Chapter 7
Tribological and Sensory Properties

Sandip Panda and Jianshe Chen

Abstract Eating, functionalized by mouth physiology, is performed through a series of processes which collectively helps in food ingestion, preparing the food for swallowing, ab-initio digestion, and food sensory perceptions. Sensory properties of food are typically defined by its texture, flavor, and color. Unlike flavor and color, characterizing texture perceptions remain a daunting task because of variegated in-mouth breakdown mechanisms of food depending on several influencing factors. Therefore, it always remains a persisting challenge to correlate instrumental outputs with texture perception. Over the recent decade, principles of tribology—the subject of friction, wear, and lubrication—have been recognized in food sensory research in order to adopt novel instrumental approaches for texture perceptions. This idea of incorporating tribological principles stems from the availability of friction that arises while the tongue manipulates food over the palate during oral processing. Eventually, the terminology such as oral tribology has been introduced, and the subject is rapidly gaining maturity for food sensory applications especially to demonstrate some highly specific sensory descriptions and to define a quantifiable metric for those sensory descriptions. This chapter will revisit the various principles and applications of tribology in pertinence to texture characteristics of food in general and edible hydrocolloids in particular while attempting to identify potential research gaps and future research scopes.

Keywords Food oral processing · Soft tribology · Oral lubrication · Sensory perception · Saliva

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1 Introduction

While our grandmothers, mothers, and great chefs work hard to formulate great recipes of all times to fill our plate with delectable dishes, scientists and researchers are also relentless to find the mystery behind senses of eating. How do we sense food while eating? This is a valid question worthy of scientific interrogations. Food oral processing involves complex and dynamical physico-chemical processes which occur over a shorter time scale (from few seconds to a few minutes at most) inside mouth; and our sensory perceptions during the oral processing depend on a number of factors. The evolution and synchronization of these oral processes and various influencing factors are critical to the success behind the perception and pleasure of eating. Food components vary widely in terms of its structure, texture, and chemistry. However, our perceptions may vary based on the oral physiology and health, condition of saliva, and psychophysical factors such as culture, the geographical location, and of course the availability of food resources, and many hitherto unknown factors. All these factors lead this subject of food oral processing and sensory perception towards many folds of complexity. Influence of many of these factors on food texture perception and mouthfeel are still not well known.

Majority of food sensory research until a decade back was limited to bulk mechanics and rheological experiments and expert panels' assessment despite the realization on the importance of tribology by as early as 1980 (Chen 2009). However, in recent time, there has been a strong inclination towards understanding and enabling methods and principles of tribology in food oral processing. Tribology, being primarily an engineering subject, covers the topics of contact mechanics, friction, wear, and lubrication studies. In the early stage of developments, the subject was growing around mechanical, industrial, and orthopedic applications. However, bringing this subject in to food oral perception research is relatively nascent and opening a new era in food sensory research especially in the direction to adopt more of an instrumental approach in food texture characterization. Laguna and Sarkar (2017) reported sub-quadratic growth in research publication data based on the search with the key word, "oral tribology," over the preceding decade up to May, 2017.

Concerning the thematic limitations, this chapter will primarily focus on applications of tribological principles in food oral processing emphasizing the case studies on food hydrocolloids. In general, food hydrocolloids refer to wide spectrum of edible components; nevertheless, a handful of model hydrocolloids will be referred here in pertaining to various case studies. In the following sections, beginning with an introduction to engineering tribology, this chapter will briefly introduce various concepts and methods of tribology being applied in food oral processing research. Inside oral cavity, tongue and palate constitute a soft tribological system; so, discussions on soft tribology section will be given little more elaboration in this context. Following on, various experimental and analytical techniques will be briefly covered. Few case studies on tribological assessment of food hydrocolloids are also discussed. Finally, the positive hindsight on the prospects of quantitative framework of food sensory perception based on tribological assessment along with associated challenges and future research scopes will be discussed before the chapter concludes.

2 Tribology Basics

Tribology is the subject to study the mechanics and chemistry of interfaces between two surfaces which are moving relative to each other. Beyond the applications in engineering and design of industrial machinery, tribology in recent years has enabled us to understand and explain seemingly diverse phenomenon ranging from macro to cellular scale events such as movement of tectonic plates and glacial ice blocks, animal locomotion and physiology (Stachowiak 2017), and even in cancer growth (Pitenis et al. 2017). Therefore, concepts of tribology, at this stage, draw attention from many disciplines of science and engineering. It is nevertheless important to discuss some of the founding concepts of this subject as part of the present chapter. Figure 7.1 depicts a phenomenological schema of various independent and interdependent events which are likely to occur when two relatively moving surfaces come in contact to form a sliding interface. In a usual sliding process that involves two or three bodies in relative motion, the sliding interface experiences a series of physico-chemical interactions and phenomenological consequences such as friction, wear, and corrosion.

Phenomenological complexity and multi-physical interactions at the interface throw enormous challenges to engineers attempting to design and optimize machine elements such as bearings, gear teeth, piston ring-liner, artificial orthopedic joints,

