

Review

Textural Evaluation of Milk Products: Instrumental Techniques, Parameters, and Challenges

Sergiu Pădureț 

Faculty of Food Engineering, Stefan cel Mare University of Suceava, 13 University Str., 720229 Suceava, Romania; sergiu.padureț@fia.usv.ro

Abstract

Milk products are a diverse group of foods and important sources of essential nutrients, including high-quality proteins, fatty acids, vitamins, and minerals. Among their key quality attributes, texture is particularly critical, as it strongly influences consumer perception and overall product quality. Numerous devices and techniques have been developed to evaluate the texture of milk products, most of which rely on mechanical tests such as puncture, compression, shearing, creep, and relaxation. Instrumental evaluations are essential for correlating physical measurements with sensory perceptions, yet several challenges limit their reliability. Inconsistencies in testing protocols—such as reporting force versus penetration depth versus force versus time; variations in testing temperature, sample shape and dimensions; probe geometry; compression depth; and container size for semisolid samples contribute to discrepancies across studies. Additionally, many studies omit these critical methodological details, reducing reproducibility and comparability. This review systematically examines the current methods used to assess dairy product texture, identifies gaps and challenges in standardization, and provides guidance to support future research aimed at obtaining accurate, reproducible, and meaningful texture measurements.

Keywords: milk products; texture; instrumental methods; testing parameters



Academic Editor: Giovanni Bittante

Received: 3 July 2025

Revised: 2 October 2025

Accepted: 10 October 2025

Published: 14 October 2025

Citation: Pădureț, S. Textural Evaluation of Milk Products: Instrumental Techniques, Parameters, and Challenges. *Dairy* **2025**, *6*, 58. <https://doi.org/10.3390/dairy6050058>

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1. Milk Products: Diversity and History

Milk products represent a heterogeneous group of products, defined by Codex Alimentarius [1] as products obtained from milk processing, which may include the addition of food additives and other ingredients essential for their production. This group includes various products consumed globally (Figure 1), such as fermented milk products (e.g., yogurt, sour milk, dahi, kefir, lassi, kumiss, and shrikhand), different types of cheese (very hard, hard, semi-hard, semi-soft and soft), butter, ghee, dairy fat spreads, cream, and ice cream. Additionally, this category also encompasses condensed and evaporated milk, cream, milk and cream powders, whey-based products, and casein [2].

Globally, milk production is projected to reach 979 million tons in 2024, a 1.4% increase from 2023, driven primarily by growth in Asia, particularly India, China, and Pakistan [3,4]. According to the European Union Statistical Office, milk production in 2023 was estimated at approximately 160.8 million tons, of which 96% was cow's milk, while the remaining 4% came from sheep, goat, and buffalo milk. This represents an increase of approximately 0.8 million tons compared to the previous year and 15.8 million tons compared to the 2013 level. Regarding the use of whole milk for processing within the European Union, approximately 70% of the total quantity was allocated to the production of cheese (10.6 million tons) and butter (2.3 million tons) [5]. The variety of dairy products exhibits considerable

regional and national variation, influenced by dietary traditions, available milk processing technologies, market demands, and sociocultural factors. Milk products such as fermented milk, butter, and cheese have a long history, with production dating back to at least 3000 BC. However, the industrialization of milk processing did not commence until the mid-19th century [6]. Among the oldest methods for extending milk’s shelf life, fermented milk products have been produced for thousands of years across numerous countries [7]. Butter, a water-in-oil emulsion and one of the earliest dairy products, also shares ancient origins, likely emerging during the prehistoric stages of animal husbandry [8]. Similarly, cheese-making is an ancient practice, with research suggesting its origins trace back to the Neolithic period, coinciding with the domestication of animals [9]. Cheese classification is based on several key factors, including the type of milk used (such as cow, sheep, goat, or buffalo), fat content, moisture content (categorized as very hard, hard, semi-hard, semi-soft, and soft), production process, fermentation type, and ripening period. These diverse criteria contribute to over 1000 distinct cheese variants and varieties worldwide [10]. Variations in milk chemical composition (milk fat content and fatty acid profile, protein) significantly influence the appearance, texture, and overall sensory characteristics of these products. Recognizing this diversity is fundamental for understanding and evaluating texture, a complex attribute affected by multiple interacting factors [11]. The origins of fermented milk products are believed to lie in the Middle East and the Balkans. Today, the production of these products is a global practice combining traditional techniques with modern scientific disciplines, with approximately 400 distinct names used to classify both traditional and industrialized varieties [7]. These early developments in dairy processing highlight the long-standing relationship between humans and domesticated animals in the evolution of food preservation techniques.

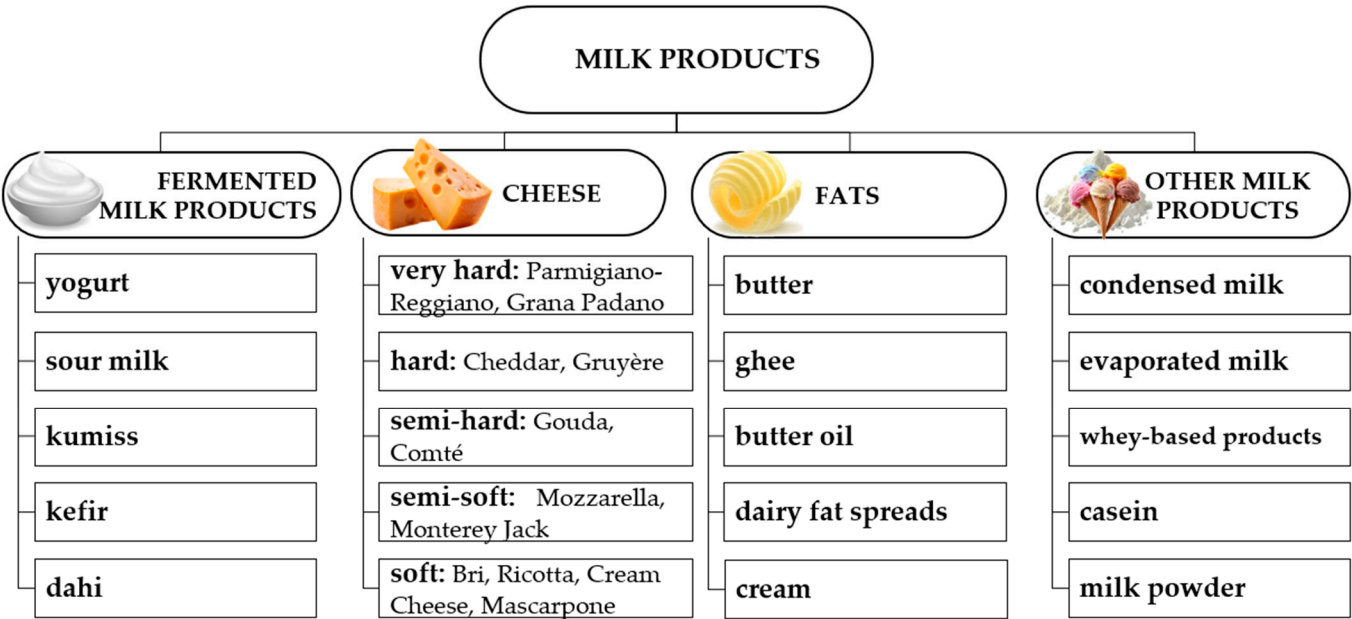


Figure 1. The variety of milk products.

