 2023). Alterations in the product's rheological attributes are one of the main challenges in this regard. This section focuses on the effects of incorporating various plant-based ingredients into functional dairy products from a rheological perspective (Table 3).

Phenolic compounds are the most commonly used plant-based constituents to improve the functional aspects of dairy products. However, the integration of phenolic compounds, which have antioxidant properties, can cause several challenges. For instance, phenolic compounds form linkages with milk proteins, affecting the nutritional and sensory properties of dairy products. Protein-phenolic interactions are based on multiple weak interactions such as hydrophobic, van der Waals, hydrogen bonds, and ionic interactions, and are surface phenomena. In acidified dairy gels such as yogurt, protein-phenolic affinity plays an important role in controlling syneresis, which is a key factor determining yogurt quality (Chandimala et al., 2024; Dönmez et al., 2017). Chandimala and Ajtony (2025) reported that protein-phenolic affinity can result in the formation of complexes that are not fully dissolved within the product, causing sedimentation, or enhanced viscosity and thickness in the product, thus modifying the overall sensory experience. In a study, Dönmez et al. (2017) reported that syneresis in yogurt can be significantly decreased by incorporating green coffee powder and green tea powder at 2% and 0.02% rates, respectively. Similarly, Jalilzadeh-Afshari and Fadaei (2021) revealed an increase in dry matter content and viscosity in milk enriched with bitter orange peel extract, which affected the product's general acceptability. Conversely, Acharjee et al. (2021) reported a significant reduction in the firmness of the yogurt fortified with orange pomace powder. Such protein-phenolic interactions form aggregates that can be used to improve the gel properties of processed cheese. In a study, Deng et al. (2023) supplemented processed cream cheese with an apple extract rich in chlorogenic acid and proanthocyanidins. Fortifying processed cream cheese with apple polyphenols (1.6%) demonstrated a shear-thinning behaviour and the suitability of the gelation properties of the functional cheese for 3D food printing. Han et al. (2011) also reported that the incorporation of polyphenol-rich ingredients (grape extract, green tea extract, and dehydrated cranberry powder) affected all gel-forming parameters of cheese curd due to the effect of polyphenols on the pH of milk.

Developing plant-dairy protein blends with improved nutritional and therapeutic potential is another trend widely seen in the food industry. Blends that combine animal-based dairy proteins (whey and casein) with protein-rich plant milk, such as soy, rice, and pea, are designed primarily to offer a complete amino acid profile (Dijk et al., 2023; Mohammadi et al., 2022) while improving the flavour and texture characteristics often found in pure-plant-based milk or powders. Processing conditions and formulations can influence the manner these different protein types interact at the molecular level, thereby altering the structure, functionality, and nutritional value of dairy-plant protein blends (Berrazaga et al., 2019). For example, incorporating rice bran protein (RBP), which elucidates creaminess, was found to cause a dose-dependent increase in the apparent viscosity, thixotropic index, G′, and G″ in dairy desserts, proving that RBP can be successfully used to improve the creaminess of low-fat dairy desserts (Mohammadi et al., 2022). Additionally, RBP enrichment increased the hardness and gumminess of dairy desserts while decreasing the syneresis attributed to the formation of mesh-like structures that can entrap more water. In mixed systems, whey proteins can bridge with casein micelles, while plant proteins may act as fillers or form independent networks. A study by Rafe et al. (2016) indicated that incorporating whey protein concentrate into RBP can improve the gel strength and elasticity of the binary system by reducing the gelation temperature and enhancing the storage modulus. However, the addition of RBP fibril to whey protein concentrate induced micro-phase separation, resulting in a higher tendency towards syneresis, implying that such binary gels have lower water-holding capacity and may limit the suitability of such binary gels for dairy and dessert formulations. Moreover, blending can be challenging for the emulsion stability of such binary systems; for instance, sodium caseinate is known to form less physically stable emulsions with soy and pea proteins compared to dairy-only systems (Brühan et al., 2024), which needs to be addressed by adjusting processing parameters. Heating proteins together often yields better mechanical properties than heating them separately and then mixing. However, some blends (e.g., pea and fava bean with dairy) can show anti-synergistic behaviour, resulting in weaker gels. For instance, extensive heating (e.g., UHT) often leads to uncontrolled aggregation, which can reduce solubility and gelling capacity (Berrazaga et al., 2019). High-pressure homogenisation is used in certain mixed systems to enhance the solubility of plant proteins in the dairy matrix and to reduce grittiness by producing smaller particles, thereby improving emulsion stability. For example, a recent study by Janahar et al. (2023) examined the rheological characteristics of milk and pea protein suspensions at various protein concentrations after treatment with heat, high pressure, and ultra shear. Authors indicated that the effect of ultra shear technology (UST) on the particle size and rheological behaviour of dairy-pea protein dispersions depended on the blend's fat level, and that UST treatment significantly improved the stability of dairy-pea protein blends even after heat treatment and freeze-thawing. A similar study by Janahar et al. (2022) revealed that the interaction of pressure, shear, and temperature during UST is more effective than pressure-only or thermal-only treatments in developing more stable milk-pea emulsions with varying consistencies, depending on the protein concentration, by altering particle size and thereby changing particle-particle interactions. For example, at a high milk: pea protein ratio (e.g, 1:3), UST could produce more stable gel-based pea-dairy blends with higher viscosity. Acidic conditions or low pH persisting in fermented dairy products is known to promote protein denaturation and improve the miscibility of plant proteins with dairy matrix components. Nevertheless, certain plant protein-dairy blends (e.g., chickpea-whey mix) demonstrate higher thermal stability at neutral pH conditions, whereas fragile, coarse gel structures with increased sedimentation are formed under low pH conditions (Duggan et al., 2024).

