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Review

Food formulation: rheological and tribological determinants of oral processing and flavor perception

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ABSTRACT

Understanding how food behaves during oral processing requires going beyond its chemical composition to integrate rheological and tribological determinants that shape texture, mouthfeel, and ultimately flavor perception. This review examines how viscosity, microstructure, and flow properties govern aroma release and taste perception across liquid, semi-liquid, solid, and emulsion-based foods, while oral tribology elucidates lubrication regimes that drive sensations such as creaminess, smoothness, or astringency during mastication and bolus formation. Particular emphasis is placed on the interplay with saliva, whose proteins and physicochemical properties critically modulate lubrication and sensory dynamics. By combining rheological and tribological approaches termed "rheo-tribology" with sensory analysis, this work highlights integrated mechanisms of flavor release, from controlled diffusion in viscous matrices to tribological transitions at oral surfaces. Formulation strategies using hydrocolloids, proteins, fat replacers, and emulsifiers are detailed, showing how textural engineering can tailor perception and consumer acceptance, particularly in plant-based or reformulated products. Overall, the integration of rheology and tribology provides a comprehensive, physiologically relevant model of oral processing, offering predictive power for designing sensory-optimized foods that balance nutrition, functionality, and pleasure while addressing current challenges in health-driven reformulation and sustainable food innovation.

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1. Introduction: physicochemical and mechanical determinants of sensory perception

Sensory perception of food is governed by both its chemical composition and its mechanical and interfacial characteristics. Within the latter two, rheology and tribology emerge as critical for understanding how food behaves during oral processing and how this behavior translates into textural and flavor experiences (Wolinska-Kennard et al., 2025; Xu et al., 2022). Rheology focuses on how bulk materials deform and flow under applied forces, which directly influences the texture and consistency of food. This behavior is typically characterized using a rheometer to determine key parameters such as viscosity, expressed in pascal-seconds (Pa·s), as a function of shear rate (Zheng, 2019). Viscosity, which is highly temperature-dependent, decreases in most liquids with increasing temperature due to weakened intermolecular forces.

The consumer encounters a wide variety of rheological behaviors, from shear-thinning systems, such as banana purée and fruit concentrates, to shear-thickening or dilatant fluids like cornstarch suspensions, and Bingham plastics exemplified by ketchup and mayonnaise (Rao, 2007). These rheological characteristics directly influence sensory perception, affecting not only mouthfeel and texture but also the dynamics of aroma release and swallowability (J. Chen & Stokes, 2012; Szczesniak, 2002). High-viscosity matrices prolong flavor perception by retaining volatiles, whereas low-viscosity systems facilitate rapid but transient aroma release. For populations with special needs, such as individuals with dysphagia, fine-tuning rheological parameters is vital to ensure safe and pleasant consumption (Dhamodharan et al., 2025; Tuorila & Monteleone, 2009). Moreover, rheology also influences manufacturing and shelf-life by enabling control over flow during processing and maintaining product homogeneity (Panouillé et al., 2016).

While rheology governs bulk flow and deformation, tribology, the science of friction, lubrication, and wear provides insight into the interfacial behavior of foods as they interact with oral surfaces (Joyner, 2019). Tribology, examines the lubrication properties and frictional behavior of thin films formed by food products between two surfaces, often using a tribometer (Shewan et al., 2020). In oral processing, tribology helps understand how food interacts with oral surfaces, influencing texture and mouthfeel (Pradal & Stokes, 2016). Oral tribology, in particular, plays a pivotal role in decoding mouthfeel attributes such as slipperiness, creaminess, and astringency, especially during the final stages of mastication when conventional rheological parameters lose their predictive power (Upadhyay & Chen, 2020). Tribological measurements capture frictional forces between the tongue and palate, thereby elucidating phenomena that relate to perceived smoothness and structural breakdown. This is particularly relevant for emerging food categories like plant-based alternatives, which often face challenges related to unfavorable mouthfeel, described as dry, astringent, or gritty (Moss et al., 2023).

The interaction between dietary proteins and salivary components, such as mucins, modulates lubrication and, subsequently, sensory acceptance (Çelebioğlu et al., 2020). The tribological performance of these interactions is dictated by physicochemical parameters such as viscosity, density, and thermal stability, factors also central to the behavior of bio-lubricants (Nguyen et al., 2016). Glycoproteins like mucins exhibit brush-like glycan structures that stabilize their lubricating function under physiological pressures, offering valuable analogues for designing food systems with optimized oral performance (X. Chen & Li, 2020).

Integrating rheological and tribological analyses thus allows for a more holistic understanding of oral food processing, enabling the prediction and manipulation of flavor release and texture perception across various stages of consumption. In this review, we use the term 'rheo-tribology' to emphasize the joint consideration of tribological and rheological properties in food perception. This interdisciplinary approach is not only essential for advancing scientific knowledge but also provides a strategic lever in food formulation, particularly for the development of innovative, nutritious, and sensory optimized products, whether in traditional foods, reformulated health products, or sustainable plant-based alternatives. The review emphasizes the structure–function relationships of food matrices and the influence of microstructure on flavor perception. A key factor lies in understanding how rheology and tribology contribute to the overall behavior of food products, which in turn opens opportunities to integrate rheological, tribological, and sensory analyses for a more comprehensive perspective.

2. Physical characterization and sensory implications across food matrices

Food products can be categorized based on their flow and deformation behavior which influences their texture, structure and sensory perception. These categories include liquid foods, semi-liquid foods, solid foods, and emulsions, each exhibiting distinct physical characteristics. Liquid foods, such as juices and soups, flow freely and exhibit viscosity variations that impact mouthfeel and flavor release. Semi-liquid or semi-solid foods, like yogurt and sauces, display both fluidity and structure, offering a balance between spreadability and stability. Solid foods maintain a defined shape and require mechanical breakdown during mastication, with textural attributes such as firmness and elasticity playing a key role in oral processing. Emulsions, including milk, mayonnaise, and butter, consist of two immiscible liquids, usually with one dispersed within the other., with their stability and viscosity affecting both mouthfeel and flavor perception. In addition to these descriptive characteristics, Table 1 provides a comparative overview of the physical properties, structural features, and sensory implications that differentiate liquid, semi-liquid, solid, and emulsion food matrices. To provide a methodological basis for the characterization of these properties, the principal instruments employed in the quantitative assessment of rheological behavior in food matrices are presented (Table 2). In the following sections, we will examine how the rheological and mechanical properties of each of these categories shape sensory perception, exploring their impact on mouthfeel, texture, aroma release, and overall sensory experience.

2.1. Rheological properties and sensory attributes of liquid food systems

The rheological properties of liquid foods, including viscosity and yield stress, significantly shape sensory perception during consumption. These parameters affect mouthfeel, texture, and flavor release. Viscosity, which measures a fluid's resistance to flow, is a key factor in mouthfeel. Liquids with high viscosity, such as syrups or cream-based beverages, exhibit increased resistance to flow, which promotes adhesion to oral surfaces and generates sensations perceived as thick and creamy. In contrast, low-viscosity liquids, such as juices or milk, offer minimal resistance to flow, resulting in a thin and watery mouthfeel. Viscosity also affects flavor release, with high-viscosity fluids releasing flavors more slowly, altering the intensity and timing of flavor perception. Temperature impacts the sensory perception of liquid foods. For example, cooled soups and slurry-based products are perceived as thicker due to increased viscosity, highlighting the role of environmental conditions during sensory evaluation. Shear-thinning and shear-thickening behaviors contribute to textural diversity. Shear-thinning liquids, which become less viscous under stress, offer ease of swallowing, benefiting individuals with dysphagia. On the other hand, shear-thickening fluids, which thicken with stress, require more effort to consume.

2.2. Flow behavior and sensory perception in semi-liquid food matrices

Suspensions of solid particles in liquids are commonly found in many products, ranging from liquids with suspended solids to semi-liquid or semi-solid products with complex flow behavior, such as blood, flour-water mixtures, chocolate milk, pulpy fruit juices, toothpaste, powdered drinks, and salad dressings (Denn & Morris, 2014; Tadros, 2017). Semi-liquid foods, like yogurt, sauces, soups, and ketchup, exhibit both fluid and solid-like properties, with specific viscosity and some structural stability. These foods are important in the food industry due to their wide applications. Their long shelf life, ease of transport, and sensory richness contribute significantly to consumer satisfaction and commercial value (Pal, 2024). Yield stress is critical for semi-liquid foods like custards or thick sauces. These products act as soft structured solids until the applied stress exceeds a certain point, creating an initial resistance when first consumed. Depending on the product, this property can enhance sensory appeal and influence consumer satisfaction (Bourne, 2002; De Roos, 2003; Rao, 2007; Scholten, 2017; Steffe, 1996; Szczesniak, 2002; Van De Velde et al., 2015).

The rheological properties of semi-liquid foods, such as viscosity and yield stress, directly influence their sensory perception during consumption. They determine how consumers experience the food in terms of texture, aroma release, and swallowability. For example, high viscosity can slow the release of aroma compounds, providing a longer-lasting and more satisfying flavor experience, while low viscosity allows for faster aroma release, resulting in a more intense but shorter flavor perception. The smoothness and slipperiness of semi-liquid foods also affect mouthfeel. For instance, salad dressings, with their high slipperiness allowing for easier swallowing (J. Chen & Stokes, 2012; Szczesniak, 2002).

Table 2
Instruments used for rheological tests.

