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REVIEW ARTICLE

A review on food oral tribology

Wenhu XU, Shuaike YU, Min ZHONG*
School of Mechatronics Engineering, Key Laboratory of Tribology, Nanchang University, Nanchang 330031, China

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Abstract: Food entering the oral cavity undergoes a series of complex processing behaviors. It is subjected to compression and shearing by the teeth, tongue, and palate to reduce its size and mix with saliva until it is swallowed. The oral processing behaviors are thought to be closely related to both food and oral frictional properties. Much effort has been made in recent decades about food oral tribology to explore this complicated lubrication behavior. Understanding the lubrication mechanism of food in the mouth is important for improving the consumption experience and developing the novel food. This paper provides a new perspective on the effects of composition, texture, structure, and saliva-food component interactions on lubrication properties of different foods, the relationship between sensory perception and oral frictional behavior, and the mechanism and pattern of lubrication categorized by common food types. The roles of tribology in the improvement of food taste, the search for healthier ingredient substitutes, functional foods, and the development of green foods are analyzed. Conceptual and numerical prediction models among physical properties, sensory perception, and frictional behavior of food are discussed. Studies of simulating oral processing, such as the selection of friction pair materials, physical modification of contact surfaces, addition of saliva, different modes of motion, and contact forms are concluded and classified. The progress of commercial friction apparatus as well as customized friction devices applied to the food sector in recent years are described. The characteristics, performances, and applications of these tribological instruments are analyzed and compared. In addition, the results achieved by oral tribology in identifying adulterated foods and ensuring food safety are presented. Finally, some suggestions are put forward for the current challenges and future development of food oral tribology.

Keywords: food oral tribology; *in vitro* friction tests; lubrication behavior; Stribeck curve; sensory perception; food development and detection

1 Introduction

In recent years, as the quality of life continues to improve, people's demand for food has no longer just to fill themselves. Healthy, green, nutritious, and palatable food has clearly become the future development goal of the food industry. Designing healthier and more nutritious, functionally rich, and palatable food is the main problem faced at present as shown in Fig. 1 [1, 2]. It requires an in-depth study of the mechanism and pattern of food friction in the oral cavity to solve this problem. Current studies have reported the limitations of rheology in explaining the oral processing of food [3]. For instance, the sensory properties of food products (thickness, smoothness, etc.) cannot be described by their rheological properties. And the use of tribological means can better complement the description of the lubrication mechanism [4]. This new discovery has attracted the attentions of tribologists and food researchers. Tribology is a comprehensive discipline that focuses on friction, wear, and lubrication, involving mechanical lubrication,

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*Corresponding author: Min ZHONG, E-mail: zhongmin00@126.com

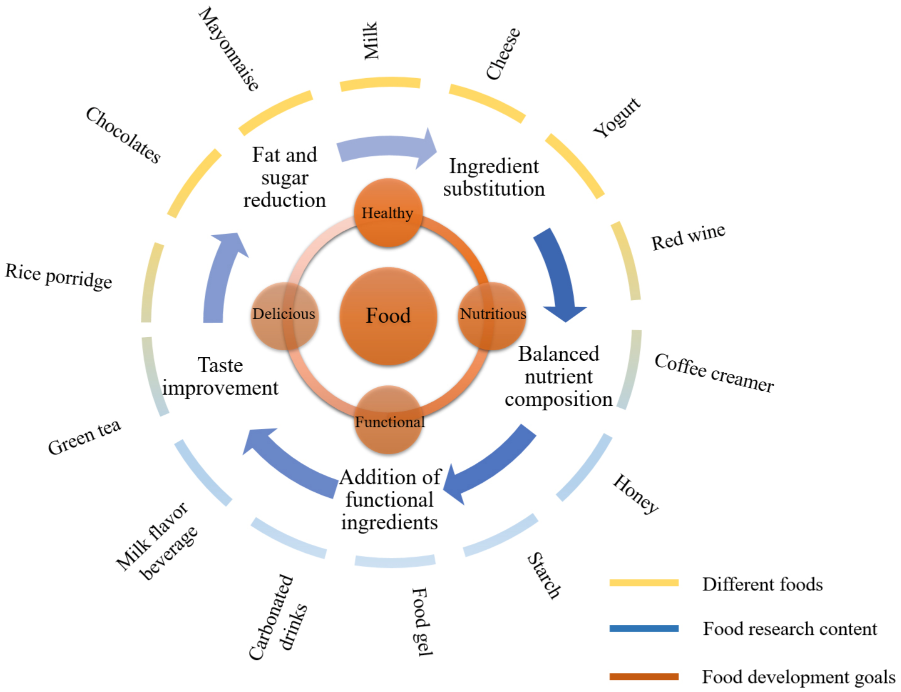

Fig. 1 Food industry development goals, approaches, and common food types.

seals, personal care products, biological friction, automotive products, and many other aspects [5–16]. Numerous previous research results prove that tribology has a bright future in food applications. For instance, tribology can help improve the taste of foods, contribute to the development of healthy foods, and provide a new method for studying oral lubrication behavior and an efficient and rapid mean of food safety testing [17–21].