A recent study by Brühan et al. (2024) indicated that pH is the main factor affecting the protein aggregate size in soy-whey protein hybrid ricotta gel structures, thereby influencing gel strength. They found that the most stable structures are formed at pH 5.0. Authors also revealed that pea proteins generally behave similarly to soy proteins, as they have similar amino acid compositions and structures. Furthermore, the authors reported poor gel-forming properties of lupin and potato with whey proteins owing to their dense molecular structures and large insoluble aggregates, respectively.

Hybrid-fermented dairy drinks are another innovative dairy formulation incorporating plant-based ingredients that has gained increasing attention in recent studies. For example, Ziarno et al. (2025) examined the structural performance of a fermented dairy-oat (1:1) hybrid drink. Their findings revealed that the structural stability of dairy matrices combined with oat milk was considerably improved while syneresis was reduced, depending on the performance of the incorporated yogurt culture. However, developing these beverages presents unique structural challenges, particularly when non-traditional bases such as camel milk are used, which cannot inherently form strong, viscous gel networks during fermentation. To address this limitation, recent research (Abdel-Rauf et al., 2025) investigated the effect of partially replacing camel milk with chickpea milk at different concentrations to produce bio-flavoured fermented camel milk. This hybrid formulation introduces a rheologically complex interaction between camel milk caseins and globulin-rich chickpea proteins that substantially alters the product's physicochemical and mechanical profile. The addition of chickpea milk reinforces the weak casein network of camel milk, which typically has low apparent viscosity and high whey separation, thereby improving water-holding capacity and enhancing the textural properties of the fluid matrix.

Plant-based emulsifiers and stabilisers, such as locust bean gum, carrageenan, pectin, starch, and xanthan gum, are commonly used in dairy dessert manufacturing. These hydrocolloids considerably modify the rheology of dairy products by increasing viscosity, enhancing gel strength, and stabilizing complex product structures. These substances interact with water, milk proteins, and fat droplets, altering the physical state of the dairy matrix (Biglarian et al., 2022). However, their effect on dairy product attributes may vary. For example, certain hydrocolloids (e.g., pectin, κ-carrageenan) bind to dairy proteins, interfering with protein-protein linkages, thereby producing softer gels, whereas some hydrocolloids (e.g., xanthan gum, locust bean gum) do not directly bind with dairy matrix proteins, generating synergistic networks that significantly increase the G' and hardness of products like cream cheese (Brighenti et al., 2020). Furthermore, Brighenti et al. (2020) found that cream cheese produced with a combination of xanthan gum, locust bean gum, and guar gum formed a strong, thermally reversible gel through synergistic interactions among stabilisers, whereas cheese containing only xanthan gum formed a weaker gel unaffected by temperature variations. Another recent study (Moghiseh et al., 2021) examined how inulin/kefiran mixtures affect the properties of low-fat mozzarella cheese and revealed that inulin incorporation resulted in a more rigid, cross-linked protein matrix with reduced meltability. This structural modification also increased cheese hardness and cohesiveness while exhibiting shear-thinning, elastic-dominant ($G' > G''$) rheological behaviour. Several studies have indicated that incorporating stabilisers, such as basil seed gum and carrageenan, increases the viscosity of dairy cream, attributed to the ability of hydrocolloid molecules to bind water, thereby creating flow resistance. Moreover, the addition of higher levels of basil seed gum can increase the emulsion's stiffness more effectively than high fat content and further enhance the elasticity of dairy cream (Biglarian et al., 2022).