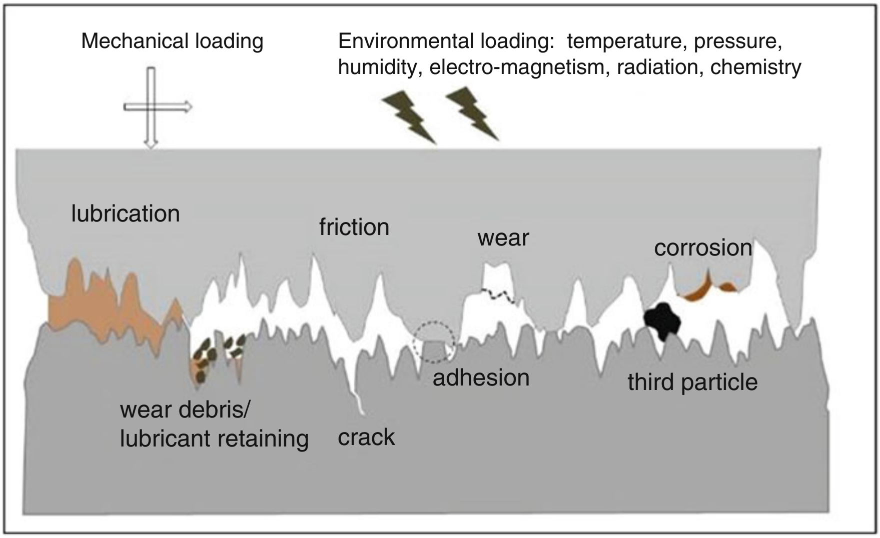


Fig. 7.1 Schema of contact phenomenology of two interacting surfaces

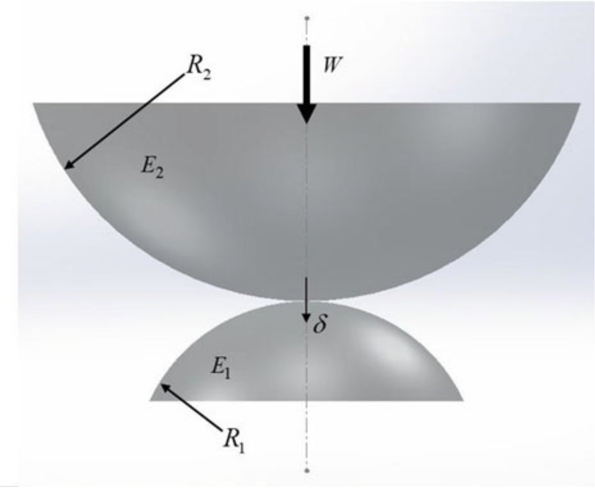


Fig. 7.2 Contact between two spherical bodies (the deformation, δ, shown here is the cumulative deformation of the surface/ point of contact and the down ward direction is assumed for representation)

and more. In the context of food oral processing, tribology of soft oral surfaces, saliva, and food ingredients in pertinence to assess food sensory properties has offered novel set of complex problems in the field and has gathered inter-disciplinary experts to collaborate in this new knowledge development process.

Contact mechanics, macroscopically, in between the nominal boundaries of the physical dimensions of the contacting surfaces, or, microscopically, in between two individual asperities often dominantly impact on the magnitude of friction. Based on classical continuum mechanics, Hertz has derived the first predictive theory for the force-displacement relationship between two spherical bodies building up a circular contact under an ideal hemi-spherical pressure distribution (Timoshenko and Goodier 1951).

Based on the Hertz theory, the mathematical relationships such as contact load-deformation and contact area-deformation can be derived in consistent with Fig. 7.2, where W is the load, a is the radius of circular contact area, and δ is the deformation and the units of the quantities are as per SI system.

$$\text{Contact load}: \quad W = KR^{1/2}\delta^{3/2} \tag{1a}$$

$$\text{Contact radius}: \quad a = (R\delta)^{1/2} \tag{1b}$$

Maximum pressure at the geometric center of contact area,

$$p_{\max} = 1.5W/\pi a^2 \tag{1c}$$

where K = Hertzian modulus, $K = (4/3)\left[\sum_{i=1}^{2}\left(1-v_i^2\right)/E_i\right]^{-1}$ and $R = \left[\sum_{i=1}^{2} 1/2R_i\right]^{-1}$, ($\nu$ = Poisson's ratio)

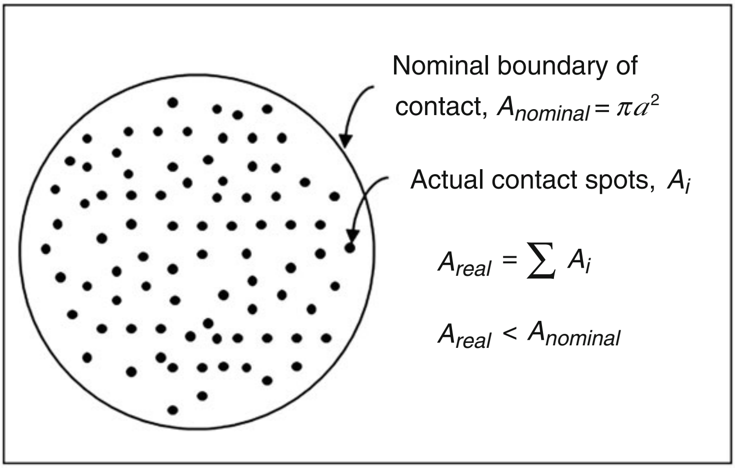


Fig. 7.3 Contact area hypothesis: circular boundary is representing the nominal contact area and black dots are representing actual contact spots over asperities introduced by randomness, hierarchy, and scale of surface roughness

However, the Hertz theory encountered limitations in some practical instances. For example, contact between highly smooth and clean elastic solids under small external load unlikely to follow Hertz theory. In such cases, surface energy associated with the contacting surfaces actively influences the local contact condition, and hence the concept of adhesive contact theory was developed at later stage (Johnson et al. 1971; Fuller and Tabor 1975). Furthermore, every solid surface has small scale geometric features which are called *asperities*. Distribution of these asperities of varying shapes and sizes over the surface space forms the random and hierarchical micro-geometric structure on the surface popularly known as *surface roughness* (Panda et al. 2017). The shape, size, and distribution of asperities are naturally built for biological surfaces and inherited through the controlled production processes for engineering surfaces. Surface roughness is albeit another important consideration in tribology studies. This inherently introduces the randomness, hierarchy, and the scales at which the surfaces come in to contact. Some of these effects in asperity interactions are largely off-limits to observations. In short, the surface roughness introduces the difference between the nominal contact and the real contact area, where nominal contact area is defined by macro-geometric boundary and the real contact area is the summed-up area of all tiny contact spots (Fig. 7.3).

Surface roughness or asperities have been found to have much greater impact on the contact condition and the resulting friction and wear (Greenwood and Williamson 1966; Whitehouse and Archard 1970). It is eventually understood that the contact pressure experienced at the tiny contact spots of individual asperities is much higher than the nominal pressure over macro-contact area since $A_{\text{real}} < A_{\text{nominal}}$. Pressure over asperities often exceeds the strength of materials at interfacial junctions and results in microscopic material failures known as *wear*.