Instrument	Purpose / What It Measures	Typical Applications
Rotational Rheometer	Flow behavior, viscosity, viscoelastic properties (steady & oscillatory tests)	Foods, gels, biopolymers, suspensions
Capillary Rheometer	Rheology at high shear rates	Polymer melts, dough, extrusion materials
Cone-and-Plate / Parallel Plate Systems	High-precision shear measurements using small samples	Liquids, soft solids, gels
Viscometer	Viscosity at one or multiple shear rates	Liquids, syrups, oils, dispersions
Texture Analyzer	Mechanical properties (hardness, adhesiveness, cohesiveness, spreadability)	Semi-solid foods, gels, dough, dairy
Dynamic Mechanical Analyzer (DMA)	Temperature/frequency-dependent viscoelastic properties of solids	Biopolymer films, packaging, composites
Oscillatory Rheometer	Storage modulus (G′), loss modulus (G″), LVR	Gelation, structure stability, fermented foods
Extensional Rheometer	Extensional (tensile) rheology	Cheese, gums, dough, gel systems
Microfluidic Rheometer	Rheology with micro-scale volumes	

2.3. *Mechanical properties of solid foods and sensory perception*

Evaluating the textural and mechanical properties of solid foods is crucial for understanding their structural characteristics, enhancing quality control in the food industry, designing processing equipment, and developing mechanical tests that could inform human or sensory profiling studies. Textural parameters such hardness, brittleness, and fracture force provide insights into the texture perception of solid foods. Physiological measurements, including mastication cycle count, sequence duration, masticatory frequency, vertical and lateral amplitudes, and closing velocity, can be correlated to textural parameters of solid foods (Gao et al., 2021; Gonzalez-Estanol et al., 2022). Oral processing of solid foods starts with their breakdown into particles during mastication. Digestion results from both mechanical and biochemical processes that occur in the mouth. During this process, hard foods are reduced in size by the teeth, while soft foods are broken down by the tongue and palate. Saliva plays a key role in moistening and hydrating solid foods before enzymatic breakdown. The mixing of solid food particles with saliva also contributes to safe swallowing (Aguayo-Mendoza et al., 2019; Nishinari & Fang, 2018). For solid foods, key sensory attributes such as hardness, adhesiveness, crunchiness, and tenderness have been identified as critical factors and are frequently examined within oral processing research. Solid foods require oral processing before they can be swallowed safely, and this mechanical breakdown leads to continuous changes in food structure that, in turn, drive the dynamic sensory perception of solid foods (Pascua et al., 2013). Increased hardness of solid foods leads to longer chewing times and elevated muscle activity and jaw movements during oral processing. Crunchiness is a key attribute of hard solid foods such as crackers and biscuits, and in biscuits, this attribute is closely linked to muscle activity during intermediate chewing cycles (Laguna et al., 2013). Tenderness can be evaluated through time intensity sensory measurements as well as oral-processing analyses. Both the initial and subsequent chewing cycles contribute to the perception of food tenderness, confirming that tenderness reflects the ease with which food can be chewed and

Table 1
Overview of physical characteristics and sensory effects across liquid, semi-liquid, solid and emulsion food matrices.

Food matrix	Short definition	Typical examples	Key physical parameters	Main sensory implications
Liquid foods	Continuous fluid phase that flows relatively easily under very small stress; some suspensions might have a small yield stress.	Fruit juices, broths, drinks, syrups.	Viscosity (η) or apparent viscosity (η_a), shear-rate dependence (Newtonian vs shear-thinning/ thickening); temperature dependence	Viscosity governs perceived thickness, mouth coating, flavor release and taste intensity; shear-thinning/ thickening affects ease of swallowing.
Semi-liquid/ semi-solid foods	Systems with both fluidity and some structural elements; flow when stressed but can support light loads; often show yield stress.	Yogurt, custards, sauces, ketchup, pulpy juices, dressings.	Apparent viscosity (typically shear-thinning, shear-thickening is uncommon); time-dependent behavior (thixotropic or rheopectic); yield stress (τ_0); viscoelastic moduli (G′ and G″).	Yield stress affects spooning or squeezing contributing to perceived thickness and firmness; internal structure influences spreadability and aroma release; lubrication and slipperiness affect smoothness and ease of swallowing.
Solid foods	Materials that maintain their structure and require mechanical breakdown; may be brittle, elastic or plastic depending on microstructure.	Biscuits, fruit pieces, cooked meat, bread crust, chocolate (depending on temperature).	Hardness, fracturability/ brittleness, cohesiveness, chewiness, resilience, springiness/ gumminess; particle size during oral breakdown.	Texture perception is dominated by bite/ crispness, chewiness and the mastication pathway; particle breakdown and saliva uptake control bolus formation and subsequent flavor release.
Food emulsions	Biphasic system of two immiscible liquids with one dispersed in the other (O/W or W/O). Phase ratio and interfacial properties strongly influence stability.	Milk, mayonnaise (O/W), butter, margarine, high-fat dairy spreads (W/O)	Viscosity or viscoelasticity; droplet size distribution, volume fraction; microstructure/ morphology; interfacial properties; fat content.	Fat content and droplet size modulate creaminess and mouthcoating; high fat/ viscosity can affect the release of lipophilic volatiles and change flavor profile; thickeners modify flavor release and mouthfeel.

prepared for swallowing (Ilić et al., 2022). Muscle activity, number of chews, and chewing-sequence duration were statistically associated with springiness, firmness, perceived particle size after five chews, and the number of chews assessed by trained sensory panellists (Çakır et al., 2012).

2.4. Rheological properties of emulsions and their influence on flavor release

Emulsions are systems formed by dispersing one immiscible liquid into another, typically composed of oil and water. They are found in various foods such as milk, butter, mayonnaise, and ice cream. Emulsions are mainly classified into oil-in-water (O/W) and water-in-oil (W/O) types, with their behavior influenced by factors like droplet size and composition (McClements, 2004). The rheology of emulsions, which studies their flow and deformation under stress, plays a critical role in understanding food texture, stability, and functionality (Tatar et al., 2017). Rheological measurements help define product characteristics like viscosity, shear-thinning behavior, and elasticity, which influence sensory attributes like texture, mouthfeel, and flavor release. For instance, low-viscosity emulsions like milk allow faster flavor release, while high-viscosity emulsions, such as cream or mayonnaise, release flavor more slowly, providing a longer-lasting, richer sensory experience (Schädle, Bader-Mittermaier, & Sanahuja, 2022a).

Fat content significantly impacts flavor perception in emulsions. Higher lipid levels reduce the release of lipophilic aroma compounds due to their solubility in fat, altering the intensity and profile of flavors. Conversely, reduced-fat formulations can change both aroma and flavor perception, often resulting in a lighter taste (Frank et al., 2011; Schädle, Bader-Mittermaier, & Sanahuja, 2022a). Hydrocolloids used in emulsions also influence flavor release. For example, emulsions with thickeners tend to slow down flavor release, while those with less viscosity provide a more immediate, albeit less intense, flavor (Ferry et al., 2006). The texture and flavor of emulsions are closely linked, i.e., thicker emulsions contribute to creaminess and smoothness, enhancing flavor perception. The rheological properties of emulsions, such as their viscoelastic properties, directly affect how flavors are perceived during oral processing (Bayarri et al., 2007; Linforth et al., 2010).

3. Role of rheology and tribology in texture and flavor perception

3.1. Rheological and physical parameters governing sensory and flavor perception

Beyond measurable physical properties, sensory attributes like creaminess or crumbliness depend on oral processing, including chewing, swallowing, and mouth cleaning, along with interactions with taste and aroma. Understanding these phenomena requires linking food composition, colloidal properties, and oral behavior (Van Vliet et al., 2009). To fully grasp the relationship between food rheology and sensory perception, it is essential to focus on key physical properties influencing taste and mouthfeel: viscosity, density, surface structure, shape and texture interactions. These parameters determine how food behaves in the mouth and modulate flavor release, intensity, and duration, shaping overall sensory experience.

3.1.1. Viscosity as a modulator of flavor release

Viscosity, defined as the resistance of a liquid to flow is a fundamental rheological property of food, significantly influencing flavor perception. Low-viscosity foods, such as water or light beverages, allow tastants to diffuse rapidly across the tongue, leading to quicker recognition of flavors like sweetness or saltiness. In contrast, high-viscosity matrices, such as cream soups or yogurts, significantly slow down the binding to the sensory receptors and release mechanisms of flavor compounds (Boland, 2004; Rao, 2007). Consequently, viscosity modulates the flavor perception (Agarwal et al., 2018). Furthermore, warm, high-viscosity liquids often exhibit more pronounced flavor profiles than their cold counterparts. This interplay between viscosity and sensory properties underscores the importance of rheology in both food formulation and sensory evaluation (Chojnicka-Paszun et al., 2012). Culturally, viscosity preferences may vary: some populations associate thickness with health and richness, while others may prefer thinner consistencies for hydration and freshness. These differences highlight the importance of viscosity not only as a physical property but as a multisensory cue integrated into overall flavor perception and food enjoyment. In product development, adjusting viscosity can be a strategic lever to align a food product with specific sensory targets, whether to enhance creaminess, improve swallowability, or evoke a premium texture profile.