Levan is another natural plant-based stabilizer (a fructan) used in dairy products. In a study, Li et al. (2025) reported that incorporating levan at 0.3% resulted in optimal stability, improving the stability of both set and stirred yogurt during refrigerated storage for 21 days, and yogurts exhibiting shear-thinning behaviour. Moreover, levan incorporation improved the firmness and gel strength of stirred yogurt while enhancing the stability of the fat-protein network.

However, the stage of incorporating plant-based ingredients into the dairy product must be carefully considered, as it may significantly affect the rheological properties of the final product. For instance, thermal processing of milk is a critical step in the production of dairy products that can affect the interactions of plant-based ingredients with other constituents present in the milk, causing rheological changes in the product. Furthermore, in products such as yogurt and kefir, there may be possible interactions between microbial cultures, polyphenols, and dairy matrix ingredients during microbial fermentation, affecting the rheological attributes of the product. It is therefore crucial to investigate the potential rheological changes in functional dairy products that may occur in the phase of supplementing the plant-based ingredients (before or after thermalisation, before or after fermentation).

4 Conclusion

Overall, this article presented the rheological properties of various dairy products and explained the scientific principles underlying their textural and rheological attributes. Further, this study systematically summarised the rheological tests and measurements (empirical, imitative, and fundamental) conducted at the research scale and in the dairy product processing industry. The findings support the fact that product composition and product processing parameters are the most important factors in dairy product rheology. Especially when plant-based ingredients are integrated into the dairy matrix to develop functional dairy products, the supplementation stage can significantly affect the rheological behaviour of the final product, thereby influencing consumer acceptance and shelf life. Furthermore, interactions between dairy matrix components and plant ingredients can lead to complex particle-particle interactions, resulting in rheological changes. Certain research gaps in the rheology of plant-dairy blends include understanding the interfacial viscoelasticity arising from multifaceted interactions between dairy matrix components and plant ingredients, enhancing the hybrid emulsion's stability, and mimicking conventional dairy textures. Therefore, future research should particularly focus on the molecular mechanisms of dairy and plant protein/fat interactions during pre-aggregation and gelation, and on standardising rheological measurements to enable targeted optimisation of functional dairy applications. Advancements should aim for parity with conventional dairy textures in terms of structural stability, achieved through advanced structural modelling, high-fidelity sensory mimicry, and application-specific optimisations.