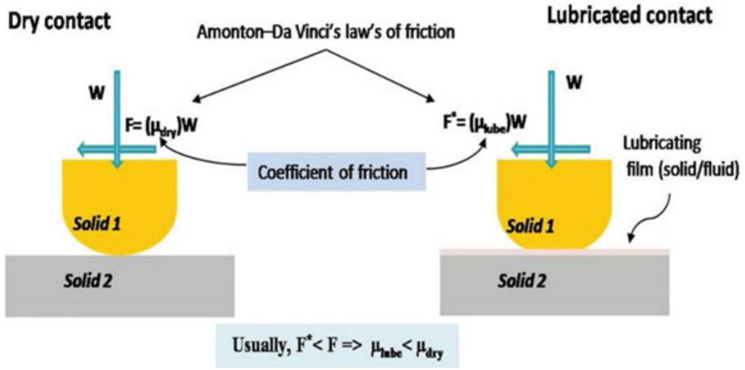


Fig. 7.4 Dry and lubricated contact scenarios

Wear of materials at the sliding/rolling interfaces resulting from the micro-mechanical failures, adhesion, and/or chemical actions are almost inevitable. A preventive action is therefore crucially important to avert excessive wear as well as to alleviate friction at the interface. Thereby, the idea of enabling a sustainable and protective film at the tribo-interface has been developed. Functions of such films are usually engineered to prevent the asperities and surfaces from coming to direct contact during sliding operation, and thereby preventing wear and reducing friction. The mechanism of interfacial film formation and its functions are commonly termed as *lubrication*. The subject of lubrication in industrial context has been well developed and optimized over the entire latter half of the previous century (Stachowiak 2017). However, in the last few decades, the knowledge of lubrication has been extended to several fields such as bio-medical, personal and beauty care product development, food oral processing, and in many other fields. In all these contexts, the use of a lubricating media such as a fluid is vital. In natural systems, the lubricant is naturally present such as synovial fluid in orthopedic joints and saliva in tongue–palate system; whereas in engineering systems, the lubricant is synthetically developed and applied depending on applications. In food oral processing context, saliva and some food compounds such as fat act as lubricating media. It is important to reiterate here that the usual understanding of lubrication is to enable easy in sliding by reducing friction. Figure 7.4 schematically demonstrates the difference between dry and lubricated contacts along with the description of Amonton–Da Vinci's laws of friction (Hutchings 2016).

Engineering insights of lubrication is usually manifested by the *Stribeck* frame work. This frame work describes the variation of coefficient of friction with respect to the product of sliding velocity, lubricants' viscosity, and inverse of normal load. Figure 7.5 shows a typical schematic of the *Stribeck* curve. This is often referred to distinguish between different regimes of lubrications termed as boundary, mixed, elasto-hydrodynamic, and purely hydrodynamic lubrication. For simplicity, the product representing the abscissa of Stribeck curve is termed as bearing parameter.

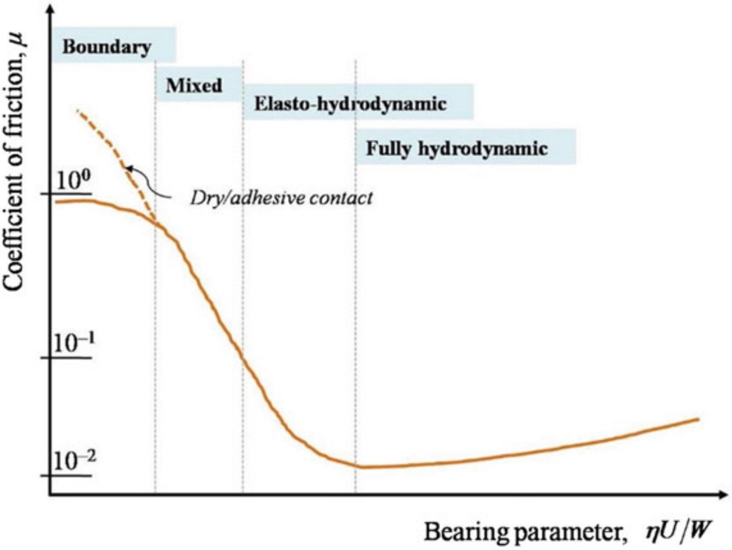


Fig. 7.5 Schematic of the Stribeck framework (η = dynamic viscosity, U = sliding velocity; W = normal load)

From this graph, it can be apparently understood that with the increase in the bearing parameter, $\eta U/W$, the coefficient of friction drops and reaches to minima before starts rising slowly again. This gradual rise in COF occurs in full film condition at high speed and attributes to the fluid viscous friction and turbulence.

Understanding and utilization of Stribeck curve has been increasingly important in oral lubrication context. Firstly, because it is hard to generalize the governing regime of lubrication concerning one typical kind of food–saliva mixture, so presenting the friction response over a range of parametric inputs might give better clarification on friction–sensory relationship. Secondly, it is also naive to claim an absolute value of friction coefficient for a system or material; so, it is more invigorating to produce a map of friction coefficient as a function of parametric inputs. In some attempts to simplify, friction coefficient is often shown as function of speed instead of the product, $\eta U/W$, in the Stribeck curve. Nevertheless, use of only sliding speed in the abscissa of Stribeck curve is actually a compromise since the precise load variation in between the oral surfaces and the real viscosity of the non-Newtonian food–saliva mixture is yet to be known.

Applications of tribology for sensory studies are rapidly emerging. While the model of tongue–food/saliva–palate sliding system can be easily recognized, the challenges persist in establishing an appropriate tribological set-up to replicate this tribo-system. This is critically important to note here that the performance of lubrication is collectively dependent on the whole system and surroundings. Therefore, lubrication and/or friction are not intrinsic properties of any specific material such as food articles in the present context. Some of the most influencing parameters are load, speed, lubricant's viscosity, temperature, interfacial chemistry, surface roughness, and materials' properties. Moreover, oral surface materials are soft biological tissues which exhibit typical visco-elastic behavior. Therefore, mechanics and tribology of soft materials ought to be understood in some details.

3 Soft Tribology in Oral Processing

Soft tribology basically deals with the studies on governing principles behind tribological performances of soft materials such as elastomers, biological tissues, and bio-polymers (Pitenis et al. 2017). From an engineering point of view, solid or semi-solid material systems below elastic moduli of 100 MPa are usually considered as soft materials; however, in biological structures, materials below 100 kPa are commonly found and possess an even ultra-soft characteristic. The low elastic modulus governs the load-deformation behavior of these material systems, the system encounters large deformations even under extremely low load, which makes these systems vulnerable to inaccurate measurements and linear theories of mechanics often become inadequate to describe some of these behaviors. It is likely that soft material behaviors are somewhere in between the solid and fluid constitutive characteristics, so a combined constitutive behavior termed as visco-elasticity needs to be properly evaluated for the soft material systems. From the tribological perspectives of soft materials, large deformation leads to a larger area of contact under small load which drastically reduces the contact pressure, and thereby, exhibits a unique frictional response which is different from most engineering materials such as metals, alloys, and hard polymers.