2. The Nutritional Impact and Significance of Milk Products

Dairy products are widely recognized as valuable sources of essential nutrients, including high-quality proteins, fatty acids, vitamins, and minerals [12], which supports immune function, cardiovascular health, and bone density [13], nervous system activity, vision, muscle and nerve function, and overall health [14]. They are effective carriers for bioactive compounds and provide key nutrients, including calcium, potassium, zinc, phosphorus,

vitamin A, riboflavin, vitamin B12, and iodine, which contribute significantly to dietary intake. While dairy products contain saturated fats, current evidence does not associate their consumption with increased cardiovascular disease risk. Instead, fermented dairy products, such as yogurt and cheese, may offer cardiometabolic benefits [12,15]. Milk proteins, including caseins and whey proteins (lactoglobulin, lactalbumin, immunoglobulins), are rich in bioactive peptides that inhibit angiotensin-I-converting enzyme, a key regulator of blood pressure and fluid-electrolyte balance [16]. Milk, yogurt, and cheese are the dairy products with the highest calcium concentrations. In the Nordic and Baltic regions, dairy products provide about 60% of total dietary calcium intake and contribute about 50% of dietary saturated fat intake [17].

Dairy fat is among the most complex natural fats due to its diverse fatty acid profile, with over 400 fatty acids identified in butter, spanning carbon chain lengths of 4 to 26 [18]. This composition critically influences milk products' physicochemical properties, sensory attributes, and nutritional quality. Primarily esterified as triacylglycerols or phospholipids, fatty acids in milk fat can also exist as non-esterified fatty acids, formed via enzymatic lipolysis [19]. Although present in minimal amounts in milk, short-chain non-esterified fatty acids play a crucial role in shaping the characteristic flavors of fermented dairy products, particularly cheese [20]. According to Huth, conjugated linoleic acid and vaccenic acid, naturally occurring fatty acids found in dairy products, have been linked to potential anti-carcinogenic and antiatherogenic properties [16]. These findings highlight the complexity of dairy's impact on health and underscore the importance of considering the type and processing of dairy products in dietary recommendations. Nutritional guidelines recommend reducing saturated fat intake, increasing polyunsaturated fats, and avoiding trans fats, which can make up to 60% of fat in partially hydrogenated fats. In contrast, ruminant-derived trans fats are present in dairy products in lower amounts, typically around 2–5% of the total fatty acids, and are considered less concerning for cardiovascular health [20–22].

3. Food Texture: Concepts and Definitions

The texture of food products significantly influences consumer preferences and represents a multi-parameter attribute that serves as a key indicator of food quality, alongside flavor, appearance, and nutritional properties. It refers to the sensory perception of a food's physical characteristics in the mouth, described by terms such as "hard," "soft," "creamy," or "crispy." These descriptors are linked to physical properties like density, viscosity, and surface tension. Historically, texture has been considered part of the appearance-related sensory attributes in quality scoring systems, often described using terms such as 'firmness,' 'tenderness,' 'consistency,' 'succulence,' and 'body' [23]. These characteristics, termed 'kinesthetic,' are associated with the sense of touch and correspond to the product's resistance to applied forces, whether during mastication in the mouth or through physical handling. Several authors have contributed to the definition of texture [24–26], with the ISO 11036 [27] standard offering the most comprehensive description: "Texture represents the combination of the mechanical, geometric, and surface properties of a food product, perceptible through tactile or mechanical receptors and, where applicable, visual and auditory receptors." Mechanical properties refer to the product's response to applied forces and are categorized into five primary characteristics (hardness, cohesiveness, viscosity, elasticity, and adhesiveness) and three secondary characteristics (fracturability, chewiness, and gumminess), Table 1. Geometric properties pertain to attributes such as particle size, shape, and spatial arrangement within the product's structure. In contrast, surface properties relate to the sensations perceived during consumption, primarily influenced by moisture and fat content. These sensations are modulated during mastication, depending on the manner and rate at which these constituents are released. One of the earliest definitions

of the texture of a dairy product—specifically cheese—was provided by Davis [28], who described texture as the aspect observable by the eye, excluding color. The term “texture” may vary in meaning across different regions, but it is often understood to encompass both the degree of closeness (i.e., the absence of cracks) and shortness or brittleness (the ease with which a plug breaks). Additionally, Davis distinguished “body” as a separate attribute, referring to the quality of the product that can be perceived through touch.

Texture also represents a critical attribute in consumer evaluation of food product quality. It not only contributes to the physical perception of a product but also plays a significant role in determining flavor and taste perception. Taste is a complex sensory experience arising from the sensations in the mouth and on the tongue after ingestion of food, and it is closely influenced by the product’s physical characteristics, including density, viscosity, surface tension, and related properties [29]. Overall, these definitions show a shift from early, visually based descriptions toward multidimensional frameworks that integrate mechanical, geometric, and surface properties. For dairy products, the broader ISO 11036 approach is especially useful because fat content, moisture distribution, and protein structure together influence the textural characteristics. Considering these aspects allows for a more complete understanding of how composition and microstructure shape texture and consumer perception. The texture parameters of milk products are inherently determined by their composition, with components such as fat, protein, and water content, as well as additives like emulsifiers, playing a crucial role in shaping these characteristics. Dairy products exhibit a wide variety of textures and consistencies, ranging from low-viscosity liquids like milk and cream to soft, airy foams in products such as whipped cream, and further extending to solid, hard cheeses and milk powders [30]. Each of these categories presents distinct challenges for texture analysis, as their unique structural and physical state properties require specialized analytical methods to assess their textural characteristics accurately.

Table 1. Definitions of the mechanical properties.