Table 1: Overview of important rheological measurements

Type of rheological test	**Rheological measurement**	**Definition**	**Remarks**	**Ref.**
Creep and recovery test	Initial compliance (J_0)	Measures the immediate elastic deformation, which occurs at the moment when the stress is applied (pure elastic behaviour)	Materials flexing instantly, which resulting in a softer texture, generate higher values	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
	Retarded compliance (J_1)	Measures the delayed, time-dependent elastic deformation that develops over time (slow elastic structural change)	Highly flexible matrix with lower hardness generates higher values	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
	Retardation period (λ)	The time needed for the material to reach 63.2% of its total retarded deformation	Longer periods represent a longer stress-relaxation time, making a cream/paste easier to spread	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
	Residual viscosity ($\eta 0$)	The steady, irreversible flow resistance at the end of the loading phase	Higher values denote enhanced particle interactions and better structural consistency	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
	Elastic recovery (J_e)	Measure of the portion of the deformation that instantly springs back when the stress is removed	High recovery indicates a bouncy, gel-like texture; low recovery indicates a plastic, dough-like texture	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
	Permanent deformation (J_v)	The permanent, unrecoverable strain remaining at the end of the test	Higher values represent a highly fluid or spreadable paste that does not push back after being shaped	(Pekmez et al., 2025; Steffe, 1996; Tunick, 2000)
Dynamic rheological tests	Storage or elastic modulus (G′)	Measure of the deformation energy stored in the sample during the shear process (represents the elastic behaviour of a sample)	If G′¿G″, the material will behave more like a solid (the deformations will be essentially elastic or recoverable). If G″¿G′, the energy used to deform the material is dissipated viscously and the material's behaviour is liquid-like.	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)
	Loss or viscous modulus (G″)	Measure of the deformation energy used up in the sample during the shear and lost to the sample afterwards (represents the viscous behaviour of a sample)	If G′¿G″, the material will behave more like a solid (the deformations will be essentially elastic or recoverable). If G″¿G′, the energy used to deform the material is dissipated viscously and the material's behaviour is liquid-like.	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)
	Loss factor (tan δ)	tan δ = (G″/G), the ratio of the viscous to the elastic portion of the material's deformation behaviour	A phase angle $\delta = 0°$ or tan δ = 0 corresponds to an elastic response, and $\delta = 90°$ or tan δ = ∞ is a viscous response. If the phase angle is within the limits of 0° ¡ δ ¡ 90°, the material is viscoelastic	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)

Overview of important rheological measurements (continued)

Type of rheological test	**Rheological measurement**	**Definition**	**Remarks**	**Ref.**
	Complex modulus (G*)		It provides information about all viscoelastic characteristics	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)
	Complex viscosity (η *)	η * = (G*/ω) where ω is the frequency of oscillation (rad s−1)	It provides information about all viscoelastic flows	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)
	Yield stress (σy)	The stress level required to initiate the flow. It is a measure of the difficulty in breaking strands, representing the fracture properties of the gel that depend on the number of bonds per cross section of a strand and the strength of each bond	A good measurement of the sensory initial perception of a gel-like product	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tunick, 2000)
Texture Profile Analysis (TPA)	Fracturability	The force with which food fractures	Force at the first significant break in the TPA curve	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)
	Hardness	Force needed to attain a given deformation	Maximum force during the first compression cycle	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)
	Adhesiveness	Work needed to overcome the attraction between a food and another surface	The force area of the negative peak following the first peak	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)

Overview of important rheological measurements (continued)

Type of rheological test	**Rheological measurement**	**Definition**	**Remarks**	**Ref.**
	Cohesiveness	Strength of food's internal bonds	Ratio of the positive force area of the second peak to that of the first peak	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)
	Springiness	The rate at which deformed food returns to its original condition after the removal of force	Height specimen recovers between the end of the first compression cycle and the start of the second	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)
	Gumminess	The force needed to disintegrate a semi-solid food to a state ready for swallowing	Product of hardness and cohesiveness	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)
	Chewiness	Work needed to masticate a solid food to a state ready for swallowing	Product of hardness, cohesiveness, and springiness	(Adebowale, n.d.; Gibson & Newsham, 2018; Steffe, 1996; Tabilo-Munizaga & Barbosa-Cánovas, 2005; Tunick, 2000)

Table 2: Effects of processing conditions and milk constituents on rheology of dairy products