Food experiences a set of complicated movements after entering the mouth: Teeth chewing, tongue stirring, food-saliva mixing, tongue and upper jaw squeezing and shearing, food mass formation, and swallowing [22–24]. The perception of food texture is related to the mechanical stimulation of the oral surface and becomes different influenced by the properties the oral surface and the components and structures of the food [25, 26]. Many efforts have been made by tribologists to reconstruct the tongue and upper jaw characteristics. For example, rubber, steel, porcine tongue and esophagus, glass, and polydimethylsiloxane (PDMS) have been used in the selection of frictional pair materials [27–29]. In terms of contact forms of tribo-pairs, flat-plate, pin-disc, and ball-disc are applied [30–32]. Different roughness and texture shapes are applied to the contact surfaces so as to change the surface morphology of the friction pairs [33, 34]. For surface modification, wetting treatment is applied [35]. These research results have accelerated the development of tribology in the field of food.

Different foods bring different experiences, which are mainly reflected on the composition of food. For example, theaflavins in tea and tannins in red wine stimulate the tongue to experience astringency, fat in dairy products is associated with creaminess in the mouth, and dietary fiber in bread causes dryness [36–39]. The texture profile method, quantitative descriptive analysis (QDA), and temporal dominance of sensations (TDS) techniques are common methods of evaluating food sensory perception and have played an important role [40–42]. However, it is difficult to evaluate the relationship between food and sensory perception accurately because the evaluation team members are affected by the members' status and training effects. The use of tribological methods in conjunction with them will quantify the relationship more accurately.

The application of tribological instruments in the food industry has also got some progress, and currently common equipment are mini-traction machine (MTM), optical tribological configuration (OTC), high frequency reciprocating rig (HFRR), surface forces apparatus (SFA), etc. [34, 35, 43, 44]. However, great limitations still exist in related research because of expensive instruments. Many scholars have started to work on more flexible, and inexpensive tribological instruments and have achieved some achievements [45, 46]. The authors believe that more tribological instruments for food applications will be developed and put into use in the future. Stribeck curve was used as an important and effective way in tribology to study the lubrication behavior under different working conditions [47]. Nowadays it is applied to explore the lubrication pattern and mechanism of food oral processing [48, 49]. The diversity of food types and the complexity of oral processing both pose great challenges for the application of tribology in the food industry. In addition to the above aspects, food tribology have been conducted in food safety testing and new food research [2, 50]. This also proves that tribology has great potential for applications in food field. Table 1 summarizes the application of tribology in food technology in recent years. The research on the lubrication mechanisms and influencing factors of different food products under oral processing conditions is collectively referred to by the authors as food oral tribology in this review.

This review focuses on the frictional behaviors of different food products, influence factors, and the relationship between frictional properties and sensory perception. Firstly, Section 2 is divided by food groups and describes the physical properties, compositions, structures, and interactions with saliva of different foods followed by their effects on oral lubrication behaviors and sensory perception. Afterwards the role of tribology in improving the tastes of novel foods is described. Section 3 illustrates the numerical modeling of the quantitative relationships among the physical parameters of foods, the prediction of friction coefficients, and sensory perception, and the conceptual models of foods are also explained and discussed. Section 4 describes the efforts of tribologists in simulating realistic oral processing environments for food. Section 5 shows the recent advances in friction equipment used in the oral food tribology. Section 6 presents the new method offered by oral tribology for food adulteration determination. Section 7 proposes the current challenges facing oral tribology of food products and suggestions for the future development.

2 Food oral tribology research

Different types of food properties affect the oral processing and bring us different eating experiences. This section will list the results obtained by tribologists in the study of common foods.

2.1 Milk

Milk is popular with people all over the world as a nutritious and cheap liquid food. However, many young people are not attracted to it since milk tastes inferior to many commercially available beverages. To make milk palatable, it is necessary to study the sensory properties of milk and its lubricating behavior under oral movement. Appearance, aroma, texture, and flavor are all factors affecting the perception of milk [103]. The smooth sensation produced by oral consumption of liquid foods was shown to be related to and frictional forces [104]. Milk is a kind of fluid with low-viscosity, most of the friction comes from the actual contact between tongue and upper jaw, and only a very thin single molecular film will remain in the contact gap [105]. Fat plays a non-negligible role in milk, and Chojnicka-Paszun et al. [38] prepared homogenized milk with different fat contents and tested their rheological and frictional behaviors. When fat content was >1%, the apparent viscosity of milk increased and the curves were clearly differentiated, otherwise the curves almost overlapped. Friction experiments have found that the fat content and the coefficient friction of milk are inversely proportional at the same speed. The friction curve tends to decrease with the increasing fat, and the experiments under silicone rubber illustrate the significant effect of the increasing fat content (>1%) on the friction coefficient, which is thought to be related to shear-induced agglomeration of fat. From the evaluation of the sensory panel (Fig. 2(a)), it is known that there is a certain correspondence between creaminess and fat content. This implies that the act of friction in the mouth influences the sensation of food processed in the mouth.