Any tribological pair can be categorized as hard–hard, hard–soft, and soft–soft systems based on the contacting materials' constitutive behaviors in relative to each other. Measurements and theories have been optimized over the years to bring in our present day understanding on the behaviors of the engineering systems to deal with hard–hard and, to some extent, hard–soft contacts. These developments for conventional systems are nevertheless limited to capture the behavior of soft–soft systems; where each material has non-linear, time dependent, visco-elastic characteristics which often limit the use of linear theories of mechanics. Both in nature and engineering applications, numerous examples of soft–soft systems can be found. Understanding and capturing the behavior of soft–soft tribo-systems therefore have burgeoning research scopes to bring in novel applications and to optimize the existing applications for societal needs. In particulate to oral systems, both tongue and palate are made up of biological tissues and constitutively soft on their surfaces as well as bulk. Noteworthy, the palate is comparatively harder than the tongue. Thereby, tongue–palate system is an excellent example of soft tribology applications in nature which is crucial to food oral processing and sensory perceptions. Figure 7.6 shows a schematic depiction of tongue–palate system.

In the process of eating, at certain stage the tongue manipulates food by sweeping it on the surface of the upper palate. At this stage the friction that arises at the interfaces between food and tongue contributes to certain amount of sensory

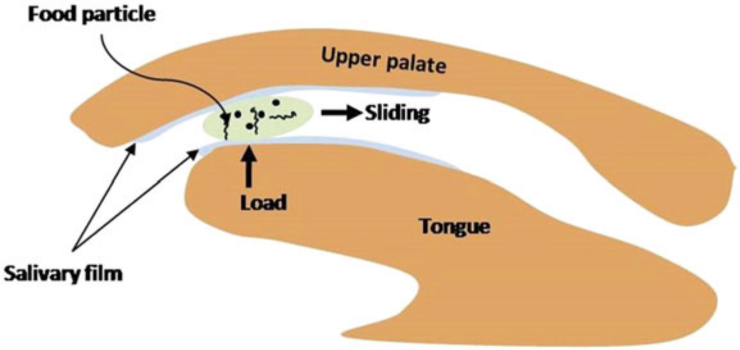


Fig. 7.6 Schematic of tongue–palate tribo-system

perceptions such as smoothness, creaminess, and slipperiness (Kokini et al. 1977; Kokini 1987).

Saliva keeps the oral surfaces protected from bacterial colonization and irritated rubbing. One can perform simple voluntary experiments to check the saliva starved situation on oral surfaces: for example, dry up the tongue and palate by wiping the surfaces with a piece of cotton and then allow tongue to slide on the palate; the irritation can be easily felt. This kind of oral irritation results from the rise in friction by the absence of saliva. In tongue-palate systems, presently it has been well recognized that salivary film works as a lubricant. Friction coefficients of mechanically stimulated saliva roughly fall in between 0.02 and 0.45 when tested in a PDMS (poly-di-methyl-siloxane) ball-on-disc tribo-system; and interestingly, friction coefficient of saliva remained always lower while compared to fresh water under various tribological testing conditions (Bongaerts et al. 2007b). Typically, salvia consists of nearly 99% water and around 1% of other components which include mostly proteins, enzymes, and some inorganic elements. Therefore, the low friction coefficient of saliva as compared to water may be attributed to certain other major components such as mucin proteins. Overall, the viscosity, the coating ability, and the lubricating behavior of saliva are governed by the intertwining actions of various mucins. More detailed information about saliva and the functions of mucin can be drawn from a recent review on age-saliva relationships (Xu et al. 2019), a special issue on food–saliva interactions (Mosca et al. 2019), and a model demonstrating the anchoring of MUC5B mucin on the oral epithelial cells (Ployon et al. 2016).

In pertinence to the lubricating characteristics of saliva, tribological experimentation can be an important instrumental approach for assessing typical sensory attributes such as *astringency*. Astringency is thought out to be due to high friction out of saliva starved situation or saliva breakdown during oral processing of a variety of foods and beverages such as fruits, tea, and wine (Upadhyay et al. 2016; Laguna and Sarkar 2017).

It has been practically important to analyze the soft tongue-palate tribo-system in presence of salivary fluid and food article in order to establish friction-sensory relationships. This is a complex natural system; nevertheless, the theory of soft elasto-hydrodynamic (soft-EHL) lubrication received much appreciation in this context (de Vicente et al. 2006; Bongaerts et al. 2007a). In usual engineering lubrication studies, Stribeck curve accommodates elasto-hydrodynamic lubrication regime as a threshold frictional response before the full film hydrodynamic lubrication. This regime is special because of its dependency on two apparently important factors: (1) the elastic response of contacting materials; and (2) lubricant's piezo-viscous characteristics. Several empirical correlations manifest dramatic increase in the viscosity of lubricants with respect to pressure (Sargent 1983); and this phenomenon is known as piezo-viscous. Thereby, under piezo-viscous situation, an increase in contact pressure results in thickening of the lubricating fluid.

In much opposed to the hypothesis of classical EHL theory, in soft contacts—where elastic moduli are in the order of few MPa or few kPa—an increase in contact load is easily accommodated by more deformation of the soft materials. More contact deformation in turn alleviates contact pressure. This can be simply checked by deploying Hertz contact equations (Eqs. 1a, b, and c) for equal *W* and *R*, and varying *K* for a hard–hard, hard–soft, and soft–soft contacts. The dramatic reduction in contact pressure for soft–soft contacts results in trivial piezo-viscous influences. Also, more deformation at the contact allows lubricant to easily spread out and might result in further alleviation of the piezo-viscous impact. Recently, Masjedi and Khonsari (2017) estimated trivial differences ($<0.5\%$ error for central film thickness) between piezo-viscous and iso-viscous solutions for mixed-EHL contacts of soft materials having elastic moduli of 100 MPa. It is therefore fair to consider an iso-viscous condition for the soft-EHL contacts. Overall, the visco-elastic behavior of soft materials and lubricating characteristic of salivary fluid jointly define the frictional response of tongue–food/saliva–palate tribo-system.