3.1.2. Shape and density factors in sensory dynamics

The physical characteristics of food, such as shape and density, directly impact how flavors are released and perceived. Denser food systems, like gels or puddings, often trap flavor compounds, releasing them gradually during consumption. This controlled release mechanism creates a more sustained flavor profile, enhancing the sensory experience over time. Additionally, the rheological behavior of these foods under shear stress provides valuable insights into how they behave during mastication. For instance, sauces and dressings designed with shear-thinning properties become less viscous as they are stirred or poured, enhancing their palatability while maintaining flavor intensity (Agarwal et al., 2018). In previous studies on salt replacements, it has been reported that substituting sodium chloride (NaCl) with potassium or magnesium salts in products like bread resulted in unpleasant metallic, bitter, and off-tastes. Rama et al. demonstrated that the size of salt crystals influences the rate of salt perception (Rama et al., 2013). Larger salt crystals dissolve more slowly compared to smaller crystals, which extends the duration of the taste perception. Smaller salt crystals enhance perceived saltiness, allowing for reduced sodium content without compromising flavor. Moreover, it is well-established that as the viscosity of hydrocolloid-thickened products increases, particularly when the concentration of the hydrocolloid exceeds the critical overlap concentration, flavor perception decreases. Indeed, increased viscosity reduce tastant diffusion, thereby diminishing flavor perception. The type of hydrocolloid used in a product can also have a significant impact on flavor and taste perception, for example, starch-thickened products tend to show better taste and flavor perception compared to those thickened with xanthan (Agarwal et al., 2018).

3.1.3. Microstructural attributes and their impact on flavor retention

The structural properties of food matrices, especially those involving fiber networks, significantly influence the duration of flavor perception. Foods with intricate microstructures, such as entangled cellulosic fibers, have been shown to slow down the release of tastants and aromas, leading to extended sensory experiences. For example, studies on softwood cellulosic fibers revealed that their gel-like viscoelastic properties retain flavor compounds longer, allowing for a more sustained salty taste perception (Agarwal et al., 2018). These findings suggest a promising avenue for designing functional and plant-based foods that not only meet dietary requirements but also enhance consumer satisfaction.

Beyond fiber-based structures, the microstructure of food matrices encompasses a wider range of physical features that collectively govern flavor retention and release. Key attributes include particle size and distribution, which determine surface area for mass transfer; aggregation behavior and network density, which influence matrix porosity and diffusion pathways; and the size and organization of fat droplets, which are critical for the solubilization and release of hydrophobic aroma compounds. Additional microstructural elements such as starch granules, protein aggregates, air cells, and cellular structures contribute to matrix integrity and its breakdown during oral processing. The distribution of water represents another central factor, as it regulates molecular mobility and consequently the transport of hydrophilic tastants. Moisture heterogeneity or localized water binding can slow diffusion, resulting in prolonged flavor perception. Structural components such as fibers, insoluble particulates, and porosity further modulate both textural properties and the dynamics of flavor release during mastication. Together, these microstructural parameters form an integrated architecture that shapes the kinetics of flavor delivery and overall sensory experience. A summary of the principal microstructural features and their functional implications is provided in Table 3.

3.2. Oral tribology and its functional implications for sensory perception

Tribology is the science of friction, lubrication, and wear in interacting surfaces in relative motion. It examines how surfaces behave when they move against each other and how lubrication affects friction reduction and wear prevention. In the context of food science, oral tribology relates to the perception of food texture through interactions with oral surfaces such as the tongue, palate, and teeth (Sarkar & Krop, 2019). Tribological measurements are diverses (Table 4) and help predict and understand various textural attributes of food, as perceived during eating (Prakash et al., 2013). One of the key tools in tribology is the Stribeck curve, which plots friction coefficients against slidind speeds to distinguish three main different lubrication regimes (boundary, mixed, and hydrodynamic) as depicted in Fig. 1 (Sarkar et al., 2021). The elastohydrodynamic regime is sometimes considered a subset of the mixed or hydrodynamic regimes, particularly when elastic deformation of surfaces and pressure-dependent viscosity play a role (Fig. 1). These regimes describe the different states of lubrication that occur between two surfaces in relative motion, influencing sensory perception (Nguyen et al., 2016).

The composition and structural properties of food, such as fat content (Chojnicka-Paszun et al., 2012), particle size (Sonne et al., 2014), and the presence of emulsions (Qian et al., 2024), play a crucial role in tribological behavior and related sensory attributes. Tribological studies have shown that friction coefficients can be statistically correlated with specific sensory perceptions such as creaminess, astringency, and fat-related texture (Pradal & Stokes, 2016). For example, full-fat yogurts tend to have lower friction coefficients and are perceived as creamier than low-fat versions (Laguna et al., 2017). Tribology also provides valuable insights into astringency. The interaction of polyphenols with salivary proteins can lead to tribo-chemical changes, shifting lubrication from a hydrodynamic to a boundary regime, which increases friction and enhances sensations of roughness and dryness. Techniques such as tribometers and friction testers offer objective ways to quantify these frictional changes, linking them to sensory impact (Gamaniel et al., 2024). Three main tribological regimes (boundary regime, mixed regime and hydrodynamic regime), reflect distinct frictional behaviors in foods, each influencing texture perception in different ways.

3.2.1. Boundary lubrication regime

The boundary regime dominates at low speeds, where direct surface contact occurs. High friction in this regime can lead to perceptions of roughness or dryness. For instance, beers with higher friction coefficients in this regime can result in a drier, more astringent sensory experience (Fox et al., 2022). Similarly, in semi-solid food matrices like purees, high boundary friction has been statistically correlated with dense, grainy, or thick sensory attributes, giving the impression of a less lubricated or dry texture (Sharma et al., 2022). This aligns with astringent mouthfeel descriptions in beverages such as non-alcoholic beverages (Fox et al., 2022). Additionally, in plant-based foods, high levels of polyphenols can interact specifically with salivary proline-rich proteins through hydrophobic interactions and hydrogen bonding, leading to the formation of large, often insoluble protein–polyphenol complexes. These aggregates deplete proline-rich proteins and other lubricating components from the salivary film and destabilize the mucosal pellicle, thereby impairing lubrication and increasing the coefficient of friction at the tongue–palate interface (Boehm et al., 2026; Canon et al., 2021; Gibbins & Carpenter, 2013). This tribological shift from mixed or hydrodynamic lubrication towards a boundary regime is now regarded as a key mechanistic basis for the dry and rough sensations statistically associated with astringency in many plant-based matrices (F. N. Brown et al., 2021; Gamaniel et al., 2024; Sarkar, 2024). Moreover, the plant proteins themselves can exacerbate these tribological effects: due to their lower solubility, greater propensity for aggregation, and reduced

Table 3
Food microstructure and structural distribution.

Component / Feature	Parameter / Property	Typical Range / Notes	Effect on Food Properties / Examples
Particles / Cells	Size	10–500 µm (plant cells), 50–200 µm (animal cells)	Texture, chewiness, water retention; e.g., apple, meat
Fat Droplets / Oil Bodies	Size	0.1–10 µm (milk), 1–50 µm (emulsions)	Creaminess, lubrication, stability; e.g., milk, mayonnaise
Protein Aggregates / Networks	Distribution / Density	0.1–5 µm (casein micelles), network porosity varies	Gel strength, elasticity, water binding; e.g., cheese, tofu
Starch Granules / Crystals	Size	5–50 µm (cereal starch), 2–10 µm (tuber starch)	Gelatinization, viscosity, texture; e.g., rice, potato
Air / Gas Cells	Size / Distribution	50–2000 µm	Porosity, lightness, mouthfeel; e.g., bread, meringue
Fibers / Particulates	Size / Density	50–1000 µm	Structural integrity, water retention; e.g., whole grains, fruit pulp
Moisture Distribution	Water content	5–90% depending on food type	Softness, juiciness, microbial stability; e.g., fruits, yogurt
Solid Particles in Suspensions	Particle size / Volume fraction	0.1–100 µm, depends on formulation	Viscosity, mouthfeel; e.g., sauces, dressings
Nano-structures	Nano-scale assemblies	10–500 nm	Stability, texture, nutrient release; e.g., nano-emulsions, protein aggregates

Table 4
Instruments used for the measurement of tribology parameters.

Instrument	What It Measures / Purpose	Typical Applications
Pin-on-Disk Tribometer	Friction coefficient, wear rate under sliding motion	Metals, coatings, lubricants
Ball-on-Disk Tribometer	Friction and wear using a ball sliding on a rotating disk	Lubricants, polymers, thin films
Ball-on-Flat / Ball-on-Plate Tribometer	Friction between spherical and flat surfaces	Food surfaces, soft materials, polymers
Rotational Tribometer	Friction & lubrication under rotational contact	Oils, greases, food lubrication tests
Reciprocating Tribometer (Linear Tribometer)	Friction in back-and-forth sliding motion	Chewing simulation, textiles, food tribology
Universal Mechanical Tester (UMT)	Multi-mode wear, friction, scratch testing	Advanced coatings, composites, surface engineering
Micro-tribometer	Small-scale friction and wear	Microcomponents, microcoatings, biomaterials
Nano-tribometer / AFM Tribology	Nanoscale friction, adhesion, wear	Nanomaterials, thin films, surface chemistry
Rheo-tribometer	Combination of rheology and tribology; lubrication behavior	Food mouthfeel, creaminess, cosmetic formulations
Scratch Tester	Scratch resistance, coating adhesion, wear depth	Paints, coatings, films