By evaluating the appearances of milk with different fat contents, the sensory panel found that more fat contents made the milk emulsion less transparent and much whiter in color. This provides an enlightenment for the development of skim milk and

Table 1 Summary of tribological applications to common foods in recent years.

Food types	Designing delicious food	Developing healthy food	Innovating functional food	Food safety testing	Improving swallowing	Reference
Milk	√	√	√	√	—	[18, 19, 21, 38, 51–55]
Yogurt	√	√	√	—	—	[2, 56–60]
Cheese	√	√	√	—	—	[61–65]
Chocolate	√	√	—	—	—	[31, 44, 66–75]
Mayonnaise	√	√	√	—	—	[76–80]
Red Wine	√	—	—	—	—	[81–84]
Starch	√	—	—	—	—	[85–90]
Carbonated drinks	√	—	—	—	—	[91, 92]
Food gel	√	—	—	—	—	[3, 20, 93–95]
Drug	—	—	—	—	√	[96, 97]
Honey	—	—	—	√	—	[50]
Chinese rice wine	√	—	—	—	—	[98]
Coffee creamer	√	—	—	—	—	[99]
Tea	√	—	—	—	—	[100]
Mashed potato	√	—	—	—	—	[101]
Apple	√	—	—	—	—	[102]

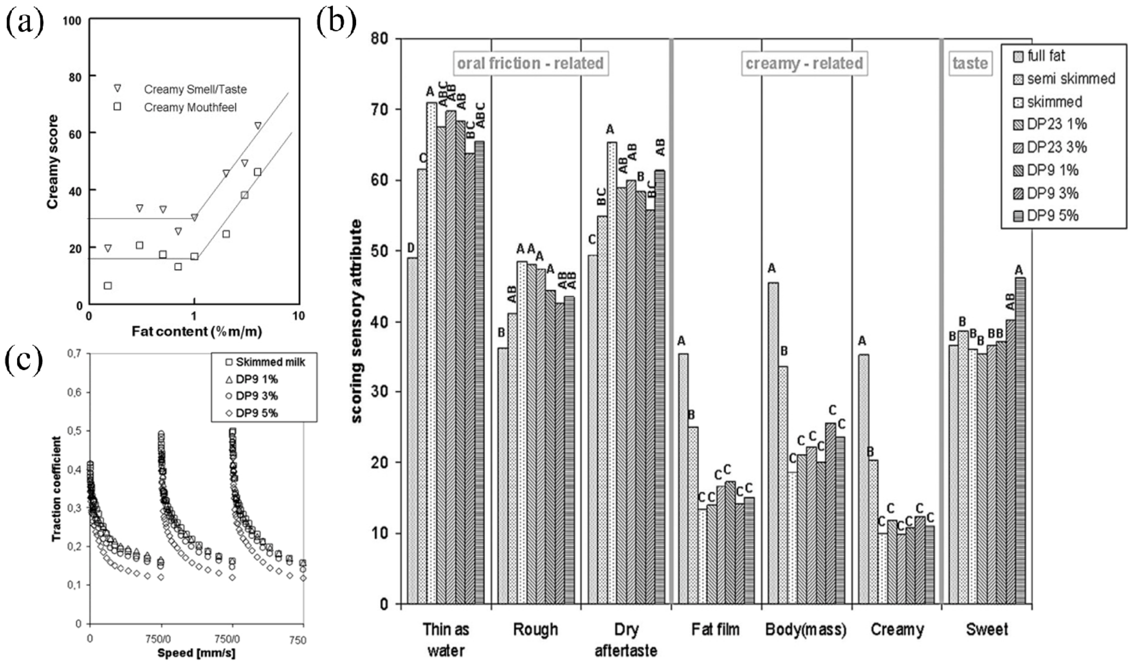

Fig. 2 (a) Relationship between fat content and creaminess evaluation. Reproduced with permission from Ref. [38], © Elsevier, 2012. (b) Sensory evaluation scores of skim milk with inulin and different commercial milk and (c) comparison of traction coefficients of milk with different contents of inulin and skim milk. Reproduced with permission from Ref. [21]. © Wiley, 2011.