Type of dairy Type of dairy	Rheological effects of processing parameters and/or constituents Fact	Rheological effects of processing parameters and/or constituents Observation	Ref.
Milk	The concentration of casein micelles, stabilized by steric and electrostatic interactions, directly influences the milk viscosity. Heat treatments and homogenization can cause increased milk viscosity due to the denaturation of β-lactoglobulin and enhanced clumping of fat globules with proteins.	An increase in milk pH leads to enhanced viscosity due to the swelling of casein micelles. Conversely, a slight decrease in pH results in a slight decrease in viscosity, while a greater decline in pH can cause a substantial increase in milk viscosity due to casein aggregation In skim milk, viscosity decreases during heat treatments above pasteurization up to 130°C, followed by cooling to ambient temperature. Nevertheless, this model reverses at temperatures above 130°C due to the destabilization of milk colloids.	(Karlsson et al., 2005; Park, 2007)
	The concentration of casein micelles, stabilized by steric and electrostatic interactions, directly influences the milk viscosity. Heat treatments and homogenization can cause increased milk viscosity due to the denaturation of β-lactoglobulin and enhanced clumping of fat globules with proteins.	An increase in milk pH leads to enhanced viscosity due to the swelling of casein micelles. Conversely, a slight decrease in pH results in a slight decrease in viscosity, while a greater decline in pH can cause a substantial increase in milk viscosity due to casein aggregation In skim milk, viscosity decreases during heat treatments above pasteurization up to 130°C, followed by cooling to ambient temperature. Nevertheless, this model reverses at temperatures above 130°C due to the destabilization of milk colloids.	(Khetra et al., 2018)
Concentrated milk	In the manufacture of concentrated milk, the removal of water increases the concentration of total solids and reduces the distance between matrix components (e.g., casein micelles, whey protein molecules), leading to increased milk viscosity and non-Newtonian flow behaviour. However, the overall behaviour is affected by processing parameters and composition.	Evaporating milk at temperatures above 40°C to achieve 30% solid content results in Newtonian flow behaviour, whereas ultrafiltration leads to pseudoplastic behaviour. A drop in pH from 6.5 to 5.8 in skim milk causes a dramatic decline in G' of concentrated milk due to reduced interactions between casein micelles. Incorporating NaCl or KCl salts into ultra-filtered skim milk concentrate can increase the apparent viscosity at various shear stress levels. Under low shear stress, the flow behaviour is Newtonian, while at intermediate shear stress, it is shear-thinning.	(Karlsson et al., 2005; Khetra et al., 2018)

Effects of processing conditions and milk constituents on rheology of dairy products (continued)

Type of dairy **Type of dairy**	**Rheological effects of processing parameters and/or constituents Fact**	**Rheological effects of processing parameters and/or constituents Observation**	**Ref.**
Milk protein concentrates	Fresh and reconstituted milk protein concentrates exhibit rheological differences under standard and processing conditions.	Reconstituted milk protein concentrates made from commercial milk protein powders unveil higher viscosities than fresh ones, and intense shearing causes a loss of structure and a significant viscosity decrease, whereas fresh milk protein concentrates exhibit an inverse effect. Additionally, reconstituted milk protein concentrates show gel–like properties above a certain protein content (13% w/w), attributed to protein–protein interactions in the milk protein powder, which are induced by manufacturing and/or storing conditions.	(Kieferle et al., 2019)
Yogurt	Increasing the total solids and proteins in the yogurt matrix can increase the water-binding capacity of the protein networks over time, increasing the firmness of the yogurt. These changes in the microstructure of casein gels are caused by alterations in the network's cross-link density, heterogeneity, particle size, and pore size. Processing conditions influence the texture and rheological behaviour (viscoelasticity, time dependence, yield stress and shear-thinning behaviour) of yogurt.	Adding hydrocolloids (e.g., gelatin, inulin, carrageenan, and xanthan gum), or milk powder into yogurt improves the viscosity, consistency, mouthfeel, body and overall texture of yogurt. However, the exact effect of viscosity is influenced by the molecular weight, conformation, and loading of these ingredients in the yogurt matrix. Applying increased shear intensity during rebodying reduces elasticity, viscosity, and firmness. The G' and G'' values of set and stirred yogurt rise with incubation temperature. Conversely, the G' and G'' values of yogurt decrease with the use of bacterial strains producing exopolysaccharides.	(Basiri et al., 2022; Gilbert & Turgeon, 2021; Lal et al., 2006; Mokoonlall et al., 2016)
Cheese	Enzymatic gel structure can be reorganized over time at different stages of maturation due to the non-equilibrium resulting from the increasing number of bonds between colloids in the casein network, causing an increase in the shear modulus of the gel. Cheese fracturability varies with processing temperatures, tension or shear, deformation rate and the repeatability of specimen geometry.	Increase in the proportion of casein-bound cations raises G' and G'' of cheese whereas an increase in cations precipitated as micellar calcium phosphate leads to a reduction in tanδ, regardless of gel firmness. Milk homogenization increases the levels of casein submicelles associated with smaller lipid droplets on the surface. In addition, microfluidization treatment, which reduces the size of fat globules, alters the fat-protein interactions, causing changes in melting and related rheological attributes of Mozzarella cheese.	(Bauland et al., 2022; Hekken et al., 2007; Park, 2007; Tunick, 2000)