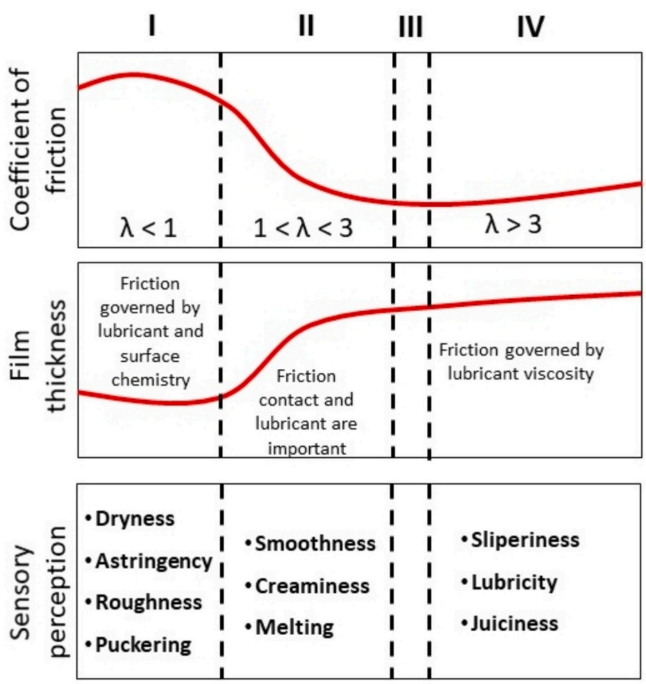

Fig. 1. Lubrication regimes in the Stribeck curve: boundary (I), mixed (II), elastohydrodynamic (III), and hydrodynamic (IV), illustrating frictional behavior across increasing lubrication efficiency (λ represents the ratio of lubricant film thickness to surface roughness). The associated sensory perceptions are indicated for each regime.

adsorption capacity at oral surfaces, unpurified pea and soy proteins form thinner and less elastic lubricating films than dairy proteins, leading to higher mixed-regime friction and requiring nearly twice the fluid film thickness to reach elastohydrodynamic lubrication (F. Brown et al., 2025). Such intrinsic differences in adsorption and film-forming ability contribute further to sensations of dryness or roughness in plant-based formulations, independently of polyphenol-induced astringency.

3.2.2. Mixed lubrication regime

The mixed regime occurs at intermediate speeds, where both fluid film formation and surface interactions influence friction. This balance affects perceptions of creaminess and thickness in sensory analysis. For example, products with moderate oral friction, such as non-alcoholic beers, are often perceived as having a fuller mouthfeel compared to their higher-alcohol counterparts (Fox et al., 2022). In semi-solid foods like purees and cream cheese, friction in this regime is balanced by food viscosity and surface interactions, contributing to a smooth and creamy sensory experience (Sharma et al., 2022).

3.2.3. Hydrodynamic lubrication regime

The hydrodynamic regime dominates at high speeds and is characterized by a thick fluid film separating surfaces. This reduces friction, leading to sensory perceptions of slipperiness, smoothness, and creaminess (Fox et al., 2022; Sharma et al., 2022). In semi-solid foods, such as creamy purees or full-bodied foods, this regime enhances the feeling of lubrication, often due to higher water or creaminess content (Sharma et al., 2022). Similarly, in beverages, lower friction coefficients in this regime contribute to the smooth, slippery mouthfeel observed in non-alcoholic beers (Fox et al., 2022).

4. Tribological dynamics during oral processing

Oral tribology constitutes a critical dimension of food texture analysis, providing mechanistic insights into the frictional and lubricative interactions occurring between oral surfaces during consumption. The interfacial dynamics are particularly relevant during the latter stages of oral processing, where saliva–food interactions and surface contacts modulate key sensory attributes such as smoothness, astringency, and creaminess. The following section will describe and examine tribological regimes roles in shaping texture perception across various food systems.

4.1. Formation and molecular organization of saliva–food surface films

The tribological behavior during oral processing exhibits distinct transitional phases characterized by specific molecular interactions at each stage(Fig. 2). The development of surface films during oral processing involves complex molecular organization processes that significantly influence tribological properties. In the boundary lubrication regime, which dominates during initial food contact, molecular interactions between surface-bound proteins and food components determine the friction coefficient (Fig. 2, Region I). This transitions to a mixed regime during early mastication, where both surface interactions and bulk fluid properties contribute to lubrication (Fig. 2, Region II). Initial saliva protein adsorption occurs through electrostatic and hydrophobic interactions, creating a primary layer that modifies surface properties, reducing friction and facilitating lubrication (Shi et al., 2000). The hydrodynamic regime emerges in later stages of oral processing (Fig. 2, Region III), characterized by complete separation of surfaces by a fluid film, with rheological properties of the food-saliva mixture governing the tribological behavior (Pradal & Stokes, 2016). Subsequent molecular reorganisation involves conformational changes in adsorbed proteins, leading to the exposure of specific binding sites that facilitate secondary interactions with food components. The stability and properties of these films are modulated by local environmental conditions, including temperature-dependent changes in molecular mobility and pH-induced alterations in protein charge distribution (Engelen et al., 2007). In addition to these physicochemical factors, recent work has demonstrated that ionic strength, specifically the presence of salivary monovalent (Na^{+}, K^{+}) and divalent (Ca^{2+}) cations, modulates the structure and lubricating performance of mucin-based films. Increasing ionic concentration screens electrostatic repulsion between negatively charged mucin glycans, alters film organization by inducing compaction or apparent swelling, and leads to a marked reduction in friction coefficients, with higher-valency cations producing stronger effects (Weston et al., 2023).

4.2. Physical and biochemical interactions during mastication

The integration of physical and chemical changes during oral processing creates a dynamic system where mechanical forces influence molecular interactions and vice versa. Shear forces applied during mastication can expose new reactive sites within food matrices, accelerating enzymatic hydrolysis and changing the rate of flavor release (Hoebler et al., 1998). The breakdown of complex food structures follows specific pathways influenced by both mechanical stress and enzymatic activity, with the rate and extent of breakdown determined by the interplay between these factors. Local changes in pH and ionic strength, resulting from the release of food components and salivary buffering, can alter protein solubility and polysaccharide gelation, significantly modifying protein-protein and protein-polysaccharide interactions. These changes influence texture perception and bolus cohesion during oral processing (Prinz et al., 2007).

Therefore, oral processing involves a series of complex interactions and transitions that are key to food texture, lubrication, and sensory perception. The interactions between food matrices, saliva, and oral surfaces result in significant tribological changes during mastication, from friction modulation to bolus formation (De Wijk & Prinz, 2005). The dynamic interplay of mechanical forces, enzymatic breakdown, and

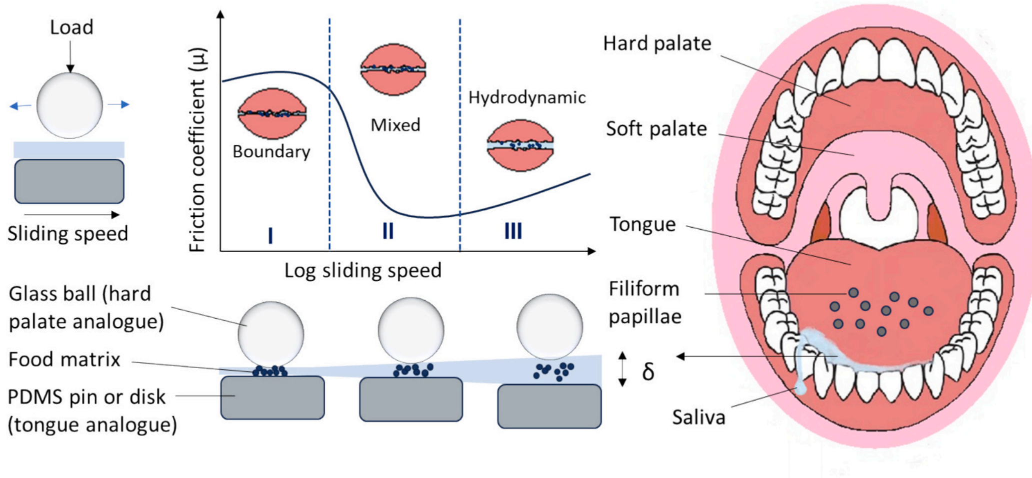

Fig. 2. Saliva-mediated lubrication during oral processing, showing tongue and palate surfaces, the tribology analogue (glass ball and PDMS pin or disk) and saliva or lubricating film thickness (δ) changes across boundary, mixed and hydrodynamic regimes.

salivary components, such as mucins, α-amylase, and proteins, shapes food structure and texture perception, impacting smoothness (Al-Manei et al., 2020), flavor release, and sensory experience (Boichot et al., 2022). Moreover, the oral microbiome influences food breakdown and flavor dynamics, further modifying the sensory attributes of the food (Muradova et al., 2023). Understanding these mechanisms is crucial for reformulation and optimizing structure design, enhancing consumer experience, and advancing the field of food tribology..

4.3. Multimodal interactions between texture and flavor perception

Texture plays a crucial role in shaping our sensory experience of food, particularly influencing the perception of taste. Various studies have shown that the texture of food can significantly impact how we perceive flavors, with smooth, creamy textures often enhancing the sensation of sweetness and richness. This was illustrated in a study showing that pureeing not only altered the release of volatile and taste compounds, but also increased tongue involvement during oral manipulation; together, these texture-driven changes led to a quantifiable loss of flavor and a marked reduction in perceived aroma intensity (Horie et al., 2024). Additionaly, changes in mastication patterns, bolus formation, and saliva incorporation can substantially alter how texture is perceived, highlighting that oral-processing behavior is also a fundamental driver of sensory experience (Van Eck et al., 2019).