inspires people to focus on its appearance attributes along with fat reduction in milk [103]. Influenced by the development of healthy diet, low-fat products are also becoming more and more popular. Because of the lack of fat, nonfat milk loses some of its taste. In order to maintain the same taste as low-fat milk, Meyer et al. [21] used inulin to enhance the taste of skim milk. Inulin as a carbohydrate can be obtained in garlic, onion, banana, and chicory roots [106]. Affected by fiber properties and antimicrobial effects, inulin has a high nutritional and technological value [107]. Previous studies have shown that the addition of inulin can help to increase creamy sensation [108, 109]. It has a large value in replacing fat and improving the texture of emulsions. Two inulin powders with different degrees of polymerization (DP9 and DP23) were prepared, added to skim milk in different proportions, and evaluated by the sensory panel together with fat-containing milk (Fig. 2(b)). The sensory properties of skim milk after the addition of inulin are more similar to those of low-fat milk (thin as water, dry aftertaste). Friction-related attributes do not have a significant impact (except for DP9 3%). As the inulin content increased, the overall friction coefficient of milk showed a decreasing trend, which improves the perception of milk in the mouth (Fig. 2(c)). Another fat substitute: Phytosterols have also attracted the interest of the food industry. It has a similar structure with cholesterol, but does not contain any calories and has some medical value [55, 110]. However, the addition of phytosterols may affect the milk eating experience. In the study of milk added phytosterols, it is found that this component can improve the lubrication of the emulsion without losing the taste of milk itself [51].

Laguna et al. [54] investigated the effects of saliva and fat on milk and found that the friction behavior of milk can be distinguished at high speeds. Milk with different fat contents has different sensory experience, but this difference will not be reflected in rheological properties. Pasteurization is a common processing method for milk, and different pasteurization methods may cause different effects on the texture of milk, for example, ultra-pasteurization can cause flavor changes in milk [111]. In the study of milk lubrication behavior, different pasteurization methods and storage time were used to treat milk with different fat contents. However, it was found that the effect of pasteurization on lubrication behavior was limited compared with storage time, which was due to the three-dimensional structure produced by the binding of whey protein and casein micelles [53]. Compared with pure milk, milk-flavored beverages are more popular among young people due to their diverse flavors and certain nutritional values [112]. Zhu et al. [52] investigated the effects of different hydrocolloid and whey protein casein ratios on the frictional behaviors and rheological properties of chocolate milk. Experiments have found that an increase in the proportion of whey protein in emulsions can improve the lubrication and viscosity of chocolate milk, and the correlation between the friction coefficient and sensory attributes (powdery sensation, astringency) was obtained.

2.2 Yogurt

Enhancing the functionality of yogurt has also attracted widespread attention from the dairy enterprises. Inulin and agave fructans can significantly improve the sensory characteristics of low-fat yogurt [59]. Scanning electron microscopy (SEM) showed that (Figs. 3(a)–3(c)) the yogurt with agave fructans covered the casein micelles, which was affected by the surface fructose, forming a more concentrated casein network, and the yogurt with inulin formed secondary gel structure. The oscillatory shear test showed the correlation between the viscoelasticity of yogurt and the sensory evaluation. Ng et al. [57] also confirmed the possibility of inulin as an added ingredient in their experiments. The addition of inulin did not significantly affect the original texture and perception of the yogurt. Kieserling et al. [2] reported that the addition of orange fiber derived from plants increased the nutritional and functional properties of yogurt. It was found that low concentration of fiber has less effect on the texture and can reduce the dehydration of yogurt. High concentration of fiber (especially coarse fiber) affects the perception of granularity, accelerates the construction of fiber network, forms a tighter matrix (Figs. 3(d)–3(f)), and increases the coefficient friction. This is because coarse fibers hinder the formation of casein network, while fine fibers act as fillers to stabilize the network. Micronized whey protein (MWP) was studied as an alternative to fat [18], and the trend of Stribeck curves and friction behaviors were analyzed to verify the possibility of MWP as a fat alternative. Fish gelatin–anion polysaccharide (FG–AP) complexes were explored as yogurt additive ingredients by Huang et al. [56]. It replaces fat and enhances the smoothness of the emulsion. The experimental results demonstrated that the yogurt