Effects of processing conditions and milk constituents on rheology of dairy products (continued)

Type of dairy **Type of dairy**	**Rheological effects of processing parameters and/or constituents Fact**	**Rheological effects of processing parameters and/or constituents Observation**	**Ref.**
Butter	The linear viscoelastic region (LVR) of butter is limited to strains of less than 0.1%. For larger strains, the rheological parameters within the LVR are strongly dependent on temperature.	Butter shows desirable spreadability in a limited temperature range (10-20°C) due to the changes in the solid fat content. At lower temperatures, triacylglycerol crystallization is improved, creating a solid fat network. At higher temperatures the creep analysis of butter results in retarded elasticity and less viscous flow. Butter should contain 20-40% solid yield stress values below 125 kPa to improve its spreadability. An increase in oscillation frequency causes a decrease in η^* and G'' and an increase in G' of butter.	(Ahmed, 2018; Gibson & Newsham, 2018; Steffe, 1996)
Creams	Whippability of creams varies with factors such as composition, cream tempering, fat globular size and homogenisation	The stability of whipped cream can be maintained by lowering the temperature, adding more protein and vegetable gums. Added polysaccharides and proteins form additional cross-linked networks, improving the emulsifying properties of dairy creams. Low and high-fat dairy cream shows pseudoplastic thixotropic behaviour, and the pseudoplasticity can be improved by adding stabilizers (e.g., whey protein, basil seed gum, and κ-carrageenan). High-fat dairy cream has smaller globular aggregates than low-fat dairy cream, resulting in more water retention capacity in high-fat samples.	(Biglarian et al., 2022; Gibson & Newsham, 2018)
Foams	Casein proteins play a major role during foaming while whey proteins significantly contribute to the stabilization of foam by forming a more rigid film at the air-water interface of the foam. Fat content in milk also affects the foam stability. However, the flow behaviour of milk forms is strongly dependent on their microstructure characteristics (e.g., bubble size distribution and fraction of gas volume), which are frequently subject to heterogeneity within the foam.	Skim milk, which has reduced fat with or without fortified proteins, makes foams more easily. Full-fat milk foams are richer in texture and taste, although increasing the fat levels up to 5% can reduce the stability of milk foams. Conversely, the stability starts to increase again after 10% fat, resulting in more stable cream-type foams. During the whipping process, milk proteins are denatured and coalesce with cholesterol and phospholipids, surrounding the solid fat globules in chilled cream, resulting in a floating behaviour of fat globules separate from one another and the liquid water in cream. Milk foams generated through steam injection exhibit viscoelastic behaviour below the yield point and thereafter, liquid-like behaviour during the transient destabilization process.	(Chen et al., 2025; Gibson & Newsham, 2018; Jimenez-Junca et al., 2011; Völp et al., 2021)

Effects of processing conditions and milk constituents on rheology of dairy products (continued)

Type of dairy Type of dairy	Rheological effects of processing parameters and/or constituents Fact	Rheological effects of processing parameters and/or constituents Observation	Ref.
Low-fat dairy desserts	Reduction of fat concentrations in dairy desserts causes a significant impact on the rheological properties of the product, influencing sensory attributes and technological performance. Adding hydrocolloids that interact with casein micelles, forming double helices and network structures, can improve the texture of low-fat dairy desserts.	Adding λ-carrageenan at low concentrations ¡0.01% provides higher tan δ values and lower G' values in skim milk desserts compared to whole milk desserts. Nevertheless, increasing the λ-carrageenan concentration (0.1% - 0.3%) in skim milk dessert resulted in higher G' values. Adding starch and κ-carrageenan mixtures improves consistency index and apparent viscosity values of low-fat dairy desserts. Adding inulin (0-4%) to low-fat (2%) yogurts improved the yield stress, firmness, and creaminess values of the final product. Collagen peptide and β-glucan combinations also improved the gel continuity, creaminess and smoothness while reducing the syneresis rate in skim milk yogurt.	(González-Tomás et al., 2008; Guggisberg et al., 2009; Wijk et al., 2006; Zhang et al., 2025)