The relationship between texture and flavor is not limited to physical properties but also extends to how textures influence our other senses, such as vision and auditory perception (Eremenko et al., 2025). Research indicates that rough-textured foods may be perceived as more flavorful than smoother ones, suggesting that texture can enhance the intensity of taste. This sensory interaction is essential for creating a more complex and enjoyable eating experience, where the texture complements the flavors and affects our overall satisfaction (Breen et al., 2019).

Furthermore, cultural differences and individual preferences play a significant role in texture perception. For example, in Japanese cuisine, texture is highly valued, with a focus on the mouthfeel of ingredients like seaweed and pickled vegetables, which can range from chewy to crunchy. Texture also impacts how much we eat, with soft foods encouraging faster consumption, while chewy foods may slow us down and reduce intake. In conclusion, the interplay between texture and taste is vital in food enjoyment. Chefs and food manufacturers use texture modification to enhance flavor release and overall sensory appeal, creating more satisfying culinary experiences (Breen et al., 2019).

5. Formulation strategies for sensory optimization through rheo-tribology

The effect of rheological and tribological properties of food systems on the binding, retention, and release of flavor compounds is considered of great importance as they directly influence sensory perception (Guichard, 2002). The texture and viscosity of food products determine how flavor compounds are entrapped within the food's structure and the rate at which they are released during consumption. Variations in these properties can lead to significant changes in the balance of perceived flavors in a food material and its sensory experience, either enhancing or suppressing their release, which is crucial for optimizing the flavor profile and flavor delivery of food products. The relationship between these properties and flavor release profiles has been examined in both liquid and semisolid/solid systems, revealing a strong effect caused either by physical binding of the volatile compounds to the food ingredients or by texture specific interactions, as well as by the way food is broken down during mastication.

5.1. Rheological tuning for controlled flavor release in liquid systems

5.1.1. Effects of viscosity and hydrocolloids on flavor and taste release

The binding and release of flavor compounds is closely related to the viscosity of the food matrix. Biomacromolecules (e.g., polysaccharides and proteins) facilitate the binding of flavor compounds by increasing viscosity, while maintaining stability. For example, the use of hydrocolloid thickeners in various food products, even at low concentrations, is a common practice for regulating the product's texture, consistency and flavor (Bylaite et al., 2005; Hollowood, 2002; Lin et al., 2025). It is often considered the main cause of the apparent decrease in flavor release, mainly through two mechanisms: a) reduction of the diffusion rate in the food matrix due to increased viscosity or structure modification (Bylaite et al., 2005; Secouard et al., 2003; Terta et al., 2006), and b) molecular binding interactions between the flavor compounds and the hydrocolloid matrix components (Bylaite et al., 2004, Bylaite et al., 2005; Secouard et al., 2003). However, Bylaite et al. referred to other studies which observed no significant effects of the high viscosity of the food matrix on the rate of aroma release when mastication was included in the experimental procedure (Bylaite et al., 2005). It should be noted that, unlike food systems in a stationary state, where aroma transport occurs through molecular diffusion (resulting in a lower aroma release rate), the mastication process involves eddy diffusion, resulting in a higher aroma release rate from the food surface (Roberts & Taylor, 2000).

A wide variety of hydrocolloids are frequently used in the food industry, such as starch, gelatine, whey proteins and gums (Table 5). Depending on the nature of hydrocolloid used in the food formulation, two types of systems can be formed: a thickened solution, characterized by its viscosity, or a gelled system, characterized by its gel strength. An increasing viscosity of the product's through the incorporation of thickener hydrocolloids at concentrations above the critical coil overlap concentration (c^*) leads to a decrease in aroma and taste perception (Bylaite et al., 2005; Ferry et al., 2006; Hollowood, 2002). It was proposed that the c^* is the concentration at which the hydrodynamic volume occupied by the biopolymer/hydrocolloid start to overlap driving the formation of a supramolecular network (Bayarri et al., 2007; Morris et al., 1981). Above this concentration, the viscosity of the food matrix increases rapidly with the concentration, while flavor perception decrease. In contrast, below this concentration, the hydrocolloid chains move independently, consequently flavor perception is less influenced (Baines & Morris, 1987; Cook et al., 2002; Hollowood, 2002). For example, guar gum had no notable impact on the perception of sweetness or flavor below the c^* concentration. However, above this threshold, the perceived intensity of both attributes gradually decreased as the guar gum concentration increased. The xanthan gum was also found to reduce the sweetness additionally to the sourness and the saltiness (Dhamodharan et al., 2025). The effect is also dependent of the hydrocolloids, for example, the addition of hydroxypropylmethyl cellulose at concentrations above its critical concentration c^* changed the sweetness intensity in solutions containing sweet molecules as sucrose, fructose, aspartame and neohesperidine dihydrochalcone, as well as the salty taste of a sodium chloride solution, but did not affect the sourness or bitterness (Cook et al., 2002). For the same taste modality, such as sweetness with equivalent intensity and similar viscosity in plain water, the effect will vary depending on the hydrocolloid used, but also on the nature of the molecule promoting the taste. While guar gum generally produces stronger reductions than CMC or oat gum, the magnitude of suppression also varies with the sweet compound, being more pronounced for sucrose and fructose than for high-intensity sweeteners like aspartame (Mälkki et al., 1993). These findings indicate that sweetness suppression is not governed solely by the thickener used, but also by the physicochemical properties of the sweet molecules. In line with this, it was demonstrated that maltodextrins at a viscosity of 5 mPa reduced the sweetness of sucrose but had no effect on glucose (Hollowood, 2002; Mälkki et al., 1993). These results emphasizing that the interaction between hydrocolloids and sweet compounds is matrix- and molecule-dependent, rather than determined by viscosity alone.

Starch composition also plays a significant role in modulating aroma release. Indeed, another study showed that additionally to the sweetness suppression an aroma reduction was also observed with an increasing corn starch concentration in a lemon pie. The reduction was much lower for corn starch than expected when compared to other hydrocolloids of equivalent viscosity (Hill et al., 1995). The degree of starch's effect on flavor suppression and release is statistically correlated with its amylose-amylopectin content ratio, which influences the formation of complexes and viscosity (Ferry et al., 2006). Based on the molecular type of the aroma compound, the intensity of the aroma perception will be different using the same thickener type. For example, Pangborn and Szczesniak added sodium alginate to aroma solutions and observed a decrease in butyric acid intensity, no effect on acetophenone intensity, and an increase in acetaldehyde intensity (Pangborn & Szczesniak, 1974). In sour milk, gelatine addition induced a decrease in the fruity intensity of 2-methyl-butanoic acid but had no impact on maltol intensity (Wendin et al., 1997).

5.1.2. Microstructure and interfacial mechanisms governing aroma release in emulsions and hydroalcoholic systems

In the case of emulsions, oil droplet size is strongly connected to texture and significantly affects the release of aroma compounds, regardless of their partition coefficients. In general, smaller oil droplets enhance the diffusion of volatile compounds due to the inverse relationship between droplet diameter and oil–water surface area. As droplet size decreases, surface area sharply increases, facilitating greater volatile diffusion into the water and air phases (Tamaru et al., 2020). Since aroma compounds in o/w emulsions must first transfer from oil droplets to the water phase before being released into the vapor phase, droplet size directly impacts the mass transfer path length and diffusion efficiency. This phenomenon, was observed experimentally, showing for example that limonene, a lipophilic compound, is released in higher amounts from emulsions with ~1 μm droplets compared to 12.5 μm

Table 5
Comparative effects of thickening agents on flavor perception in liquid food systems.

Thickening Agent	Type / Composition	Effect on Aroma Release	References
Carboxymethylcellulose (CMC)	Modified cellulose	Reduces sweetness intensity, especially for sucrose	(Mälkki et al., 1993)
Corn Starch	Polysaccharide (corn, modified)	Less impact on sweetness and flavor perception compared to other hydrocolloids	(Ferry et al., 2006; Hill et al., 1995; Vaisey et al., 1969)
Gelatine	Protein-based gelling agent	Decreases fruity intensity of 2-methyl-butanoic acid in sour milk	(Wendin et al., 1997)
Guar Gum	Polysaccharide	Reduces sweetness and flavor perception above critical concentration (c*)	(Bylaite et al., 2005; Ferry et al., 2006; Hollowood, 2002)
Hydroxypropylmethyl cellulose (HPMC)	Modified cellulose	Changes sweetness and salty taste intensity above c*	(Cook et al., 2002)
Hydrocolloids	Biopolymers (e.g., polysaccharides, proteins)	Decrease in aroma release due to increased viscosity and molecular binding	(Bylaite et al., 2005; Hollowood, 2002; Secouard et al., 2003; Terta et al., 2006)
Maltodextrins	Starch derivative	Reduces sweetness of sucrose but not glucose	(Portmann, 1992)
Oat Gum	Polysaccharide	Least impact on reducing sweetness intensity among tested hydrocolloids	(Mälkki et al., 1993)
Sodium Alginate	Polysaccharide (sodium salt of alginic acid)	Decreases butyric acid intensity, increases acetaldehyde intensity	(Pangborn & Szczesniak, 1974)
Xanthan Gum	Microbial polysaccharide	Reduces sweetness, sourness, bitterness; no effect on saltiness	(Pangborn et al., 1973)

droplets (Karaiskou et al., 2008). A strong correlation has been observed between droplet surface area and release rate, particularly for aroma compounds with high octanol–air partition coefficient ($\log P_{oa}$) values (Tamaru et al., 2020). The influence of droplet size on flavor release was also observed in model emulsions as well as food product like salad dressings (Charles et al., 2000; Tamaru et al., 2020).