In the theory of lubrication, Reynolds' equation governs the flow and pressure development in the mixed, EHL, and hydrodynamic regimes. The equation is fundamentally a reduced form of the well-known Navier-Stokes' equation which governs the fluid mechanics. A detailed discussion on the derivation and solution of the Reynolds' equation is beyond the scope of the present chapter. However, it is important to include some contextual solutions of the Reynolds' equation: de Vicente et al. (2006) solved the Reynolds' equation for soft-EHL problems concerning food colloids (e.g. xanthan gum, guar gum, etc.) as lubricating media and estimated an empirical formulation of friction coefficient in EHL regime as given below:

$$\mu_{\mathrm{EHL}} = \frac{0.75(\mathrm{SRR})(\eta U)^{0.34}}{R^{0.09}W^{0.12}K^{0.22}} \tag{2}$$

In the above expression, SRR is the slide to roll ratio. SRR can be defined for any given tribo-pair mechanisms (e.g. gear teeth, ball/roller bearings, ball-on-disc, etc.). Mathematically, it is the ratio of *relative* sliding velocity to the *mean* sliding velocity at the center of contact. For instance, in case of a ball-on-disc tribometer, if $U_{\mathrm{ball}} \neq U_{\mathrm{disc}}$, then:

Table 7.1 Tribological case studies on food hydrocolloids

Reference	Experimental details	Coefficients and indices to fit "master" Stribeck curve
(Bongaerts et al. 2007a)	• Ball-on-disc (PDMS-PDMS) • Ball dia. = 19 mm • Composite RMS roughness ~ 27.4 nm • SRR = 0.5; $W = 1.3$ N; $U = 1$–2400 mm/s • Samples: Water; Corn syrup (95%)	$h = 4.75$; $k = 0.11$; $l = 0.07$; $m = 2.7$; $n = 0.5$; $B = 3.8\text{e-}5$ $(10^{-7} < \eta U < 2)$
(Krop et al. 2019)	• Ball-on-disc (PDMS-PDMS) • Ball dia. = 19 mm • Composite cla roughness ~50 nm • SRR = 0.5; $W = 2$ N; $U = 1$–1000 mm/s • Samples: hydrogels ($\kappa-$Carrageenan; $\kappa-$C + locust bean gum; $\kappa-$C+ calcium/sodium alginate)	$h = 11$; $k = 0.0065$; $l = 0.075$; $m = 1$; $n = 0.55$; B = 3.3e-5 $(10^{-6} < \eta U < 10)$

RMS Root mean square, *CLA* Center line average, *SRR* Slide to roll ratio

$$\mathrm{SRR} = |U_{\mathrm{ball}} - U_{\mathrm{disc}}|/U, \quad \text{where} \quad U = (U_{\mathrm{ball}} + U_{\mathrm{disc}})/2 \tag{3}$$

Physically, the value of SRR determines whether the contact is sliding or rolling motion dominated. *SRR* can be 0 for a *pure rolling* condition and 2 for a *pure sliding* condition. Moreover, a value of *SRR* below 1 means that the contact is mostly rolling and above 1 means it is mostly sliding. Notably, *SRR* of the tongue–palate system is hitherto unknown; nevertheless, a value of 0.5 is usually taken in oral tribology experiments. This is albeit counter intuitive. In consistent with the expression of *SRR*, if either disc or ball is static, then SRR = 2. This means, if one element in the tribo-pair is fixed or quasi-static, then the contact predominantly slides. In tongue-palate system, the palate is almost quasi-static with respect to the tongue. Therefore, an *SRR* of more than 1 seems more appropriate choice for oral tribology experiments.

Bongaerts et al. (2007a) attempted to fit a "master" Stribeck curve by covering entire regimes of lubrication and proposed an empirical expression of friction coefficient assuming power law characteristics:

$$\mu = \mu_{\mathrm{EHL}} + \left(\frac{|\nu_{\mathrm{Boundary}} - \mu_{\mathrm{EHL}}|}{1 + (\eta U/B)^m}\right) \quad \text{where,} \quad \mu_{\mathrm{EHL}} = k(\eta U)^n \quad \text{and} \quad \mu_{\mathrm{boundary}} = h(\eta U)^l \tag{4}$$

Further, the coefficients *h, k,* and indices *l, m,* and *n* can be estimated by fitting experimental data with the above equation. Moreover, the value of *B* is the upper limit of η^U for boundary lubrication regime for any given case. It is important to note here that not all but many experimental data may be fitted with the above equation to plot a "master" Stribeck curve. Table 7.1 shows data from two cases on tribological testing of food hydrocolloids, where the above equation has been used to obtain the "master" Stribeck curve.

Significant differences in these two experimental cases are in food samples, tribo–pair roughness, load, and range of speeds. Substantial changes in the fitting parameters are in the values of h and k; notably, h and k are power law coefficients in boundary and EHL lubrication regimes (Eq. 4), respectively. In logarithmic scales, these coefficients determine the intercept on friction coefficient axis. Physically, an increase in h means the boundary friction value rises towards the lower limit of ηU, and a drop in the value of k means, the limiting friction for starting-up EHL regime is reduced. This means, in the case of (Krop et al. 2019), the boundary and mixed regime are elongated as compared to the EHL regime. Therefore, two different studies on different hydrocolloid samples produced two different Stribeck curves. This is a caveat; and the idea of producing generic “master” Stribeck curve for hydrocolloid samples need more data for further optimizations. In fact, some important effects such as surface roughness, hydrophobicity, and presence of surface active elements are hitherto not included. These effects significantly influence the performance of biological surfaces such as the tongue.

Tongue surface is biologically textured with two main types of papillae (Sarkar et al. 2019) covering nearly 70% of the frontal surface area: (1) filly form, without any taste buds and with hair like appearance on top; (2) fungi form, containing taste buds, and has mushroom like appearance. The filly form hairs high around 250 μm are most protruding and taking part in active sliding friction while tongue swipes over the palate. These altogether constitute an intricate micro-geometric structure on the surface of tongue. Saliva introduces further complexity. Mucin in saliva forms a *salivary pellicle* of thickness up to 100 nm by getting adsorbed on the base surface of tongue, and this *salivary pellicle* holds the fluidic structure of the saliva. The salivary pellicle thickness varies and at some point may be nearly vanishing during oral processing. This leads to a saliva starved situation. Sarkar et al. (2019) postulated three types of adsorbed film formation: (1) saliva-rich/deficient film; (2) saliva–food mixture dominated film; and (3) food dominated film. One or more of these adsorption films implicate the food–saliva chemistry which in turn impact on the friction and mechano-sensation during oral processing and generates a series of sensory perceptions such as astringency, creaminess, smoothness, etc.