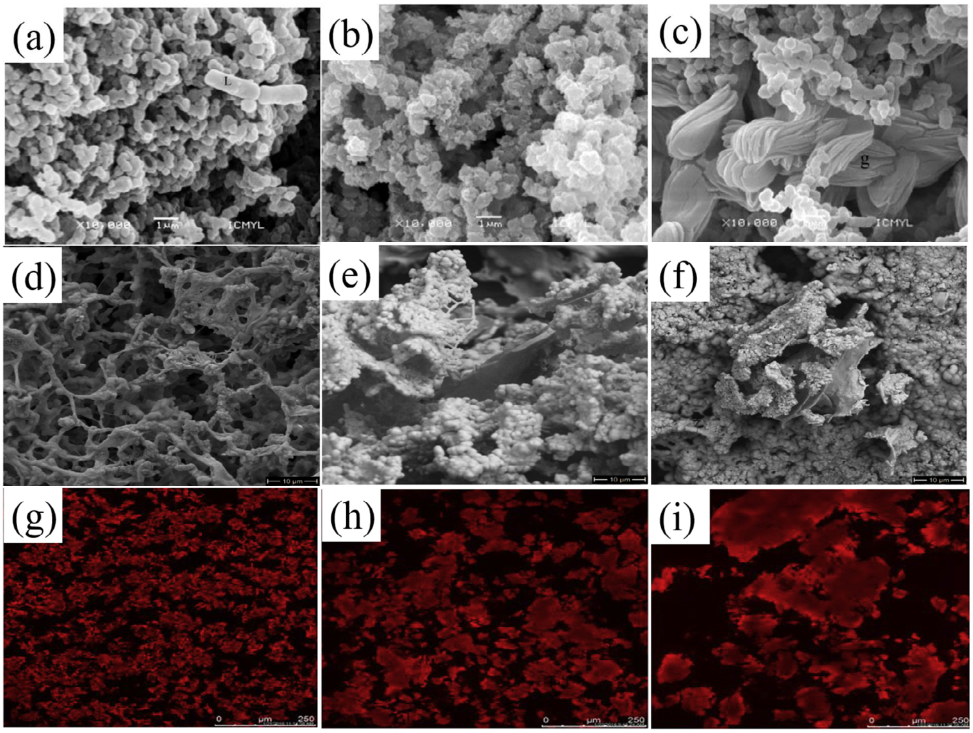

Fig. 3 (a–c) SEM observation of full-fat yogurt and low-fat yogurt with added agave fructans/inulin. Reproduced with permission from Ref. [59], © Elsevier, 2015. (d–f) SEM results of plain yogurt and yogurt with 1% coarse and fine fibers. Reproduced with permission from Ref. [2], © Elsevier, 2019. (g–i) Protein network images of 10% phosphate–buffered saline (PBS) diluted stirred yogurt in confocal laser scanning microscopy (CLSM): whey protein/casein ratios of 80/20, 60/40, and 50/50, respectively. Reproduced with permission from Ref. [58], © Elsevier, 2017.

with the addition of FG–AP has the best lubricity behavior and showed the prospect of developing new yogurt using FG–AP.

Yogurt is more popular than milk due to its unique sweet and sour flavors and high nutritional value [113]. Thickness, creaminess, and smoothness are common oral sensations when tasting yogurt. Bruzzone et al. [60] explored the effects of the concentrations of different components on yogurt perception by varying the ratio of gelatin, starch, and fat in yogurt using the QDA and TDS sensory evaluation methods. The increase in gelatin concentration improved the effects on thickness and gelation perception, but reduced the evaluation of creaminess. In addition to fat, the increased starch content also enhanced the evaluation of creaminess. In the experiments of acidic emulsion gels [114], it was also found that the proportion of starch exerts a large influence on the frictional behavior of yogurt. Similar findings were demonstrated in the research of Morell et al. [115], and taste experiments also concluded that starch reduced the sense of astringency. The effects of different ratios of whey protein in yogurt cannot be ignored either. Laiho et al. [58] found that an increase in the percentage of whey protein accelerated its self-aggregation, formed larger protein particles and clusters (Figs. 3(g)–3(i)), and was excluded in contact area. With the increase of particle size, the evaluation of creaminess and smoothness decreased, and the friction coefficient increased. A good correlation exists between friction experiments and sensory evaluation. Sonne et al. [116] examined the influences of different components' (fat, protein, casein, and whey protein) contents on the lubricity behaviors of stirred yogurt. The experimental results were correlated with the sensory evaluation, and the relevant data were imported into the regression equation, which successfully predicted the viscosity and creaminess of the yogurt and obtained a link between yogurt composition and taste.

People's perception of food is related to the stimulation received in the oral environment. A higher coefficient of friction produces greater mechanical stimulation, which usually does not contribute to enjoying food. The presence of fat in food changes the production of such mechanical stimuli and creaminess [117], which influences the public's consumption of yogurt, and its role cannot be ignored. Krzeminski et al. [118] performed experiments in a simulated oral environment by the tribological module of a rheometer in a steel ball-rubber pad, where yogurt friction profiles were clearly differentiated for different lipid contents. Huc et al. [119] also reported the friction in fat-containing yogurt is significantly less than that in fat-free yogurt. The fat content improved the lubrication conditions, which was attributed to the superior lubricating properties of fat and the formation of an oil film deposited in the contact area [35]. Similar results were obtained in the study (Fig. 4(a)) and the importance of saliva for the lubricating properties of the emulsion is also emphasized [4]. Figure 4(b) shows the friction curves for dairy products with different fat contents adding saliva at constant load and velocity over time. The presence of saliva changes the properties of the contact surface. The coefficient of friction remains constant after a period of time as a result of the loss of food and the destruction of the saliva structure, which degrades the lubricating properties. The difference in the friction coefficient in the final steady state was influenced by the characteristics of the sample and the fat content. The flocculation produced by the mixing of yogurt samples and saliva was observed by photoelectron microscopy (Fig. 4(c)), which is one of the factors affecting the perception of yogurt.