With regard to ethanol-containing systems, the chemical composition along with structural organization significantly affects the air–liquid partitioning of volatile compounds. The study of Paraskevopoulou et al. on hydroalcoholic emulsions containing mastic gum oil have demonstrated that factors such as emulsifier type, oil droplet size, lipid phase composition, and temperature critically affect the release behavior of the aroma compounds (Paraskevopoulou et al., 2009). Sodium caseinate proved to be the most effective emulsifier in retaining aroma compounds in comparison to whey protein isolate (WPI) and Tween 40 due to its ability to form dense interfacial layers and interact with aroma compounds in the bulk phase. Aroma release was further modulated by droplet size, with smaller droplets generally enhancing release, at higher temperatures (37 °C and 50 °C) and by lipid type, with butter fat promoting greater aroma entrapment than sunflower oil due to its saturation level and temperature-dependent phase behavior.

Similarly, in model wine systems, interactions between aroma volatiles and matrix constituents significantly impacted volatility. Low concentrations of grape-derived tannins and polysaccharides such as pectin and arabinogalactan generally enhanced aroma release, while higher levels led to compound-specific effects, including salting-out phenomena for hydrophobic volatiles. Additionally, the presence of saliva shifted aroma release dynamics during simulated oral processing, increasing volatility for hydrophobic compounds while retaining hydrophilic ones (Mitropoulou et al., 2011).

5.2. Texture and lubrication engineering in semi-solid and solid food systems

Texture is considered a key aspect of food perception, both before and during consumption. Though not a direct factor in olfactory perception, texture influences aroma volatility by altering the matrix's rheology (Guichard, 2002). Many studies have explored how texture influences flavor binding and release, revealing a complex relationship. Mechanical processes such as shearing or chewing can break down the matrix and increase surface area, further affecting aroma release.

5.2.1. Effects of gel structure and biopolymer matrices on aroma retention and release

The impact of texture has been studied in both model and real systems containing thickeners, such as gel matrices (Table 6). Boland et al. evidenced a decrease in the olfactory intensity of strawberry aroma compounds as the hardness of pectin and gelatine gels increased (Boland et al., 2006). Pectin was also found to reduce both sourness intensity and fruity taste in orange-flavored jelly cubes and strawberry jam (Guichard et al., 1991), while having only a mild suppressive effect on sweetness intensity. Adding higher HPMC concentrations in a solution led to higher viscosity and steadily decreased perceived aroma intensity (Hollowood, 2002). Significant variations in retention and release are observed based on the starch type and the type of bonds involved in aroma compound interactions (Emmanouil et al., 2025). The development of WPI and CMC strong elastic gels through ionic interactions at low pH altered the volatility of incorporated orange oil compounds (Paraskevopoulou et al., 2013). The gel matrix was more effective in retaining terpenic components such as limonene and linalool, suggesting that a denser texture reduced volatile diffusion and evaporation, while the retention of polar aroma compounds like aldehydes (octanal and decanal) remained largely unaffected, indicating that molecular interactions and compound polarity are also important. Similarly, incorporating egg yolk into WPI heat-set gels strengthened the matrix, modulated volatile release, and suppressed undesirable compounds, while GC–olfactometry highlighted key aroma contributors from both ingredients (Paraskevopoulou et al., 2014). Notably, butanoic acid, a rancid/cheesy compound detected in pure WPI gels, was absent in EY–WPI gels, suggesting that modifications in the gel network can selectively suppress undesirable aroma release. Beyond their structural role, dietary proteins can profoundly influence flavor perception by modulating both texture and off-flavor development, particularly in plant-based matrices where protein concentration and type govern the balance between desirable and undesirable sensory notes (Ciancetta et al., 2026).

5.2.2. Role of fat content and fat replacers in texture modification and aroma dynamics

Besides, there is an intricate relationship between fat content, texture, and flavor perception in food products. Fat plays a crucial role in shaping the physical properties of foods by influencing both texture and flavor perception. Fat addition increased both the consistency index and apparent viscosity of dairy custards (González-Tomás et al., 2007). It also reduced the headspace concentration of aroma compounds, with greater aroma release observed in skimmed-milk matrices compared to full-fat ones with greater aroma release observed in skimmed-milk matrices compared to full-fat ones. This effect is statistically linked to the hydrophobicity of the volatiles, as fat more strongly retains hydrophobic compounds (González-Tomás et al., 2007; Keršienė et al., 2008; Nongonierma et al., 2006). In milk gels with 5% fat, aroma compounds primarily dissolved in the fat phase, with minimal interaction with proteins (Nongonierma et al., 2006). In general, fat slows aroma release, and drive a more gradual release pattern (González-Tomás et al., 2007). However, fat reduction is a common practice in the food industry, driven by health concerns and the demand for lower-calorie products. Both fat content and thickener type play a decisive role in aroma release. It was observed that increasing fat level in a lemon-flavored o/w emulsion (5% vs. 30%; whole vs. skimmed milk) significantly influenced the delivery of the lipophilic compound linalool to the nasal cavity, while having little effect on the less lipophilic cis-3-hexen-1-ol. In contrast, cumulative aroma release profiles measured through nose-breath analyses were more strongly governed by the type of thickener, with starch- and CMC-based matrices showing distinct impacts. These release patterns aligned with sensory evaluations, which confirmed perceptible differences in flavor (Arancibia et al., 2011, Arancibia et al., 2015).

The critical role of texture modification in flavor release through fat replacement is also highlighted in a more recent study (Balivo et al., 2024). They reported that incorporating whipped chickpea aquafaba (WAF) and WPI alters the rheological properties of low-fat coffee ice cream, leading to increased hardness and reduced overrun, which in turn affects the release of aroma compounds. Hydrophobic pyrazines were retained longer, whereas phenolic compounds such as guaiacol and 4-vinylguaiacol exhibited increased headspace release, particularly in formulations with higher cream replacement (80% substitution). In another study, it was found that replacing 50% of fat with corn dextrin in processed cheese spread largely preserved the overall aroma release profile compared to the full-fat sample. However, individual compounds responded differently: hydrophobic aromas were more affected than hydrophilic ones, likely due to changes in matrix interactions and diffusion properties (Schädle, Bader-Mittermaier, & Sanahuja, 2022b.

5.2.3. Microstructural and interfacial factors governing aroma diffusion in emulsions and gels

Fat and emulsifier content also affect the release of butter volatile compounds from model margarine emulsions. Hydrophilic volatiles, such as 2,3-butanedione and butanoic acid, were more released in margarine samples with increased fat content (70–80%), whereas lipophilic compounds (2-heptanone, 2-nonanone, 2-undecanone, hexanoic acid, and δ-decalactone) in lower-fat formulations (60%) (Dadalı & Elmacı, 2019). Furthermore, increased fat content was statistically

Table 6
Comparative effects of thickening agents on flavor perception in semi-solid and solid foods.

Thickening Agent	Type / Composition	Effect on Aroma Release	References
Corn Dextrin	Starch derivative	Balances viscosity and aroma release, mimics fat's lubrication	(Schädle, Bader-Mittermaier, & Sanahuja, 2022a)
Corn Dextrin or Lactose Blends	Starch derivative or blend	Maintains aroma release patterns, improves spreadability	(Schädle, Bader-Mittermaier, & Sanahuja, 2022b)
Emulsifier (Lecithin, Mono-, and Diglycerides)	Mixture of emulsifiers	Reduces release of specific lipophilic compounds	(Calligaris et al., 2010; Dadalı & Elmacı, 2019; Karaiskou et al., 2008)
Egg Yolk or Yolk Plasma with whey protein isolate (WPI)	Protein and lipid	Modulates volatile release, suppresses undesirable aroma	(Paraskevopoulou et al., 2014)
Gelatin	Protein-based gelling agent	Reduces sourness and fruity taste, mild effect on sweetness	(Boland et al., 2006; Guichard et al., 1991)
Gellan Gels with Salts	Polysaccharide with salts	Enhances aroma retention with increased gel rigidity, affected by aroma concentration	(Evageliou et al., 2012)
Hydroxypropylmethyl cellulose	Modified cellulose	Decreases perceived aroma intensity with increased viscosity	(Hollowood, 2002)
Inulin	Prebiotic fiber	Restores viscosity, affects release of lipophilic compounds	(Schädle, Sanahuja, & Bader-Mittermaier, 2022)
Microparticulated Whey Protein (MWP)	Protein-based	Increases viscosity beyond full-fat levels	(Schädle, Sanahuja, & Bader-Mittermaier, 2022)
Pectin	Polysaccharide	Decreases olfactory intensity of aroma compounds with increased hardness	(Boland et al., 2006; Guichard et al., 1991)
Polydextrose	Synthetic polymer	Restores viscosity, affects release of lipophilic compounds	(Schädle, Sanahuja, & Bader-Mittermaier, 2022)
Soy Protein Isolate	Protein isolate	Forms coarse emulsion gels, affects aroma release based on compound properties	(Hou et al., 2016)
Soy protein isolate/sugar beet pectin complexes	Protein and polysaccharide complex	Produces fine emulsion gels, affects aroma release based on compound properties	(Hou et al., 2016)
Starch	Polysaccharide (corn, modified)	Enhances stability, affects release of lipophilic compounds	(Arancibia et al., 2011, Arancibia et al., 2015)
Sugar Beet Pectin	Polysaccharide	Forms coarse emulsion gels, affects aroma release based on compound properties	(Hou et al., 2016)
Whipped Aquafaba (WAF) and whey protein isolate (WPI)	Protein and plant-based foam	Increases hardness, affects release of hydrophobic and phenolic compounds	(Balivo et al., 2024)
Whey protein isolate (WPI) and Carboxymethylcellulose (CMC)	Protein and modified cellulose	Retains terpenic components, reduces diffusion of volatiles	(Paraskevopoulou et al., 2013)

correlated with greater hardness, reinforcing the role of fat in textural modifications alongside volatile release behavior. Sensory analysis confirmed more intense butter and cheese flavors in high-fat formulations, whereas a creamier character was more pronounced in lower-fat margarines. Additionally, higher emulsifier (mixture of lecithin, mono- and diglycerides) levels reduced the release of specific lipophilic compounds, likely by forming interfacial barriers that hinder diffusion or increasing emulsion viscosity, thereby restricting volatile migration (Calligaris et al., 2010; Karaiskou et al., 2008). Similarly, slow volatile release and reduced air–gel partition coefficients at equilibrium have been reported for emulsion-filled WPI gels compared to non-gelled systems, suggesting their potential as delivery systems or in fat-reduced foods with improved flavor profile. Higher WPI content led to a more compact gel network and lower volatile release rates, while oil content primarily influenced volatile partitioning at equilibrium (Mao et al., 2014).