Mechanical Texture Property	Conceptual Explanation	Physical States of Food Samples	Dairy Lexicon	Bibliography
Hardness	Indicates the force required to deform or penetrate a product, typically perceived by compressing it between teeth (for solids) or between tongue and palate (for semi-solids).	Solid and semi-solids	hard soft	[31]
Cohesiveness	Describes the degree to which a food sample can withstand deformation before undergoing structural failure.	Solids and semi-solids	springy gummy	[32]
Viscosity	Represents the fluid’s resistance to flow, quantifying the force required to transfer the liquid from a utensil to the tongue or to spread it across a surface.	Semi-solids	milky yogurt-like creamy spreadable unctuous	[27]
Springiness/Elasticity	Describes both the rate and degree of shape recovery of a food sample after the deforming force has been removed	Solids and semi-solids	springy plastic	[33]
Adhesiveness	Indicates the force necessary to detach food that adheres to the mouth or a substrate.	Solids and semi-solids	sticky gluey	[27]
Fracturability/Brittleness	Pertains to the food material’s cohesiveness and the force required to crumble, crack, or shatter it into fragments.	Rather for solids	crumbly brittle fragile	[31]
Chewiness	Related to cohesiveness, it is defined as the time or number of chewing cycles required to masticate a solid product, at a constant rate of force application, until it reaches a consistency suitable for swallowing.	Solid	chewy tender	[27]

Table 1. Cont.

Mechanical Texture Property	Conceptual Explanation	Physical States of Food Samples	Dairy Lexicon	Bibliography
Gumminess	Represents the perceived denseness that is sustained throughout mastication or the mechanical energy needed to break down a food sample to a consistency suitable for swallowing, assessed by compressing the sample between the tongue and palate.	Semi-solid	gummy	[33]

These compositional elements determine key textural characteristics, including hardness, creaminess, cohesiveness, and viscosity, which are essential for both sensory evaluation and quality control in dairy product manufacturing. The interaction between these constituents leads to a range of textures, from the smooth and creamy consistency of yogurt to the firm, crumbly nature of matured cheese. Understanding the relationship between composition and texture is critical for optimizing product formulations, ensuring consistency, and identifying consumer expectations regarding mouthfeel and overall sensory experience [34]. Furthermore, texture analysis techniques, including instrumental measurements and sensory panels, provide valuable insights into how changes in composition impact the final texture of dairy products. Therefore, a comprehensive approach to texture characterization must consider not only the physical properties of the product but also the complex interactions of its ingredients.

According to Bourne [35] food products can be classified into three categories based on the significance of texture: critical (texture represents the primary quality attribute), important (texture significantly contributes to overall quality, alongside flavor and appearance), and minor (texture has an insignificant impact on overall quality). Within these categories, dairy products, particularly cheeses, fall into the second category, where texture plays an important role in determining overall quality. In these products, texture is not only a decisive characteristic but also interacts with flavor and appearance to profile consumer perception and acceptance.

The texture of food products can be evaluated as follows:

- (i) Descriptive sensory analysis or human sensory methods—a subjective measurement;
- (ii) Instrumental analysis—an objective measurement [29,33].

3.1. Subjective Texture Measurement

The subjective measurement of texture, often referred to as sensory perception or sensory evaluation, encompasses all methods used to assess, analyze, and interpret human responses to the properties of food as perceived through the five senses: taste, smell, touch, sight, and hearing [36]. Although the tactile sense (touch) is the primary means by which sensory measurement of texture is perceived, sight and hearing can also provide valuable information about certain key components of a product’s texture profile. According to Bourne, sensory methods for measuring food texture may lack precision, a limitation that is particularly problematic in scientific research due to individual variability and potential fluctuations in personal preferences over time (e.g., from hour to hour or day to day). Despite these challenges, sensory measurement of texture remains an essential component of evaluating food product quality and cannot be overlooked [37]. The principal methods of sensory evaluation are categorized into analytical and hedonic tests. Analytical tests utilize trained sensory panels to obtain detailed and objective information about the sensory characteristics of food products. In contrast, hedonic tests assess the responses of untrained consumers to evaluate sensory attributes such as taste and overall acceptability [38]. Hedonic testing generally requires a larger number of participants, who serve as

a representative subsample of the target population. Although these methods are often associated with marketing activities within the food industry, they should be integrated at the earliest stages of product development. Early application of hedonic testing can provide more accurate, consumer-oriented insights that enhance the direction and effectiveness of research and innovation efforts [39]. A well-trained sensory panel should produce results that are consistent with instrumental data, underscoring the importance of precision and reproducibility in panel performance. A critical factor in achieving this consistency is the use of a clearly defined lexicon [32]. Such definitions not only streamline training and reduce variability but also provide a structured framework for correlating sensory perceptions with instrumental measurements [37]. In the context of cheese firmness evaluation, the appropriate sensory or physical action can vary depending on the type and texture of the cheese. This raises the question of which method is most suitable—manual compression with the fingers, bite force using the incisors or molars, or compression between the tongue and the hard palate. The optimal approach may differ according to the specific texture characteristics of the cheese, emphasizing the need for standardized measurement protocols in sensory evaluation [40]. For the evaluation of springiness, the cheese sample is compressed between the thumb and index finger to approximately 30% of its original size for 1–2 s, without damaging. The overall degree of recovery after compression is then assessed. If the sample fractures during compression, it is classified as no springy [41].

3.2. Objective Texture Measurement

The objective methods used to evaluate food texture can be categorized into direct (destructive) and indirect (non-destructive) techniques. Direct methods assess the actual texture properties of food materials, providing highly accurate and reproducible measurements of mechanical properties, though they are generally slower and may require specialized equipment. In contrast, indirect methods, including optical, chemical, and acoustic approaches, evaluate physical characteristics that can be correlated with one or more textural properties. They are typically faster and non-destructive, allowing rapid or continuous analysis, but their accuracy and reproducibility can be more variable and often require calibration against direct measurements [37]. Instrumental methods provide reproducible numerical values that describe the mechanical properties of food products. Many scientists, engineers, and technologists in the food industry have investigated these properties to better understand food texture from the consumer's perspective, either through descriptive sensory analysis or human sensory perception. In parallel, researchers in materials science have approached the subject through rheology and fracture mechanics to gain a broader understanding of the material characteristics of food [36,42]. Direct methods can be further subdivided into three categories: fundamental, empirical, and imitative tests. Fundamental tests are classical techniques used in material science that involve deforming a sample of a well-defined shape under controlled conditions. These methods allow for the precise interpretation of results using rheological theories. Such tests typically involve small deformations (1–3%), require isotropic and homogeneous materials, and use probes of regular geometry. While these tests offer highly accurate and reproducible data, they are often difficult to perform, require expensive equipment, and show a weaker correlation with sensory evaluation when compared to empirical methods [37,43]. Empirical tests, developed from practical experience, measure parameters that are not strictly defined. Despite their limitations, they are the most widely used texture assessment techniques in the food industry due to their simplicity and rapid execution. However, empirical tests are often criticized for being arbitrary, lacking standardization, and having limited applicability across different food types [38]. Imitative tests are designed to replicate specific human interactions with food, such as biting or manual compression. These tests

simulate conditions that occur during the initial stages of mastication by subjecting the food sample to controlled compression. The resulting data can be used to create a texture profile that reflects the sensory experience. Imitative methods utilize instruments to mimic the processes occurring in the oral cavity during chewing, thus providing a more consumer-relevant assessment [43].