2.3 Cheese

Cheese, as a soft solid food, is made of fat, protein, and water. It has become an indispensable food in many countries as a common accompaniment in their diet. A key factor in evaluating the cheese is its texture [120], which is recognized by many customers who consume cheese regularly. Thus, it is particularly important to understand the texture of cheese. Textural terms to describe the cheese itself were introduced in Ref. [121]. Table 2 shows a summary of common perceptual description terms associated with cheese. Jack et al. [122] analyzed the texture of cheese by chewing experiments. Low sensory acceptability (graininess, roughness, and friability) was obtained in the early stage of the chewing experiment, which was attributed to the age and low cohesion of the cheese. As time increases, the chewing experience begins to improve with smoothness and creaminess being the primary perceived attributes. Creaminess was found to correlate with thickness and smoothness in oral perception in Ref. [123]. And thickness and smoothness sensation were shown to be related to friction measurements and shear stresses during oral processing.

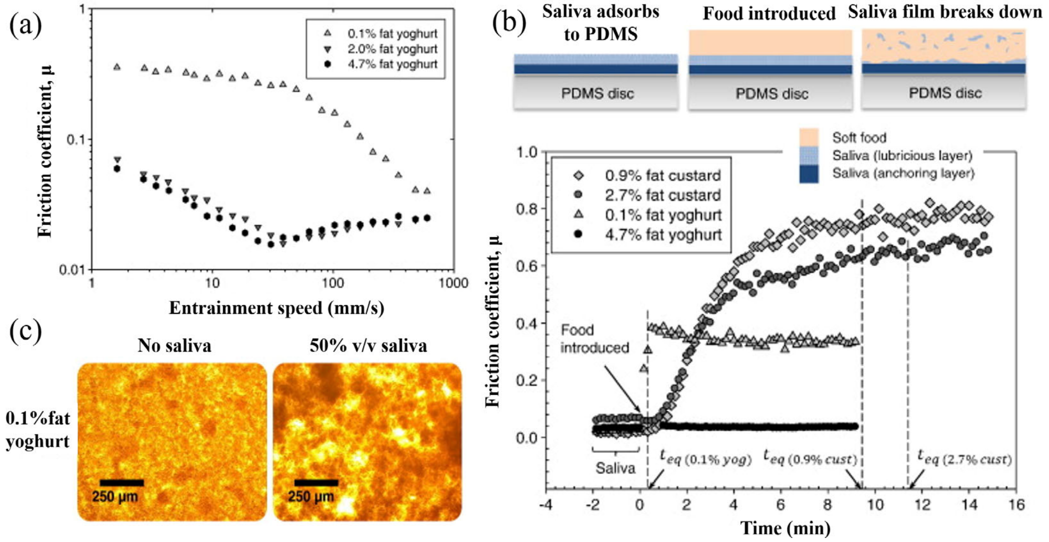

Fig. 4 (a) Effect of fat contents on the friction coefficient of yogurt, (b) comparison of lubrication curves of different dairy products under saliva, and (c) comparison of microscopic observation of yogurt with/without saliva. Reproduced with permission from Ref. [4], © Elsevier, 2013.

Table 2 Common cheese perception description words and interpretations.

Term [126]	Definition
Sticky/stickiness	The degree of adhesion of cheese to the surface of the mouth and teeth during oral processing
Smooth/smoothness	Perception of smoothness of object surfaces during tongue–palate shearing
Rubbery/rubberiness	Recovery performance of structures that have undergone oral processing
Grainy	Perception of particles after shear reduction of food in the mouth
Firm/firmness	Degree of force during oral processing of food
Dry	Measure of perceived dryness on the surface of the tongue
Crumbly/crumbliness	The rate at which food breaks down in the mouth
Creamy/creaminess	Degree of decomposition into a creamy liquid (similar to the feeling of melting cream)
Cohesiveness	Ability to agglomerate after oral processing

The evaluation score of creaminess can be deduced from the parameters they measure.