Apart from droplet size and emulsifier/thickener type, emulsification process, and resulting microstructure are key factors influencing aroma diffusion across the oil–water interface. It was observed that fine emulsion gels formed using a microfluidizer with soy protein isolate/sugar beet pectin complexes had a more compact interfacial network and greater emulsifier adsorption at the oil–water interface than those prepared with a high-speed shear homogenizer (Hou et al., 2016). This structural difference influenced gel texture, as emulsion gels with smaller droplets exhibited greater fragmentation after mastication. Aroma release depended on the compounds' physicochemical properties, i.e., the hydrophilic ethyl butyrate showed a lower release rate in gels with a denser interfacial network, while the more hydrophobic ethyl octanoate remained unaffected by gel microstructure. Additionally, the thermal effects and shearing are also important when considering controlled flavor release (Lubbers & Butler, 2010). For example, the less textured custard exhibited a higher aroma kinetic release due to heat transfer within the matrix rather than rheological changes.

Structural modification can also result from the type and concentration of auxiliary materials used in food systems, such as salts in gel formation, which subsequently affects flavor release, with the concentration of flavor compounds themselves playing a crucial role. Indeed, increased gel rigidity, achieved through higher calcium chloride levels, enhanced aroma retention at a lower aroma concentration (400 ppm) (Evageliou et al., 2012). However, at a higher aroma concentration (1000 ppm), aroma release was no longer governed by mechanical properties but instead resulted from matrix saturation. Furthermore, when calcium was combined with potassium chloride, increasing calcium levels resulted in greater aroma release.

6. Integrating rheo-tribology and sensory analysis

Taken together, the different formulation strategies highlight how rheological and tribological modulation can be used to tailor texture and flavor perception across diverse food matrices. However, beyond these physicochemical and structural approaches, it is crucial to integrate instrumental data with sensory analysis in order to fully capture consumer perception. The following section will therefore explore the relationships between rheo-tribological measurements and sensory evaluations, providing a comprehensive framework to predict and optimize sensory attributes such as creaminess, smoothness, or oiliness.

Rheology-tribology combines rheological and tribological methods to assess food texture and mouthfeel, supporting links to sensory perception. Oral processing involves a transition from a rheology-dominated regime to tribology-dominated regime. Initially, the bulk properties of food (rheology) dominate texture perception. As the food is broken down and mixed with saliva, the surface interactions and lubrication (tribology) become more significant. Rheological properties help in understanding how food responds to forces such as biting, chewing, and tongue manipulation. Tribology becomes more relevant in the later stages of eating when food particles are smaller, and a thin film of food-saliva mixture forms between oral surfaces. This thin film affects the perceived texture through lubrication and friction (J. Chen & Stokes, 2012). The transition from rheology to tribology explains why certain textural features are perceived differently at various stages of eating. For example, creaminess and smoothness can be affected by the bulk viscosity of the food (rheology) and the lubrication properties of the food-saliva mixture (tribology). Integrating rheological and tribological data provides a more physiologically relevant model of oral processing and enhances the prediction of texture and sensory related attributes such as creaminess and smoothness (Nguyen et al., 2016), but also astringency, slipperiness, dryness, adhesiveness, and roughness across liquid, semi-liquid, and solid food matrices.

Texture perception refers to the sensory experience of a food's physical properties, detected by the senses of touch, sight, and hearing. It involves the interaction between the food's structure and sensory receptors in the mouth—including taste and thermal receptors—and in the nose, particularly the olfactory receptors responsible for aroma perception, all of which ultimately contribute to the perception of various sensory attributes (Table 7). The perception of texture is influenced by the mechanical, geometrical, and surface characteristics of food, which can be measured by rheology and tribology simultaneously or sequentially (J. Chen & Stokes, 2012; Kew et al., 2021). The combination of these methods with sensory analysis is fundamental for improving food formulations because texture plays a crucial role in consumer acceptance and preference, which may additionally differ according to cultures (Engelen, 2018).

Different sensory methods based on trained and untrained (consumers) panels have been developed to evaluate the texture properties of food (Kohyama, 2020). However, the correlation of sensory data with both rheological and tribological data to provide insights into the overall mouthfeel is confined to few works (Laguna et al., 2017; Stokes et al., 2013). A study standing for a first attempt to predict sensory perceptions from a combination of rheological and tribological measurements was conducted on yogurt, in particular for evaluating the sensory attributes such as viscosity and creaminess (Sonne et al., 2014). The predictive ability for sensory viscosity increased when both rheological and tribological data were combined, resulted in a correlation coefficient $r^2 = 0.91$. Viscosity affects the thickness and flow behavior of yogurt, contributing to its perceived smoothness and consistency. Higher viscosity generally results in a thicker, more substantial mouthfeel, which is statistically associated with higher quality. Similarly, the predictive ability for sensory creaminess also improved with the combination of rheological and tribological data, with the correlation coefficient increasing from $r^2 = 0.89$ to $r^2 = 0.97$. Creaminess is statistically linked to the perception of indulgence and quality. Consumers tend to associate creamy textures with premium products, even in low-fat or fat-reduced versions. High viscosity, small particle size, and low friction are key factors for achieving a creamy texture in yogurt. A study carried out on emulsion-filled gels (Mu et al., 2022) concluded that both rheological and tribological properties are highly statistically correlated with creaminess, with viscosity showing a stronger correlation than friction coefficients. Specifically, the combination of apparent viscosity at low shear rates ($0.1\ s^{-1}$ and $10\ s^{-1}$) and tribological parameters (such as the sliding speed at the transition point from zone 2 to 3 in the friction curve and the coefficients of friction f_1 and f_2) can be used to predict creaminess effectively. This relationship is visually summarised in Fig. 3, which illustrates how rheological and tribological parameters can inform perceived creaminess in sensory profiling and influence consumer acceptance. This indicated that the perception of creaminess is influenced by both the bulk rheological behavior (viscosity) and the lubrication properties of the food (tribology). In hydrogels, sensory perceptions such as slipperiness, firmness, elasticity, chewiness, cohesiveness, pastiness, and melting can be explained by a combination of rheological properties (like viscosity, yield stress and gel strength) and tribological properties (like friction coefficients) (Krop et al., 2019). The correlation of rheo-tribology with sensory attributes such as creaminess and oiliness has also been observed in other food matrices, including custard desserts. Indeed, it was found that while rheological measures such as viscosity and viscoelastic properties could be statistically correlated with bulk-related sensory attributes like thickness and stickiness, tribological measures provided additional insights into surface-related sensory attributes like oiliness and creaminess (Godoi et al., 2017). Specifically, the presence of fat significantly influenced the coefficient of friction and the establishment of tribological regimes (Fig. 3), which in turn affected the perception of creaminess and oiliness.

Even if rheo-tribological measures can provide valuable information, they need to be complemented with considerations of saliva's role to fully understand sensory attributes. To illustrate the importance of saliva, for example, a study on custard dessert noted that the presence of saliva during oral processing facilitated the breakdown of food microstructure, which was not fully replicated in the tribological experiments. In addition in another study, it was observed that incorporating saliva into instrumental testing (both rheological and tribological) provides a more realistic simulation of oral processing, leading to better correlations with sensory texture attributes (Sharma et al., 2022). This highlights the importance of considering saliva in the design and evaluation of texture-modified foods, especially emerging plant-based foods.

Integrating tribology, rheology and sensory analysis helps in understanding the complex interplay between food structure, oral processing, sensory attributes, and consumer acceptance. While the integrated rheology–tribology framework offers a powerful approach for linking instrumental measurements to sensory perception, its applicability remains strongly matrix-dependent. Liquid and semi-liquid foods, which form relatively homogeneous oral films, tend to show clearer relationships between viscosity, lubrication, and attributes such as creaminess or smoothness. In contrast, semi-solid and solid foods present additional challenges due to structural heterogeneity, particle size effects, and the progressive breakdown that occurs during mastication. These matrices often require complementary measurements of bolus formation, saliva incorporation, or microstructural evolution to fully capture mouthfeel. Furthermore, only a limited number of studies currently integrate rheology, tribology, and sensory evaluation within a unified framework, highlighting the need for methodological development.