Furthermore, the soft and protruded papillae textures constitute a spongy structure on the tongue surface. In the presence of salivary papillae and other surface active agents, the microscopic spongy maze on the tongue surface may store certain amount of salivary fluid and mechanically squeeze it out under pressure. This mechanism may possibly develop a salivary fluid film whenever the tongue applies pressure on food/palate. This may resemble the tongue surface structure as *poroelastic* material system. Poroelasticity is usually exhibited by a bi-phasic material system, where a spongy solid structure retains a fluid; and the load-deformation behavior is governed by the solid-fluid interaction. Mammalian cartilage is a striking example of *poroelastic* structure made up of collagen, water, and synovial fluid (Neville et al. 2007). In fact, tongue surface as a poroelastic structure is still a conjecture; and it is clearly naive at present to accept mechanistic behavior of tongue as closely similar to that of cartilage. Future research on the mechanistic aspects of tongue–food–palate contact is likely to bring in more insights in these aspects.

4 Experimental Techniques in Oral Tribology Characterization

In pertaining to tribology–sensory studies, an appropriate *in vitro* experimental methodology is vital in order to ascertain the situations inside oral cavity as closely as possible. Rheology and bulk mechanical experiments have dominated the food oral processing and sensory relationships over many years. The seminal work of Kokini et al. (1977) has produced ab-initio empirical models to establish the role of *friction* in addition to *flow* to provide texture perceptions such as *smoothness*, *slipperiness*, and *creaminess*:

$$\text{creaminess} \propto (\text{thickness})^{0.54} \times (\text{smoothness})^{0.84}, \quad \text{where} \quad \text{smoothness} \propto 1/\text{friction}$$

It can be naively understood from the above correlation that certain texture perceptions depend more on the tribological behavior of the food articles during oral processing.

After a decade, Hutchings and Lillford (1988) have drawn philosophical perspectives on how eating and sensation, both of which are dynamical in nature, could best be correlated with the instrumental methods. The observations hypothesized a three-dimensional "mouth process model" to demonstrate the criterion of swallowing of food following a "breakdown path" which is unique to food, individual eater, and eating occasions. In their model, one typical criterion plane defines the *"degree of lubrication*," where the other two planes are on the basis of *"degree of structure*," and *"time*." The model emphasized the importance of *"degree of lubrication"* and appended difficulties to define it. According to this model, the normal trajectory of food breakdown with respect to *time* in most cases follows a downward direction in the *degree of structure* and in the increasing direction in the *degree of lubrication*; nevertheless, in some exceptional cases such as for peanut butter or sesame paste, the trajectory may move opposite to the normal path at the initial stage of oral process by quickly absorbing saliva before taking the normal direction (i.e. decreasing the *degree of structure* and increasing the *degree of lubrication*) (Nishinari et al. 2019).

Overall, it is understood that a single instrumental approach can be very inadequate to bring in comprehensive correlation between instrumental findings and sensory perceptions, and possibly, a combination of instrumental methods ought to be designed. Surprisingly, this model did not correspond to the earlier findings of Kokini et al. (1977) in regard to the in-mouth lubrication and friction–sensory relationships. Further, despite its comprehensiveness, the Hutchings and Lillford model remained almost unrecognizable until the end of previous decade due mainly to dearth of sophisticated instrumental techniques (Chen 2009).

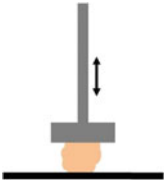
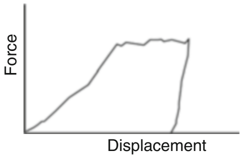
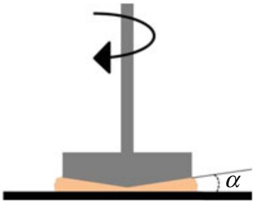
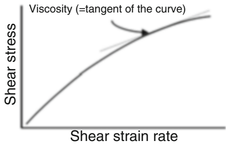
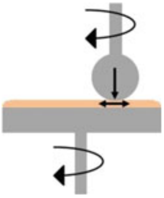
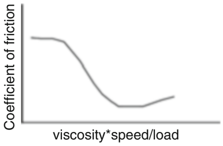
The importance of in-mouth lubrication during food oral processing for both swallowing and sensory perception has been eventually realized. These developments led towards a paradigm shift in the food sensory research which is turning towards the regimes of tribology and rheology instead of mere rheology and bulk mechanics. Chen and Stokes (2012) have illustrated the changes in the governing mechanisms of eating as a function of oral processing time. They highlighted the change in length scale of food articles which undergo changes from centimeter during ingestion to micron/sub-micron scale during swallowing. This change in length scale is governed initially by mechanical breaking, fracture, and bulk deformation and gradually by saliva mixing, moistening, and shearing. Overall, it was understood that eating or food oral processing is a complex dynamical process and so is the sensory perception. Therefore, the sensory attributes also evolve, which means the mouthfeel at an early stage of oral processing may be different than at later stage for the same food component, where the early stage mouthfeel depends largely on bulk mechanical properties and rheology and the later stage, feelings are more linked to thin film shearing resulting in friction and lubrication.

Tribological experiments on food articles have since been recognized as much important as rheology measurements and quality descriptive sensory statistics. Also, in the intermediate stage of oral processing, rheology and tribology jointly contributes to mouthfeel factors in an implicit manner. This framework is particularly useful to classify the growing vocabulary of sensory descriptions based on driving mechanisms of oral processing: mechanics; rheology; tribology; and rheo-tribology. These typical mechanisms can be adopted in instrumental techniques, and further the instrumental outputs can be linked to typical sensory descriptions. Overall, three mechanical instruments, namely, texture analyzer, rheometer, and tribometer, have been adopted and being continuously optimized for analyzing foods and colloids. A comprehensive assessment of food articles for sensory attributes can be largely possible by one or more of these instruments. The instrumental outputs can eventually be calibrated to a metric for instrumental sensory descriptions. Table 7.2 is furnished with some details about these experimental techniques and attached sensory descriptions.

It must be noted here that tribology measurements of food articles depend heavily on the systems and surroundings and thereby tribological parameters (friction/lubrication) are not intrinsic properties of food compounds. With these caveats, it is vital to have better understanding of the systems being used for *in vitro* tribological assessment which include: the instrument, model tribological pairs, model food items, application of saliva, and system operating variables and surrounding environments.