The role of fat in the perception of eating cheese is self-evident, and the loss of fat in the structure can lead to a decrease in the evaluation of cheese texture and affect the experience of cheese consumption. This is particularly obvious in low fat products [124]. Gwartney et al. [65] found large differences in hardness, smoothness, viscosity, and crispness evaluations by comparing texture perception between full-fat and low-fat cheeses. A correlation between creaminess and particle size during oral processing of cheese was found [64]. The reduction in cheese particles was accompanied by an increase in creaminess. Ningtyas et al. [63] examined the effect of fat content on cheese. The microscopic observation of high-fat cheese (Fig. 5(a)) showed that the presence of a large number of fat globules destroyed the network of the protein matrix, which loosened the structure of the cheese and increased the internal voids. In the friction experiments (Fig. 5(b)), cheeses with different fat contents were clearly distinguished at low speeds, which was caused by the disruption of the internal structure of the cheese and the weakened resistance to shear. The improvement of lubrication conditions by fat may be another important factor. The rheological experiments (Fig. 5(c)) demonstrated that the apparent viscosity of the cheese decreased with increasing fat contents. This is due to the weakening of protein interactions and the reduction of aggregation phenomena with more fat. The relationship between the critical friction coefficient f_b and fat content of cheese was also reported (Fig. 5(d)), where it was found that a rapid decrease in the friction coefficient was accompanied by an increase in fat content at low fat content (<5%) [125]. However, this trend becomes less significant under a fat content >5%. β-glucans and phytosterols were studied as fat substitutes in low-fat cheeses, their lubricating properties had close to those of full-fat cheeses in friction experiments, and both improved part of the sensory evaluation [62]. Sodium alginate as another alternative component to fat was studied by Sharma Khanal et al. [61], low-fat cheese supplemented with sodium alginate exhibited similar frictional behavior to full-fat cheese, and sodium alginate did not show significant differences from fat by *in vitro* digestibility and sensory evaluation. All these alternative ingredients provide insights to improve the tastes of low-fat cheeses.

2.4 Chocolate

Chocolate is popular among the consuming public because it is endowed with a unique texture influenced by cocoa butter [127]. Earlier studies focused on the rheological behavior of chocolate and the influencing factors [128]. The size of particle, distribution, and density affect the flow behavior in the molten state of milk chocolate [75]. There is a strong correlation between particle size and sensory properties with bigger particle size increasing the evaluation of graininess [129]. Qian et al. [67] found that cocoa concentration had a great effect on smoothness. The friction coefficient of the 50% chocolate solution correlates to the greatest extent with smoothness. The thickness of the food film was so thin during the tongue and upper-jaw shearing processing that the