Table 3: Rheological properties of functional dairy products incorporated with plant-based ingredients

Dairy product	Supplemented plant material	Level of supplementation	Rheological instrument used	Rheological measurements	Effects on the rheological properties of the product	Ref.
Set yogurt	Green coffee powder	0, 1, and 2% (w/w)	Centrifuge	Centrifugal acceleration test	Supplementation decreased the syneresis rate of yogurts in proportion to the increase in coffee concentration during storage (21 days)	(Dönmez et al., 2017)
	Green coffee powder	0, 1, and 2% (w/w)	Brookfield RVDV-II+P rheometer	Flow behaviour index	Supplementation did not affect the flow behaviour index during storage (21 days)	(Dönmez et al., 2017)
	Green coffee powder	0, 1, and 2% (w/w)	Brookfield RVDV-II+P rheometer	Consistency coefficient	Supplemented yogurt had a higher consistency coefficient than the control until 14 days of storage	(Dönmez et al., 2017)
	Green tea powder	0, 0.01, 0.02, 1, and 2% (w/w)	Centrifuge	Centrifugal acceleration test	Supplementation at 0.02% significantly reduced the syneresis rate. Supplementation at 2% increased the syneresis rate during storage (21 days)	(Dönmez et al., 2017)

Rheological properties of functional dairy products incorporated with plant-based ingredients (continued)

Dairy product	**Supplemented plant material**	**Level of supplementation**	**Rheological instrument used**	**Rheological measurements**	**Effects on the rheological properties of the product**	**Ref.**
	Green tea powder	0, 0.01, 0.02, 1, and 2% (w/w)	Brookfield RVDV-II+P rheometer	Flow behaviour index	Lower supplementation levels (0.01, 0.02%) did not affect the flow behaviour index during storage (21 days). Higher supplementation levels increased the flow behaviour index until the 14th day and remained constant during the remaining time.	(Dönmez et al., 2017)
	Green tea powder	0, 0.01, 0.02, 1, and 2% (w/w)	Brookfield RVDV-II+P rheometer	Consistency coefficient	Lower supplementation levels increased consistency compared with the control during storage. Higher supplementation levels lowered consistency coefficients than the control during storage.	(Dönmez et al., 2017)
Low-fat set yogurt with fat replacers	Cupuassu (Theobroma grandiflorum) pulp	10% (w/v)	Brookfield concentric cylinder viscometer	Apparent viscosity, yield stress, flow behaviour index	Cupuassu-fortified skimmed milk yogurt with inulin and maltodextrin showed higher apparent viscosity and yield stress values than the control. Yogurt with inulin and maltodextrin showed pseudoelastic behaviour, whereas yogurt with whey protein isolate showed dilatant behaviour.	(Costa et al., 2022)
	Cupuassu (Theobroma grandiflorum) pulp	10% (w/v)	Texture analyzer (TA. XT Plus)	Texture analysis	Cupuassu-fortified skimmed milk yogurt with inulin and maltodextrin showed a higher firmness than the control. Consistency was highest in cupuassu-supplemented yogurt with maltodextrin. Supplementation with cupuassu and fat replacers reduced the cohesion of yogurt.	(Costa et al., 2022)
Stirred yogurt	Mucilage-free flaxseed powder	3% (w/w)	Brookfield Texture Analyser	Texture analysis	Supplementation increased the hardness of yogurt in the 2nd week of storage and decreased in the 3rd week	(Basiri et al., 2022)
	Mucilage-free flaxseed powder	3% (w/w)	-	Syneresis rate	Supplementation significantly reduced the syneresis rate during storage for 21 days.	(Basiri et al., 2022)

Rheological properties of functional dairy products incorporated with plant-based ingredients (continued)