4. Instrumental Methods for Evaluating the Texture of Milk Products

Among objective techniques, direct methods are the most frequently used to evaluate textural properties in food products, offering valuable insights into their mechanical behavior. Over the years, a wide range of instrumental tests have been used in both research and industry to evaluate the texture of dairy products. Numerous devices (TA.XTplus, Instron Texture Analyzer, Stable Micro Systems Ltd. Godalming, Anglia, Universal Testing Machines (UTM), Mark 10) and techniques have been developed to determine their firmness, with most tests based on the puncture, compression, shearing, creep, relaxation, and impact [8,37].

4.1. Puncture Tests

The puncture or penetration test represents a simple, rapid, and cheap direct destructive test based on measuring the force required to penetrate a food product. It is among the most commonly used methods for evaluating textural parameters [37,44,45]. In this method, a spherical (Figure 2a), cylindrical (Figure 2b), or conical probe (Figure 2c) is mechanically driven into the sample to a predetermined depth at a constant speed, and the force is measured [46]. This test generates a force-displacement curve, providing valuable information on the product's mechanical behavior. The probe selection is made by the anticipated firmness range and the specific characteristics of the sample. Generally, firmer products impose the use of probes with smaller diameters or narrower cone angles. It is commonly applied to evaluate attributes such as hardness or tenderness in a variety of foods, including fruits, gels, and vegetables [44], and certain milk products—especially those with solid consistency, such as cheeses and butter [45,46]. In the analysis of cheese texture, cylindrical probes of varying diameters are utilized, including 6 mm [47], 2 mm [48], or other diameters, and the test speed varied from 12 mm/min to 60 mm/min. According to Bourne [37], the diameter of the sample should generally be at least three times that of the probe to ensure accurate measurements. However, for fracturable dairy products such as hard or extra-hard cheeses, the sample diameter must exceed this ratio to ensure reliable textural measurements. In addition to assessing hardness, several other textural parameters are evaluated, including crust firmness and core firmness, deformability modulus, adhesiveness (compression work), and stickiness [45]. According to Lis [46], the penetration test is the most frequently used instrumental method for evaluating butter texture parameters. For the analysis of butter samples, cone penetrometers are widely used to assess textural properties such as hardness, plasticity, and adhesiveness. These instrumental evaluations are critical for correlating physical properties with sensory perceptions in food texture research [8,49]. Hardness and spreadability of butter, measured by a conical probe, are inversely related mechanical properties and represent two of the most critical textural and rheological attributes affecting consumer perception. Increased hardness generally reduces spreadability, making the product less convenient for use, while lower hardness improves spreadability and is often associated with a more desirable mouthfeel [50]. The acquisition of force (N) versus penetration depth (mm) curves facilitated the calculation of work of penetration and adhesiveness as energy (joules) or work (N·m), following the definitions established by ISO 11036 [51] and Bourne (2002) [37]. However, this calculation is not possible when time, instead of distance, is represented on the abscissa. Butter's complexity

is further underscored by its composition of over 400 fatty acids. The textural properties of butter, including its structure and consistency, are influenced by multiple interconnected factors such as the concentration, size, shape, and distribution of fat crystals, fat globules, air bubbles, and aqueous phase droplets. Additionally, Staniewski (2021) reported that an increase in myristic fatty acids combined with a decrease in oleic fatty acids contributes to enhanced butter firmness [52]. Temperature plays a critical role in the instrumental evaluation of butter texture, significantly influencing the results of puncture tests. To ensure consistency and comparability across studies, most researchers have adopted the standardized testing temperature of 10 °C, as recommended by ISO 16305:2005 [53]; however, some researchers have conducted texture measurements at temperatures of 5, 10, 15, and 23 °C [52,54,55]. In numerous studies involving puncture tests on butter and cheese samples, critical details such as the specific shape and dimensions of the samples, as well as the test parameters, are frequently omitted. This lack of comprehensive reporting persists despite the potential impact of these factors on the test outcomes.

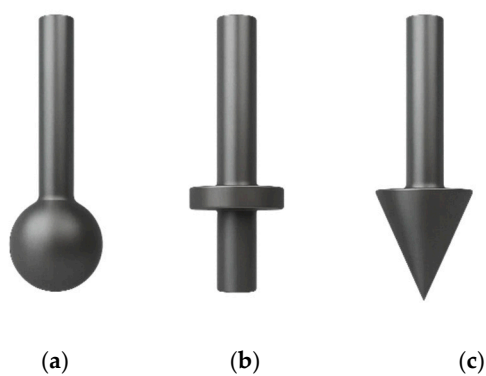


Figure 2. Puncture probes: (a) spherical probe, (b) cylindrical probe, (c) conical probe.

In puncture tests, hardness (N) is defined as the maximum force recorded during probe penetration. At the same time, adhesiveness (N·mm) is calculated as the negative area under the force–penetration depth curve during probe withdrawal. Viscosity, or adhesion force (N), is quantified as the minimum negative force observed. The work of penetration (N·mm) is defined as the mechanical work required to drive the probe into the sample to a specified depth, within the range of recorded positive forces (Table 2).

Table 2. Puncture test parameters.