In early stages of oral tribology studies, varieties of tribo-contact configurations and contacting materials were tested. Pradal and Stokes (2016) have reviewed different types of tribo-configurations. Due to available variations on the choice of instruments, material pairs, and model food systems, it is hard to argue over, advantage of one specific system over others. However, there should be clear understanding of the system and surroundings being used. Amongst all, a specialized commercial tribometer, namely, mini traction machine (MTM) has been most frequently used and eventually popularized. The machine is a modified ball-on-disc system; where a combined sliding-rolling motion of the contact is given by rotating both ball and disc and maintaining a constant slide to roll ratio. A schematic of this system can be seen in the last row of Table 7.2, the geometric figure is a

Table 7.2 Instrumental methods in food oral processing in correspondence to sensory studies

Test type	Geometric configuration	Representative test outputs	Textural attributes
Texture property analysis (Mechanical compression)		 (To characterize bulk mechanical strengths)	Hardness, Springiness, Crispness
Rheology (Flow, squeezing, and bulk shearing)		 (To characterize constitutive behavior and viscosity)	Thickness, Pasty, Smoothness, Slipperiness, Creaminess
Tribology (Thin film shearing, sliding, and rolling)		 (To characterize friction at different lubricating regimes)	Astringency, Smoothness, Slipperiness, Creaminess

Note: Textural attributes as noted in the last column are not the direct outcome of the test outputs obtained from any of the tests. In fact, the relationships between test results and sensory attributes are often complex and depend on additional parameters. For example, to use the *force-displacement* curve as an assessment of *hardness*, one needs to know the size and shape of the sample

representative tribometer; however, in the actual MTM machine the ball holder is usually tilted with respect to the disc plane in order to avoid the spinning of the ball with respect to holder axis.

Recent advances in instrumentation and material science have greatly augmented the applications of tribological experiments in food sensory research. Currently, PDMS rubber (*E*~ 1–100 MPa) is the most popular material being used as model tribo-pairs. Soft and visco-elastic behavior, tunable mechanical properties, and excellent formability, which enables advanced manufacturing technology such as 3D printing to process PDMS in desired shapes, sizes and properties, are the reasons behind the popularity of PDMS. However, properties of PDMS are still more than ten times higher than the maximum pressure experienced in oral conditions (Sarkar et al. 2019). This means the effect of contact deformation on lubrication in PDMS–PDMS contact cannot be extrapolated to draw the similar effects in biological contacts. In fact, the challenge persists to address two main aspects here: first, the elastic response of the model components which should be equivalent to biological components; and second, the model surface microstructure and chemistry should mimic the biological surfaces.

Other important aspects of oral tribological experiments are proper and adequate application of saliva to model food samples and to the system. In fact, it is challenging to address the complex salivating process in *in vitro* experiments. Currently, either simulated saliva or artificial saliva is being used to apply on the model surfaces and samples before or during experiments. Presence of saliva on tribo-surfaces is critical to the frictional response of the system; and maintaining the situation in a tribometer set-up needs challenging arrangement such as submerging the PDMS ball/disc in to saliva and/or establishing a supply system to keep applying saliva while the tribometer is running.

5 Case Studies on Tribological Evaluation of Food Hydrocolloids

In particulate to food hydrocolloids, Chojnicka-Paszun et al. (2014) examined the tribology–sensory relationships for model solutions of polysaccharides with protein particle dispersions. Three selected polysaccharide stocks are locust bean gum, pectin, and xanthan; spherical protein particles were mainly abstract from whey protein isolate/locust bean gum gel. Tribological evaluations were correlated with quantitative descriptive analysis (QDA). An attempt has been made in this chapter to summarize some of these findings in Table 7.3 below.

Looking in to these case studies on polysaccharides, it appears that tribological evaluation correlates weekly with the sensory attributes as characterized by QDA scores. In the absence of particle, lubricating ability of xanthan solution is most superior followed by pectin and LBG, respectively. This order is likely to change with the add-on protein particles. Except for pectin, the presence of particles caused dramatic changes in the lubricating ability of xanthan. In the presence of larger particle size, friction coefficient of xanthan solution increases. On the other hand, the change in “powdery” sensation is more prominent in case of xanthan. In fact, LBG without particle has poorest lubrication and paltry powdery sensation; whereas xanthan with large protein particles has superior powdery sensation despite diminishing lubricating ability. These observations are highly counterintuitive, and, therefore, the “powdery” attribute could not be directly linked to friction. Thereby, this attribute can possibly be linked to other mechanical characteristics such as *hardness* or *elasticity* of the tiny protein spheres.

It is intriguingly intuitive to link “slippery” and “stickiness” with respect to lubricating ability of the samples. Nevertheless, “slippery” and “stickiness” loosely relates to tribological evaluations of the polysaccharide solutions. These weak correlations are likely to be influenced by other factors, and may vary sample to sample as well as individual to individual. Overall, the poor reflection of tribological

Table 7.3 Relationships between lubricating ability, protein particle size, and sensory attributes for polysaccharide solutions (data from Chojnicka-Paszun et al. 2014)

Parameters		Ordering of the samples		
		Without any particles	With small protein beads of size 15 μm	With large protein beads of size 56 μm
Lubricating ability[a] ($W = 2$N; $U = 5$–100 mm/s)		**Xanthan>Pectin>LBG**	**Pectin>Xanthan>LBG**	**Pectin~LBG>Xanthan**
Sensory attributes[b]	Powdery	**Pectin>Xanthan>LBG**	**Xanthan>LBG>Pectin**	**Pectin>LBG>Xanthan**
	Slippery	**Xanthan>LBG>Pectin**		
	Stickiness	**Pectin>LBG>Xanthan**		
	Filminess			
	Sliminess			

[a] The ordering of lubricating ability of samples, xanthan (2%), pectin (2.25%), and LBG (1%) are based on **significant differences** in the values of friction coefficient plotted in the Stribeck curve

[b] The ordering of the sensory attributes of samples is based on **marginal differences** in the respective QDA scores

evaluation on sensory attributes indicates that despite tribology has become a vital instrumental approach, nevertheless, additional measurements like fracture properties, hardness, etc. should supplement the tribological evaluation in order to achieve more conclusive correlations.