Dairy product	**Supplemented plant material**	**Level of supplementation**	**Rheological instrument used**	**Rheological measurements**	**Effects on the rheological properties of the product**	**Ref.**
	Mucilage-free flaxseed powder	3% (w/w)	Rheometer (Anton Paar MCR-302)	Apparent viscosity	During refrigeration, the viscosity of supplemented yogurt was higher than the control.	(Basiri et al., 2022)
Ice cream	Bael fruit (Aegele marmelos) pulp	25, 50, 75% (w/w)	AMETEK Brookfield CT3 texture analyzer	Texture analysis	The hardness of the ice cream increased proportionally with the level of fortification. Supplementation resulted in lower cohesiveness values compared to the control. The cohesiveness of the ice cream samples considerably decreased with the increase of bael fruit supplementation levels. A detectable loss of springiness was noted with increased pulp concentrations, resulting in less elastic and resistant ice creams.	(Begum et al., n.d.)
	Grape (black queen) wine lees	50, 100, 150 g/kg (wet weight basis)	Brookfield viscometer with an RV spindle set	Apparent viscosity	Supplementation increased the viscosity of ice cream. The increase was 0.9, 1.9, and 3.2-fold with the supplementation levels of 50, 100, and 150 g/kg, respectively.	(Hwang et al., 2009)
	Grape (black queen) wine lees	50, 100, 150 g/kg (wet weight basis)	TA-XT2 Texture Analyzer	Texture analysis	Compared to the control, about 41%, 52%, and 61% reductions in the firmness were recorded at 50, 100, and 150 g/kg supplementations, respectively. Cohesiveness was not affected at 50 and 100 g/kg supplementation levels, while a 36% decline was noted with 150 g/kg supplementation.	(Hwang et al., 2009)
	Grape (black queen) wine lees	50, 100, 150 g/kg (wet weight basis)	-	Overrun	At 50g/kg supplementation, a significant change in overrun was not noticed. With higher levels of supplementation, overrun was significantly decreased.	(Hwang et al., 2009)
Processed cream cheese	Apple polyphenols with 75% purity	0-1.6% (w/w)	Rheometer (DHR-2)	Apparent viscosity	The apparent viscosity of all supplemented cheese samples gradually decreased with the increasing shear rate as well as the supplementation level.	(Deng et al., 2023)

Rheological properties of functional dairy products incorporated with plant-based ingredients (continued)

Dairy product	**Supplemented plant material**	**Level of supplementation**	**Rheological instrument used**	**Rheological measurements**	**Effects on the rheological properties of the product**	**Ref.**
	Apple polyphenols with 75% purity	0-1.6% (w/w)	Rheometer (DHR-2)	Elasticity modulus	G′ values increased up to 0.8% apple polyphenol content and gradually decreased with the increase of apple polyphenol content up to 1.6%, denoting a notable change in the protein gel network's elasticity caused by apple polyphenols.	(Deng et al., 2023)
	Apple polyphenols with 75% purity	0-1.6% (w/w)	Rheometer (DHR-2)	Viscosity modulus	G″ values decreased with the increased apple polyphonol content	(Deng et al., 2023)
Dairy dessert	Brewery malt (caramel Carahell)	1%, 3%, 5% (w/w)	Dynamic heometer (RS 300)	Elasticity modulus	G′ values increased during heating to 90 °C and continued to increase during cooling to 20 °C. G′ values rose with the increase of malt concentration from 1% to 3% but decreased at 5% supplementation.	(Szwajgier & Gustaw, 2015)
	Brewery malt (caramel Carahell)	1%, 3%, 5% (w/w)	Dynamic heometer (RS 300)	Viscosity modulus	G″ values increased during heating to 90 °C and continued to increase during cooling to 20 °C. G″ values rose with the increase of malt concentration from 1% to 3% but decreased at 5% supplementation	(Szwajgier & Gustaw, 2015)
	Brewery malt (caramel Carahell)	1%, 3%, 5% (w/w)	TA-XT2i Texture Analyser	Texture analysis	Hardness and adhesiveness of the products were not affected by 1% supplementation. The highest hardness was obtained with 3% supplementation. At 5% malt supplementation, the consistency of the desserts deteriorated.	(Szwajgier & Gustaw, 2015)

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