Parameter	Cheese	Bibliography	Butteer	Bibliography
Probe type	cylindrical (2, 3, 5, 6, 10 mm), conical (9°, 19°, 45°, and 90°)	[48,56–60]	spherical, cylindrical (5 mm), or conical probe (40°, 120°)	[8,46,55]
Test speed, mm/min	6, 12, 24, 30, 60, 240, 600	[48,56,58–61]	10–120	[8,46,54,62]
Penetration depth, mm	10, 15, 20	[48,57,59]	2.5–14	[8,54,62]
Sample form	cube cylindrical	[48,56]	cylindrical plastic containers	[63]
Sample dimensions, mm	cube 15 cylindrical, 20 × 30	[48,56,61]	35 mm in both height and diameter	[63]
Testing temperature, °C	120 × 68 × 30 20	[48,56]	4–23, recommended 10	[52,53,55]
Textural properties	hardness, adhesiveness, work of penetration, apparent viscosity	[48,58]	hardness, adhesiveness, work of penetration (plasticity) viscosity (adhesion force)	[8,46,62]

4.2. Spreadability Test

According to Bayarri [64], spreadability refers to a product’s ability to be uniformly distributed across a surface and is characterized by the amount of pressure required to

achieve this even application. From the perspective of textural analysis of milk products, this parameter can be quantitatively assessed using constant speed penetrometry, utilizing a spreadability ring test unit (Figure 3). In this method, a conical male probe cone (90° angle) is mechanically driven at a constant speed into a conical female container cone (90° angle) holding the dairy sample, while the force required for penetration is measured [60,65].

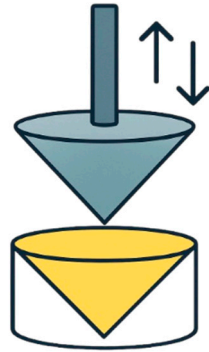


Figure 3. Spreadability test unit.

Among milk products, butter, cream cheese, soft cheeses, and ice cream can be evaluated for spreadability, a textural attribute of significant relevance to consumer perception and acceptance. The spreadability of butter and similar spreads is largely influenced by their compositional factors, with solid fat content being a primary determinant of this property. Variations in fat phase structure, fat crystal morphology, and overall formulation can significantly impact these textural characteristics [65,66].

Furthermore, increased fat crystallization diminishes butter spreadability, whereas a higher degree of milk fat unsaturation (linoleic, palmitoleic, and oleic fatty acids) enhances it [54,63,67]. The spreadability is evaluated by measuring the loading area under the force-deformation curve, N·mm [63]. However, in some studies, this textural parameter is reported in units of N·s [60,64,65,68]. Samples that spread more easily required lower forces to be displaced from the female cone; therefore, lower values indicate greater spreadability [68]. For the analysis of butter samples, testing speeds ranged from 10 mm/min to 180 mm/min across various temperatures (5 °C, 10 ± 2 °C, and 20 ± 2 °C). The gap between the two components of the testing fixture varied between 0.5 mm and 2 mm [60,63,65]. Regarding soft cheeses spreadability measurements, limited information are available, and some studies do not report the specific testing parameters; however cheese samples (cream cheese, cheese spreads) were tested at a speed of 60 mm/min, temperatures of 5 °C, 8 °C, 10 ± 1 °C, and 22 ± 1 °C, with a 2 mm gap between the two components of the testing fixture [59,64,68,69]. The evaluation of cheese spreadability has also been conducted using a spreadability ring test unit equipped with 45° cones [59,64]. According to Bayarri [64], temperature has a significant impact on the spreadability measurement of cheese. At 10 °C, samples exhibited greater differentiation than those at 22 °C, showing higher firmness, stickiness, and lower spreadability (high values). These differences are attributed not only to fat content but also to the physical state of the fat (liquid or crystalline), emphasizing the critical role of fat state in determining the mechanical properties of cheese. Other secondary texture parameters determined by this test include spreadability hardness, defined as the maximum force at the probe's deepest point of penetration [59], while adhesiveness represents the work required for product-surface separation, calculated as the negative area [63]. The evaluation of ice cream spreadability reported in various studies differs significantly from the method described in this section. A commonly used approach involves measuring the deformation of a standardized ice cream sample (a cube with 20 mm sides) under a constant applied force (100 g) over time. This method quantifies the sample's resistance

to flow or spread when subjected to a controlled mechanical load at a specified temperature, offering insight into its structural integrity and viscoelastic behavior. The resulting deformation—typically observed as an increase in diameter—is recorded at regular time intervals to monitor the extent of spread [70,71].

4.3. Texture Profile Analysis Test (TPA)

The Texture Profile Analysis (TPA) test is an instrumental method designed to simulate the mastication process (42 bites per minute and 75% deformation) by subjecting the food sample to two consecutive compression-decompression cycles (double compression), using a flat probe with a diameter larger than the sample's dimensions [46,72]. This double compression approach provides an objective evaluation of the textural properties of food products. In the late 19th and early 20th centuries, food texture evaluation primarily depended on rudimentary sensory evaluations aimed at identifying product defects. In contrast, the TPA test has emerged as a method that effectively bridges the gap between objective instrumental measurements and subjective sensory perception, enabling a more consistent and predictive characterization of food texture properties [36]. As described by Bourne [37], the typical profile of a TPA test can determine a wide range of food texture characteristics, including hardness, fracturability (brittleness), resilience, adhesiveness, springiness (elasticity), cohesiveness, gumminess, and chewiness. Hardness is defined as the maximum peak force recorded during the first compression and is expressed in Newtons [34]. Fracturability is also expressed in Newtons and refers to the force corresponding to the initial major break in the texture curve, representing how easily a material breaks or crumbles under deformation. Cohesiveness is the ratio of the area in the second compression to the first, reflecting the strength of internal bonds in a material, expressed either as a dimensionless value or as a percentage [38]. Springiness is the height recovered by the sample between compressions, indicating its ability to return to its original shape [43]. Adhesiveness is the negative area during the first compression, reflecting the work to detach the probe from the food sample, expressed as Newton·millimeters [8]. Resilience is the ratio of the first decompression area to the first compression area, measuring the sample's shape recovery ability. Gumminess is calculated as the product of hardness and cohesiveness, whereas chewiness is quantified as the product of gumminess and springiness [34,37]. Although recent studies [73] have raised concerns regarding the reliability of the TPA test due to fundamental methodological flaws, mechanical properties in material science are fundamentally based on the stress–strain relationship, where the stress is measured in pressure units and strain is dimensionless. Nevertheless, TPA continues to be widely used in the evaluation of solid and semi-solid food products, as well as dairy products. Although the textural parameters obtained from the TPA test are not material constants, being influenced by sample dimensions, measurement conditions such as compression speed, temperature, and particularly the strain, they remain highly valuable for the characterization of food products. In some studies, food samples that are unable to maintain their shape are subjected to uniaxial compression in a container to measure TPA parameters, often without assessing their physical validity or relevance [74].