Polysaccharides are quite common as thickeners in food articles; thereby, tribology–sensory relationships for these compounds are of specific interest. Zinoviadou et al. (2008) studied the role of saliva in tribology, rheology, and spreadability of cross-linked starch and LBG. The addition of saliva dramatically reduces the apparent viscosity, moderately increases friction and slightly enhances spreadability (lower contact angle) for starch samples. Overall, these comparisons attempted to capture the significance of saliva–polysaccharide interactions in oral processing and sensory implications. Furthermore, starch microstructure is more like "spherical" granules, and these shapes can be responsible for low friction; however, after being exposed to saliva, these granules breakdown. Therefore, sustenance of low friction for starch–saliva mixture as compared with pure starch sample was identified as a function of the rate at which the starch granules get affected by saliva induced digestion. The impact of oral processing time on shape and size breakdown of food compounds is therefore critical to its tribological properties and subsequent sensory perceptions. In fact, this study was not conclusive on sensory properties linked to the findings.

In another interesting study, Nguyen et al. (2017) made an appreciable attempt to mix some of the hydrocolloids (gelatin, xanthan, Carrageenan, and modified starch) with low fat skimmed yogurt ($<0.1\%$ fat) in order to arrive at a full fat yogurt experience. The study employs texture, rheology, tribology, and QDA assessment with the selected samples and total of eight different sensory attributes: thickness, smoothness, creaminess, powdery, stickiness, lumpiness, oily coating, and residue coating. From QDA statistics, the gelatin was found to be most influencing hydrocolloids to push the sensory attributes of skim yogurt for enhanced thickness, smoothness, and creaminess. The QDA assessment was in agreement with the instrumental assessments. This study implicates the utilization of hydrocolloids as fat replacements and the establishment of tribology–sensory relationship for their successful characterization.

Recently, Krop et al. (2019) have presented an extensive study on the relationships between tribology, rheology, and sensory attributes for κ-Carrageenan and some inhomogeneous gels prepared by mixing κ-Carrageenan with locust bean gum, sodium/calcium alginate, etc. In particular to "slippery," the Pearson's correlation coefficients for QDA scores of "slippery" with respect to fracture stress, fracture strain, and COF at 50 mm/s appear to be 0.80, 0.80, and 0.82, respectively. These correlations are strikingly consistent and good indicators that slippery is linked to COF and fracture properties; nevertheless, the authors pointed out that "slippery" is indeed a difficult perception and panelists ought to be properly trained to score this attribute. Additionally, on the contrary with the empirical model of Kokini (1987), the "smoothness" perception was not found to be correlated with any of the instrumental outputs; and this situation was attributed to the composite nature of the samples used in the study. Based on the assessments of comprehensive experimental observations (fracture properties; viscosity; and tribology), descriptive sensory analysis, and statistical correlations among the various quantities, the study established certain relationships between mechanical (fracture) and flow properties (viscosity), and texture attributes (smoothness, slippery, pasty, etc.) of hydrocolloids especially at early stages of oral processing.

At the later stages of oral processing, surface properties become more dominant to produce thin film on the oral surfaces, so lubrication/friction characteristics are vital to establish tribology–sensory or rheo–tribology–sensory relationships (Chen and Stokes 2012). In fact, at the early stages of oral processing of hydrocolloids, simultaneous actions of fracture, flow, and friction are crucial to determine sensory perception. It is important to mention here that food hydrocolloids structures may vary widely and ample number of inhomogeneous gel structure may be produced, there by the behavior of food structures under oral processing might vary accordingly. Follow-up studies on hydrocolloids are therefore needed to further consolidate the fracture–flow–friction–sensory relationships.

6 Challenges and Future Prospects

Challenges associated with tribology-sensory research basically originate from the fact that tribological parameters are system dependent and not intrinsic properties of the food itself. The friction/lubrication parameters are highly sensitive to the tribopair material system, model food colloids, operating variables, and environmental influences. Thereby, it requires a number of variables to be controlled in order to mimic the system as nearly as possible to the actual oral processing system. Further, replication of actual oral surfaces is yet to be achieved. Hierarchical surface texture and bulk properties of biological tongue enhances this complexity by manifolds. There have been recent advancements towards a better understanding of tongue surface texture and the mechanics (Funami 2016). Human variation of tongue topography in relation to oral tribology has also been recently investigated in some details (Wang et al. 2019). It can be easily realized that the friction/lubrication characteristics in actual oral processing has strong dependence on the “filly” and “fungi” form structures of the tongue surface. At this stage, it is important to incorporate more of the tongue surface features, material property variations, and surface characteristics such as hydrophobic effects. The motion and dynamics of oral processing are important especially when friction is to be evaluated. Thereby, implementation of actual oral motion (the ratio of rolling/sliding and impact, etc.) and the degrees of freedom that the tongue enjoys can be taken up in follow-up researches.

Saliva–food interaction is another important influencing factor to the sensory perceptions and eating experience as it was aptly put in words, *“what is perceived in-mouth is a food–saliva mixture rather than the food on the plate”* (Mosca and Chen 2017). Thereby, the food–saliva interactions in many cases may result in new compounds as well as very different microstructures, which may eventually impact on the friction and lubrication scenarios. These important effects in oral tribology experiments are yet to be captured.

Sensory perceptions are dynamical functions of food breakdown length scale and oral processing time. It is therefore vital to estimate the duration that a model food samples needs to be exposed in the tribometer in order to synchronize with the "breakdown path." These factors must be duly incorporated and optimized to corroborate the friction–sensory relationships.

7 Summary

The idea of enabling tribological principles in food sensory property assessment basically stem from three basic understanding: (1) saliva is a lubricant; (2) tongue–food/saliva–palate is a natural sliding system; (3) the friction that arises in this natural sliding system relates to a handful of sensory perceptions. The fundamental aim behind this idea is to use friction coefficient in order to arrive at some standard quantitative metric that will determine a particular sensory attribute attached to a particular food component. The impact that these ideas can bring are multifaceted: for example, to devise fat replacements having equal pleasure of fat in order to challenge obesity, to reduce the cost of employing expert sensory panel, to design food for orally impaired patients, and more.

However, tribological experiments depend largely on the systems and surroundings and the system output, usually, the friction coefficient can be variable for same food articles being tested at different set-ups in two different laboratories. Therefore, research community in the field may agree on some standards or protocols for tribological testing with food samples which can avoid redundancies and anomalies. The "master" Stribeck curve is another interesting idea; after proper optimization, a standard "master" curve representing a specific group of fundamental and integrated food articles (e.g. hydrocolloids, dairy colloids, etc.) can be very useful in the field. Further, the tribological characterization is bringing in more comprehensiveness in sensory analysis; and correlation between instrumental outputs with typical sensory descriptions with the help of quantitative metrics can be a striking breakthrough in food sensory studies.

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