7. Conclusion: integrative approaches for advancing sensory-driven food design

Sensory perception of food does not solely result from its chemical composition, but also fundamentally relies on its mechanical properties.

Table 7
Some sensory attributes of texture perception.

Hardness:	The force required to compress a food item
Cohesiveness:	The extent to which a food can be deformed before it breaks
Springiness:	The degree to which a food returns to its original shape after being compressed
Adhesiveness:	The force required to remove the food that adheres to the mouth during eating
Chewiness:	The amount of work required to chew a solid food until it is swallowable
Gumminess:	The energy needed to disintegrate a semi-solid food to a state ready for swallowing
Crispiness:	The force with which a food breaks when bitten
Crunchiness:	The sound and sensation produced when a food is chewed
Smoothness:	The absence of lumps or graininess in a food
Creaminess:	The smooth and rich texture of a food, statistically associated with dairy products
Fracturability:	The ease with which a food breaks or crumbles
Viscosity:	The thickness or resistance to flow in liquid or semi-liquid foods
Slipperiness	The ease with which the sample slides through the mouth during chewing, often perceived as slimy

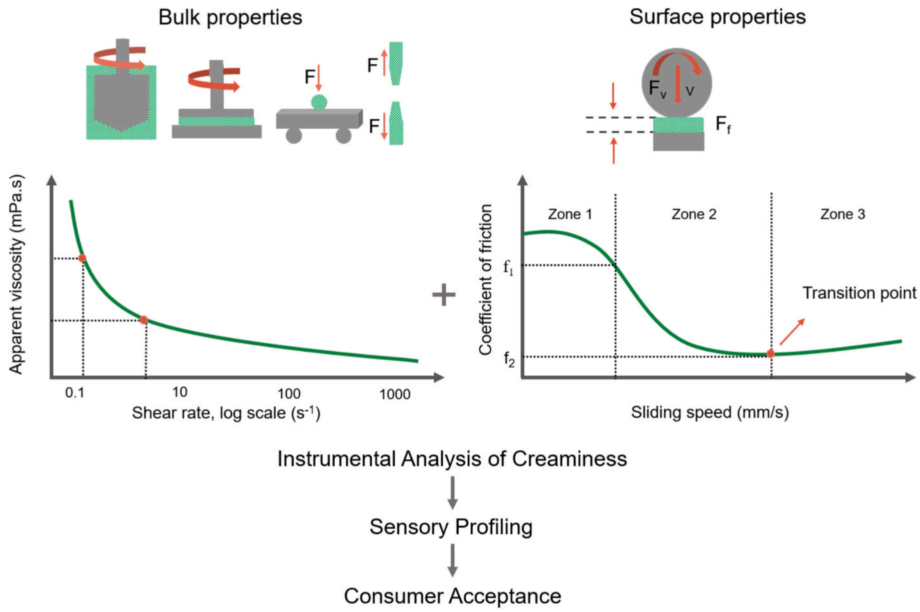

Fig. 3. Integration of rheological and tribological parameters to predict perceived creaminess.

Rheology and tribology provide powerful tools for understanding and optimizing texture, oral processing behavior, and the release of flavor compounds (Fig. 4). Rheology characterizes flow and deformation behaviors, which are essential for designing food matrices tailored to various consumer groups, particularly individuals with dysphagia. Tribology, on the other hand, enables the analysis of frictional interactions between oral surfaces and food, thereby complementing our understanding of mouthfeel, lubrication, creaminess, and astringency. The integration of these two disciplines, in conjunction with sensory analysis, allows for a more refined and objective prediction of consumer perception. The flavor molecules release kinetics depends on the food matrix itself but also on food oral processing, such as mastication behavior and food bolus formation with saliva (Canon et al., 2018; Le Quéré & Schoumacker, 2023). Integrating rheo-tribology with flavor release will enable the development of innovative formulations that balance nutrition, functionality, and sensory pleasure. From this perspective, one of the challenges for the community is to more systematically incorporate saliva into the models. Whether in conventional foods, plant-based alternatives, or texture-modified products, mastering rheo-tribology is becoming a strategic asset in food R&D (Guo et al., 2024). This approach not only enhances perceived quality but also increases the consumer acceptance of more sustainable or specifically adapted products responding to fat or sugar reduction as well as reduction of animal based proteins (McKenzie & Lee, 2022). The type, concentration and corresponding rheological properties of thickeners, along with their interactions with matrix components, are crucial in designing foods. Textural modification through thickeners also promotes bolus cohesion, facilitating safe swallowing and reducing the risk of aspiration-related complications in older adults. Ultimately, this multidisciplinary approach represents a powerful lever for innovation, contributing to the development of foods that are efficient, health-promoting, and sensorially engaging.

Author contribution

Fabrice Neiers, Atefeh Amiri-Rigi, Elsa Brandão, Hatice Kalkan Yıldırım, Adamantini Paraskevopoulou, Alessandra Rinaldi and Nagihan Bostanci coordinated the review concept and manuscript structure. Derya Alkan, Atefeh Amiri-Rigi, Elsa Brandão, Ines Ellouze, Anastasios Grigoriadis, Monica Nabil Gayed Ibrahim, Hatice Kalkan Yıldırım, İbrahim Ender Künili, Mariam Muradova, Azza Silotry Naik, Adamantini Paraskevopoulou, Foteini Pavli, Özge Cemali, Paola Piombino, Alessandra Rinaldi, Mathieu Schwartz, Song Miao, Chi Zhang, and Susana Soares contributed to literature collection, critical analysis, and section drafting. Nagihan Bostanci and Fabrice Neiers performed the final synthesis, critical revision, and harmonization of the manuscript. All authors reviewed, edited, and approved the final version of the paper and agree to be accountable for all aspects of the work.

CRediT authorship contribution statement

Fabrice Neiers: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Derya Alkan:** Writing – original draft. **Atefeh Amiri-Rigi:** Writing – original draft, Supervision, Conceptualization. **Elsa Brandão:** Writing – original draft, Supervision, Conceptualization. **Ines Ellouze:** Writing – review & editing. **Anastasios Grigoriadis:** Writing – review & editing. **Monica Nabil Gayed Ibrahim:** Writing – review & editing. **Hatice Kalkan Yıldırım:** Writing – original draft, Supervision, Conceptualization. **İbrahim Ender Künili:** Writing – review & editing. **Mariam Muradova:** Writing – original draft. **Azza Silotry Naik:** Writing – original draft. **Adamantini Paraskevopoulou:** Writing – original draft, Supervision, Conceptualization. **Foteini Pavli:** Writing – original draft. **Özge Cemali:** Writing – original draft. **Paola Piombino:** Writing – original draft. **Alessandra Rinaldi:** Writing – original draft, Validation, Conceptualization. **Mathieu Schwartz:** Writing – original draft. **Song Miao:** Writing – original draft. **Chi Zhang:** Writing – original draft. **Susana Soares:** Writing – original draft. **Nagihan Bostanci:** Writing – original draft, Supervision, Conceptualization.

Author statement

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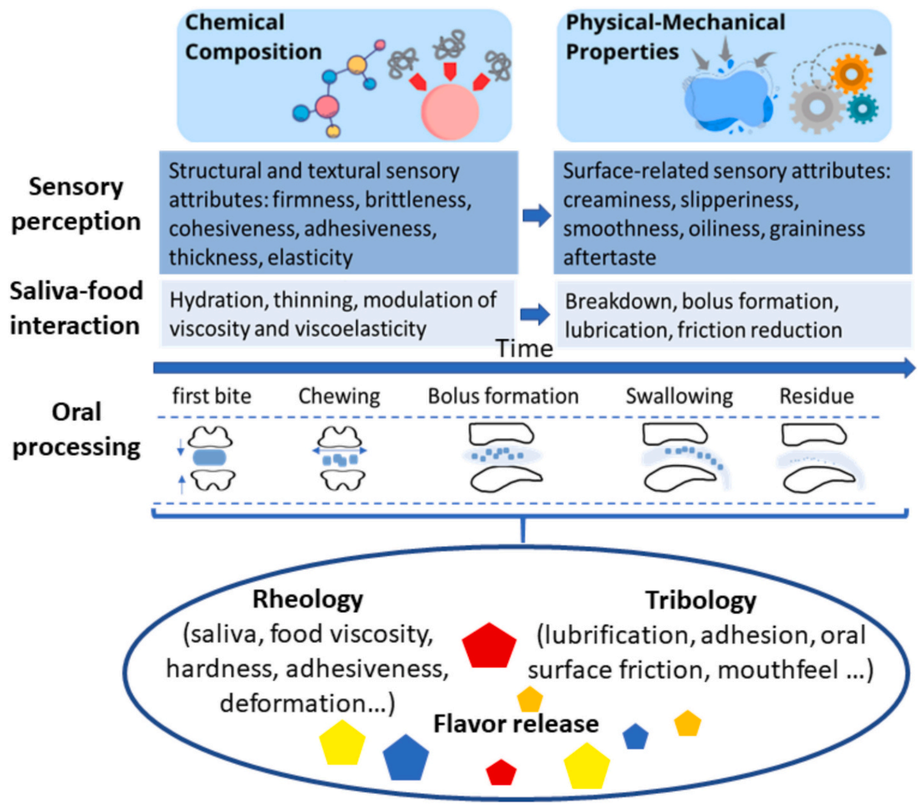

Fig. 4. Integrated rheology–tribology–sensory framework across oral processing.

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Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed.

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