The TPA test has been applied in various studies to evaluate the textural characteristics of different cheese types, including Myzithra, Mahon, Cheddar with varying fat content, Emmental, Gouda, pasta-filata cheeses (mozzarella, provolone and kashcaval), Brie, Feta, Velveeta, Monterey Jack, Muenster, and spreadable whey cheese. Measurements were performed on samples of different shapes: cylindrical (22 mm in height and diameter, diameter of 11 mm and height of 15 mm), cubic (15 and 20 mm sides), and rectangular (20 mm × 20 mm × 15 mm, 40 mm × 40 mm × 30 mm). The tests were conducted under controlled compression speeds of 10 mm/min, 20 mm/min, 24 mm/min, 48 mm/min,

50 mm/min, and 60 mm/min with deformation levels of 80%, 70%, 50%, and 30%, respectively, at various temperatures (4 °C, 6 °C, 12 °C, and 25 °C) [47,75–81]. Cylindrical testing probes with diameters ranging from 36 mm to 100 mm were used [77,82]. Cheese composition, particularly protein, fat, moisture, and NaCl content, significantly influences textural properties. Higher protein levels generally reduced adhesiveness, while increased fat content was associated with greater adhesiveness but lower firmness and chewiness. Moisture content impacted resilience and springiness, and salt content altered cohesiveness and adhesiveness. Additionally, storage temperature played a critical role, with higher temperatures negatively affecting firmness, springiness, and chewiness [81]. Variations in sample geometry, testing temperature, compression speed, and degree of deformation across studies contribute to inconsistencies in the measured textural properties. Cheese elasticity is perceived during the initial stages of mastication [41], which explains its strong correlation with mechanical properties. Samples exhibiting low fracture strain tend to break easily, resulting in low perceived elasticity, as reported for Emmental cheese. Resilience and cohesiveness are similarly associated with sensory elasticity, with comparable correlations observed in white cheeses and emulsion-filled gels. Adhesiveness shows a strong correlation with perceived stickiness, demonstrating that instrumental measurements can reliably reflect consumer sensory perception [82]. Sensory perception of cheese hardness aligns closely with mechanical measurements only at high deformations (70–90%), where fracture occurs and force values stabilize. Testing at a deformation rate of 1.0 mm/s provides the best correlation with perceived texture, while matching mechanical rates to individual chewing speeds further improves alignment, demonstrating that mechanical properties must reflect actual consumer mastication to predict sensory hardness accurately [41]. Complex sensory attributes—such as smoothness, creaminess, and fattiness—cannot be fully explained by mechanical measurements alone. These perceptions are closely associated with bolus properties, including hardness and cohesion, which are influenced by fat content. During mastication, fat melts, producing softer and more cohesive boli that enhances the perception of smoothness, creaminess, and fattiness [82].

In the case of butter, existing research includes more studies on texture determination using penetration tests than TPA; however, TPA studies still offer valuable insights into its textural characteristics. The butter samples tested through the TPA test were cylindrical (40 mm in diameter, 35 mm in diameter × 15 mm high); the tests employed flat cylindrical probes with diameters between 10 mm and 50 mm, the latter being more commonly recommended. Testing temperatures varied between studies and included 5 °C, 15 °C, and 20 °C. Compression speeds were set at 30 mm/min or 60 mm/min. Deformation level differed, with compression depths of 15 mm, 5 mm (approximately 33% strain), and 1.5 mm (10% strain). In some cases, a 15 s relaxation phase was included between the two compression cycles, allowing the sample to partially recover and thereby simulating the rest period between bites during mastication. This phase is important in Texture Profile Analysis (TPA) as it affects the measurement of parameters such as cohesiveness, resilience, and adhesiveness, contributing to more accurate and reproducible results [65]. The textural parameters observed in butter, particularly hardness, are likely influenced by the sample's chemical composition, primarily the higher content of saturated fatty acids, and the structure of fat crystal networks, which are stabilized by van der Waals forces. Variations in crystal polymorphism and crystal size also contribute to these differences. Compared to spreadable fats, butters exhibited higher values for hardness, gumminess, and chewiness, mainly due to their greater proportion of saturated fatty acids. While differences in hardness among the butter samples at 20 °C were not statistically significant, significant differences in adhesiveness and cohesiveness were observed at 5 °C [65,83].

In the case of semi-solid dairy products such as yogurt, kefir, sour milk, kumis, cream, and ice cream, samples cannot retain their shape and are tested using a container. Under these conditions, the Texture Profile Analysis (TPA) measurements necessarily involve flow of the sample between the probe and the container walls, which means that aspects of back extrusion are inherently incorporated into the test. Therefore, while the test is conducted as a TPA, it also effectively captures the characteristic response associated with back extrusion, providing a comprehensive assessment of the textural properties of semi-solid dairy products. Consumer perception of dairy products is closely associated with their mechanical properties. In yogurts, textural attributes are primary drivers of consumer liking; descriptors such as “smooth” and “good texture” are linked with positive emotional responses (e.g., “cheerful”), whereas “bad texture” corresponds to negative emotions (e.g., “nasty”) [84]. Similar trends are observed in semisolid milk desserts, where higher viscosity, creaminess, and body positively influence acceptability. Frequently cited descriptors for preferred textures include “thick,” “soft,” and “yummy.” In contrast, terms such as “liquid,” “bad texture,” and “not very creamy” are negatively associated with liking. These findings underscore the strong relationship between objectively measurable mechanical properties (e.g., viscosity, firmness) and consumer sensory preferences in dairy products [85]. Texture Profile Analysis of ice cream, a complex colloidal food system, was conducted using probes with different diameters from 2 to 36 mm. Penetration depths ranged from 15 to 20 mm, with penetration speeds of 120 to 198 mm/min. Tests were performed in cylindrical containers (approximately 40 mm high × 50 mm diameter, 40 mm diameter) at temperatures of 20–25 °C, with samples tempered at −10 °C [86–89].

The TPA test is commonly used to characterize the textural properties of yogurt, including hardness, adhesiveness, cohesiveness, springiness, gumminess, and chewiness. Various studies utilize cylindrical probes with diameters ranging from 15 to 50 mm. Some test protocols involve two sequential compression cycles with 15–30 s rest intervals. Samples are compressed to 10–30 mm or up to 70% of their original height, with speeds ranging from 60 to 300 mm/min; 60 mm/min is the most commonly used and consistent with early standardized TPA methods. Yogurt samples are generally placed in containers measuring 35–70 mm in diameter and 20–40 mm in height and tested at temperatures between 4 and 25 °C. A probe-to-container diameter ratio of at least 1:2, and in some cases up to 1:3.5, is maintained to minimize edge effects and ensure accurate texture measurements [90–100]. In certain studies [95], TPA tests involve more than two compression–decompression cycles; however, this approach deviates from the original protocol developed by Friedman and Bourne, which defines two cycles as the standard for evaluating textural properties [37,72]. In the context of Texture Profile Analysis applied to solid dairy products, authors must report key test parameters, including testing speed, the shape and size of the testing probe, the level of compression (penetration depth), the shape and dimensions of the sample, and the temperature at which the analysis is conducted. For semisolid samples, the dimensions of the container used to hold the sample, and the sample height should also be specified.

4.4. Creep and Stress–Relaxation Tests

Milk products represent complex food matrices that exhibit distinct mechanical behaviors. Although these behaviors can sometimes be approximated using simplified models such as the ideal elastic solid, the ideal viscous liquid, the ideal plastic, or combinations thereof, these models only partially capture the complexity of food systems [101]. According to Foegeding [41], and from a materials science perspective, several milk products [102,103] (e.g., cheeses, cream and whipped cream, ice cream, yogurt) are classified as viscoelastic materials, exhibiting both elastic (solid-like) and viscous (fluid-like) responses under mechanical stress, described as a dispersed phase of fat globules embedded within a

continuous protein matrix [104]. The viscoelastic behavior of milk products is generally quantified using both transient tests, such as creep and stress relaxation, and dynamic tests, whereas the viscoelastic properties are estimated using mechanical models that combine springs (elastic elements) and dashpots (viscous elements) to simulate viscoelastic behavior. Common models include the Maxwell, Kelvin–Voigt, Burgers, Herschel–Bulkley, and Peleg models, selected based on material properties and test conditions [101,105].

4.4.1. Stress Relaxation Test

A stress relaxation test involves applying a low, constant deformation or strain (10–20%), often by compressing the sample (cheese) between two parallel plates of a texture analyzer, while measuring the resulting stress over time. The test assesses how stress decreases to maintain the imposed deformation, providing insight into the material's viscoelastic properties [106,107]. In this test, the response of a material depends on its rheological characteristics. Ideal elastic materials do not show stress relaxation, whereas viscous materials relax immediately. Viscoelastic solids, such as cheeses, display time-dependent relaxation behavior influenced by their structure and gradually relax to a non-zero equilibrium stress [108]. Among milk products, cheese varieties (Cheddar, Kashar, Edam, Gouda, pasta-filata cheese, processed cheese) are the most analyzed using the stress relaxation test, and the generalized Maxwell model, composed of a spring and a dashpot connected in series, is frequently used to interpret the stress relaxation curve [76,105,109]. According to Sahin [110] adding a spring in parallel to the Maxwell model improves its ability to describe viscoelastic materials by including equilibrium stress, as shown in Equation (1) [111,112].

$$\sigma(t) = \sigma_e + (\sigma_0 - \sigma_e) \cdot \exp\left(\frac{-t}{\lambda_{rel}}\right) \quad (1)$$

where σ_e (Pa) denotes the equilibrium stress, $(\sigma_0 - \sigma_e)$ (Pa) represents the decaying stress component, λ_{rel} is the relaxation time, and t is the decay time.

4.4.2. Creep Test

Creep refers to the tendency of solid materials to undergo slow and continuous deformation over time when subjected to a constant load (stress). Accurately assessing creep behavior requires maintaining constant load and temperature conditions while monitoring the sample's deformation (strain) over time [113]. In food materials, creep testing is commonly performed in compression due to the simplicity of the method, which eliminates the need for complex gripping or fixation systems [108]. In a creep test, the key parameters are compliance, defined as the strain-to-stress ratio, and relaxation time [101,114]. According to Sharma [115] creep tests are more frequently used in viscoelastic studies of cheese, particularly for pasta-filata varieties, due to their ease of implementation and practical relevance in describing material behavior. Viscoelastic behavior is commonly described using mechanical models composed of springs (elastic behavior) and dashpots (viscous behavior) arranged in various configurations. The Burgers model combines a Kelvin–Voigt element and a Maxwell element connected in series, dividing the creep curve into three parts: instantaneous elastic deformation (Maxwell spring), viscoelastic deformation (Kelvin–Voigt element), and viscous deformation (Maxwell dashpot) [114,115]. The four-element Burgers model, defined by Equation (2), was used successfully to evaluate the creep behavior of mozzarella cheese [116].

$$J = J_0 + J_1 \cdot \left(1 - \exp\left(\frac{-t}{\lambda_{ret}}\right)\right) + \frac{t}{\mu_0} \quad (2)$$

J_0 (Pa⁻¹) represents the instantaneous elastic compliance of the Maxwell Spring, J_1 (Pa⁻¹) represents the retarded compliance of the Kelvin–Voigt element, λ_{ret} (s) represents the retardation time, and μ_0 (Pa·s) represents the Newtonian viscosity of the Maxwell dashpot.

Cheese exhibits viscoelastic behavior, with its elastic-to-viscous response depending on the duration of applied stress. Over short time scales, it behaves primarily elastically, while over longer periods, it gradually flows—even in the case of hard cheeses. This time-dependent deformation means that hard cheeses may not fully recover once stress is removed. Neglecting this property can result in deformation, such as bulging or surface inclination, particularly during distribution and retail, where cheeses of varying consistencies are often stacked without consideration [106]. In the case of mozzarella cheese, Olivares reported that proteolysis during ripening is more detectable through creep tests conducted at elevated temperatures (20, 30, and 40 °C), as the polypeptide network becomes less stabilized and creep compliance values increase [107,116].

The fit of the mechanical model to experimental data can be assessed using statistical parameters (Table 3) such as absolute average deviation (AAD—Equation (3)), the coefficient of determination (R^2 —Equation (4)), mean percentage error (MPE—Equation (5)), mean bias error (MBE—Equation (7)), root mean square error (RMSE—Equation (8)), and chi-square (χ^2 —Equation (6)). These metrics quantify the differences between experimental observations and model predictions [111,117–119].

Table 3. Statistical parameters used to assess the fit of the mechanical model to experimental data.

Statistical Parameters	Equation	Statistical Parameters	Equation
ADD	$\frac{100}{N} \cdot \sum_{i=1}^N \left \frac{y_{exp,i} - y_{prz,i}}{y_{exp,i}} \right \quad (3)$	χ^2	$\frac{\sum_{i=1}^N (y_{exp,i} - y_{prz,i})^2}{N-n} \quad (6)$
R^2	$1 - \frac{\sum_{i=1}^N (y_{exp,i} - y_{prz,i})^2}{\sum_{i=1}^N (y_{exp,i} - y_{prz,average})^2} \quad (4)$	MBE	$\frac{1}{N} \cdot \sum_{i=1}^N (y_{prz,i} - y_{exp,i}) \quad (7)$
MPE	$\frac{100}{N} \cdot \sum_{i=1}^N \left[\frac{y_{exp,i} - y_{prz,i}}{y_{exp,i}} \right] \quad (5)$	RMSE	$\left[\frac{1}{N} \sum_{i=1}^N (y_{exp,i} - y_{prz,i})^2 \right]^{1/2} \quad (8)$
Where $y_{exp,i}$ are the experimental data, $y_{prz,i}$ are the predicted data, N is the total number of data points, and n is the number of model parameters.			

Creep and stress relaxation tests have been performed on various cheese types using different sample dimensions and testing conditions. Creep tests were conducted on thin mozzarella samples (1.3 mm) under constant shear stress (25 Pa) at 20–40 °C for 180 s, or on cylindrical kashar samples (dimension not mentioned) with stress levels ranging between 12.25 and 61.25 kPa applied for 150 s [116,120]. Stress relaxation tests used cubic (2–2.5 cm sides) or cylindrical samples (10–22 mm diameter, 17.5 mm height), compressed to 10–40% deformation at speeds ranging from 1 to 60 mm/min, for durations between 150 and 600 s, at temperatures from 18 to 60 °C, with 25 and 50 mm diameter flat probe [105,111,112,120,121].

4.5. Novel Approaches in Food Texture Evaluation

Texture is essential for both the quality and processing of food products. Because it strongly influences sensory experience and consumer acceptance, developing accurate and innovative methods to measure texture has become a key focus in the food sector [122]. Recent progress has gone beyond traditional sensory panels and tools such as texture analyzers and rheometers, introducing multimodal measurement systems and artificial intelligence (AI). A notable development is the food texture prediction method using multi-

ple measurements and template data, which integrates four types of data—force, vibration, sound pressure, and moisture rate. Instead of relying on separately selected characteristics for each texture type, this approach calculates the distance between measurement data and template data, summarizing results into a distance vector. Using Gaussian Process Regression, the method predicts sensory evaluation values with high accuracy across both solid and semi-solid samples. This approach also allows easy integration of additional measurement modalities as they become available [123]. Artificial neural networks (ANNs) and other machine learning models constitute a significant and transformative development in the evaluation and prediction of food texture and quality. These systems can handle complex, nonlinear datasets and learn from examples, enabling prediction and standardization of food texture and quality. ANNs was successfully applied to yogurt production to identify key factors affecting texture, thereby improving consistency and consumer satisfaction [124]. Similarly, convolutional neural networks (CNNs) assess food texture and visual appeal, while Computer Vision Systems (CVS) detect texture and packaging defects, significantly increasing the scope of automated quality control [125]. Furthermore, AI modeling of fermentation parameters—including temperature, pH, and starter culture activity—has shown promise in optimizing yogurt texture and maintaining process stability [126]. In addition to AI tools, new technologies such as biomimetic electronic skins, electronic noses, and electronic tongues can imitate human touch and sensory perception. Combined with social media analysis of consumer preferences, these innovations help turn subjective sensory experiences into measurable and repeatable data [122]. New techniques using sonic and ultrasonic vibrations, spectroscopy, and similar technologies are now widely applied to measure indirect texture parameters, providing a deeper understanding of the structural and mechanical properties of foods [36]. While traditional mechanical tests offer quantifiable data, they are often limited to specific mechanical properties and may not fully capture overall textural characteristics [127]. Recent studies have explored methods and devices to measure vibrations generated during food fractures, providing detailed insights into texture. A magnetic food texture sensor was designed to mimic the tactile response of the human tooth. This sensor consists of four main components: a probe, a linear slider, a spring, and a circuit board, qualifying the evaluation of force and vibration during food deformation [128]. Future work aims to integrate both force and vibration data to improve texture evaluation. Integrating transducers into testing instruments enables the recording of acoustic emissions during crushing or shearing, allowing for texture assessment through acoustic envelope detection, force–displacement analysis, and evaluation of water activity. Although powerful, acoustic–force coupling methods often require complex setups. A practical acoustic–mechanical detection approach has therefore been developed to provide an effective and reproducible way to monitor textural changes during food processing [127].

5. Conclusions

Milk products display a wide range of textures and consistencies, ranging from low-viscosity liquids like milk and cream to soft, airy foams in items like whipped cream, extending to solid, firm, crumbly, and hard cheeses. Therefore, a comprehensive approach to texture characterization must consider not only the physical properties but also the complex interactions among the product's components. Instrumental methods provide reproducible data to quantify the mechanical properties of milk products, enabling objective texture measurement. Common techniques include puncture, compression, creep, and relaxation tests. Among these, the penetration test is the most frequently utilized method for evaluating the textural properties of solid dairy products. Cone penetrometers are commonly used to assess parameters such as hardness, plasticity, and adhesiveness. The spreadability of butter and similar spreads mainly depends on their formulation, with solid

fat content being a primary determinant of this property. Variations in fat phase structure, fat crystal morphology, and overall formulation can significantly impact these textural characteristics. Although the parameters obtained from Texture Profile Analysis (TPA) are not material constants, being influenced by sample dimensions and test parameters such as compression speed, temperature, and particular strain, they remain valuable for characterizing milk products. Regarding the viscoelastic behavior of dairy, they are efficiently characterized using transient tests, with mechanical models, such as the Maxwell and Burgers models, being valuable tools for interpretation. Stress relaxation tests are commonly applied to various cheese types, while creep tests are preferred for pasta-filata cheeses due to their practicality. These approaches collectively enhance the understanding of dairy product texture behavior. Inconsistencies in sample shape, testing temperature, compression speed, and deformation level contribute to variability in measured textural properties. To enhance the reliability and comparability of texture test data for solid dairy products, it is essential to report key test parameters, including testing speed, probe shape and size, compression level (penetration depth), sample dimensions, and analysis temperature. For semisolid samples, the container dimensions and sample height should also be specified. Nevertheless, instrumental evaluations are essential for correlating physical measurements with sensory perceptions in texture research. Advances in food texture analysis increasingly combine traditional mechanical methods with indirect techniques and artificial intelligence, enabling the more accurate, reproducible, and multidimensional assessment of food quality. Emerging tools, including multimodal measurement systems, machine learning models, and biomimetic sensors, provide deeper insights into structural, mechanical, and sensory properties, supporting optimized processing and consumer acceptance. Future research and industrial practice should focus on integrating these technologies to enhance product quality, efficiency, and sustainability.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The author declares no conflicts of interest.

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