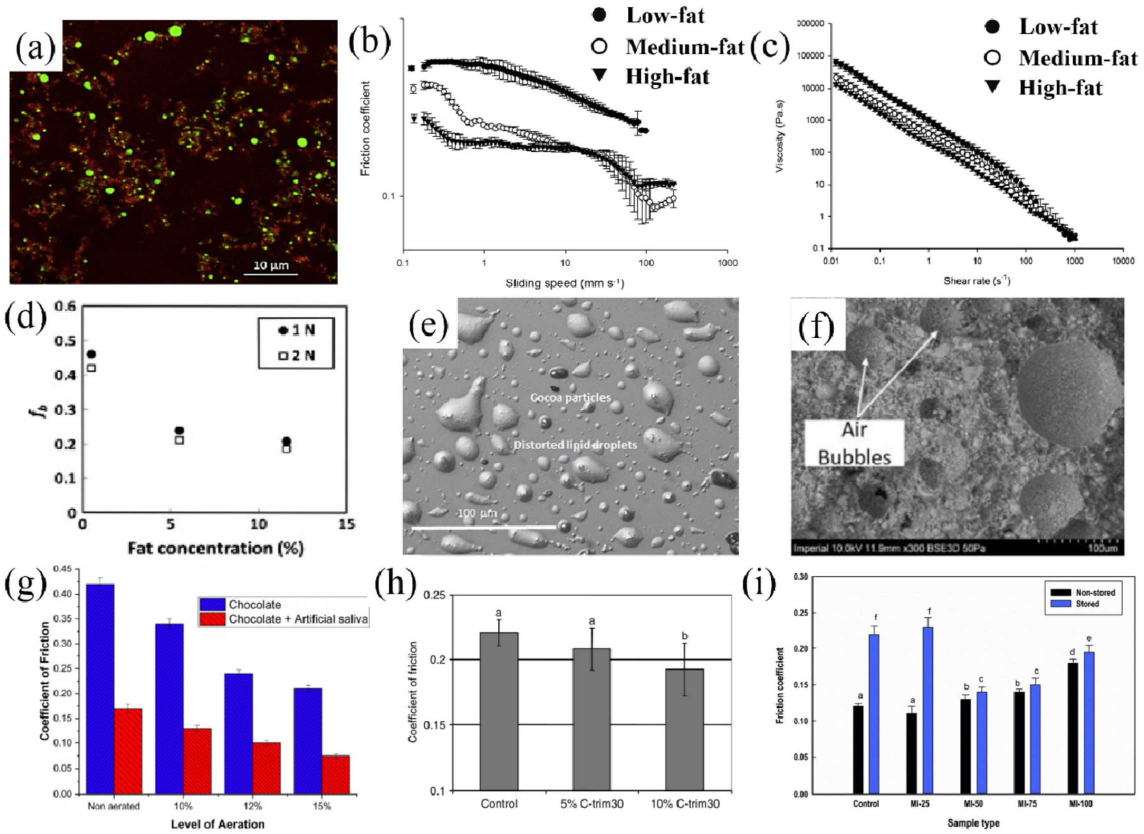

Fig. 5 (a) Microscopic observation of high fat cheese: protein (red) and fat (green), (b) change of friction coefficient with speeds for cheeses under different fat contents, and (c) change of apparent viscosity of cheeses under different fat contents. Reproduced with permission from Ref. [63], © Elsevier, 2017. (d) Critical boundary friction coefficient as a function of fat concentration. Reproduced with permission from Ref. [125], © Elsevier, 2016. (e) Microscopic image of chocolate film on contact surface after test. Reproduced with permission from Ref. [69], © The Author(s), 2018. (f) Microstructure of aerated chocolate and (g) effect of aeration treatment and saliva on the friction coefficient of chocolate. Reproduced with permission from Ref. [31], © Elsevier, 2020. (h) Variation of friction coefficient of adding different contents of C-trim gel chocolate. Reproduced with permission from Ref. [72], © Wiley, 2009. (i) Effect of modified inulin and storage time on the lubricating behavior of chocolate. Reproduced with permission from Ref. [66], © Elsevier, 2021.

rheological properties could no longer explain the chocolate lubrication behavior and perceived properties well. And the frictional behavior in the lubricating state played an important role. Masen and Cann [69] also explained that the ring-breaking decomposition of the chocolate structure during the friction process, as well as the release of fat, also contributed to the changes in the friction coefficient (Fig. 5(e)). Luengo et al. [44] found the significant effects of fat and solid particle size on lubrication behavior of chocolate samples with different components. Particles staying in the friction area as well as solid phase volume lead to changes in frictional behavior [130]. The dilution effect of saliva on chocolate was enhanced and gradually transformed into an oil in water solution, and the film lubrication was governed by different phases of bulk viscosity and contact area. The relevant chocolate lubrication model is described in Ref. [130]. Aeration of the chocolate (Fig. 5(f)) changes the microstructure and improves the taste of the chocolate. The aeration values was found to be inversely proportional to the friction coefficient. The addition of saliva obviously improved the friction behavior of chocolate on the contact surface (Fig. 5(g)) [31]. The Stribeck curve was introduced to assess the effect of saliva on the lubrication behavior of chocolate. The decrease of the friction coefficient was considered to be the result of particle entrainment [70]. He et al. [68] found that the reduction in friction coefficient was the result of adsorption of cocoa solids on the contact surface by the analysis of the structure of chocolate particles and the shape of the friction curve. A correlation between thickness and fluid lubrication state was also found. Lecithin not only affects the rheological properties of chocolate, but also has a significant effect on frictional behavior. And high concentration lecithin coverage of the particle surface effectively improves lubrication conditions and enhances flow characteristics [74]. Differences in chewing patterns also affect the perception of chocolate, and an association between the coating and frictional behavior of milk chocolate on the oral surface was found in experiments [71]. The differences in the material and hardness of the friction pairs used to simulate the friction behavior also affect the friction behavior in the sliding state [73].

As a high-fat and high-calorie product, chocolate consumption may result in obesity and other related diseases while providing us with a pleasurable eating experience [131]. How to get a balance between the enjoyment of food and health is the current challenge for chocolate development. Controlling fat intake has always been one of the requirements of a healthy diet. C-trims are extracted from plants and can provide nutritional properties needed by the body to improve the texture of chocolate [132]. It has been widely used in the development of low-fat and low-calorie foods [133, 134]. As a substitute for cocoa butter, related studies have been carried out [72]. The frictional behavior of the samples at low speed was significantly improved with the addition of 10% C-trims to the chocolate (Fig. 5(h)). However, the chocolate viscosity also changed with the C-trims content. Partial substitution of cocoa butter became possible. The addition of less sugar is also one of the goals of chocolate manufacturing. Kiumarsi et al. [66] were able to reduce the sucrose content and cost by using modified inulin as an alternative to sucrose in chocolate. Friction results showed no significant changes in the friction of chocolate with higher amounts of modified inulin (Fig. 5(i)). And modified inulin improved solid particle distribution. The sensory evaluation of the stored chocolates with modified inulin was also close to that of the non-added samples.

2.5 Mayonnaise

Mayonnaise is one of the common seasonings available in the market and consists of egg yolk, fat, and vinegar. It is a high viscosity oil in water solution [135]. Mixing mayonnaise with other foods can alter their agglomeration properties and lubricating behavior in oral processing. The food becomes easier to swallow [136]. When eating mayonnaise, people usually perceive thickness, greasiness, and melting sensations [137, 138]. The presence of fat directly affects the perception of greasiness and is more associated with creaminess [139]. The link between the physical properties and sensory perception of mayonnaise was investigated and a linear relationship between shear stress and thickness was found as shown in Fig. 6(a) [140]. Shear stress is subject to the consistency of the material and dynamic viscosity is correlated with thickness [141]. The yield value of the food was related to the sensory properties [142]. Simulation or realistic oral processing is of great significance to understand the lubrication behavior of mayonnaise. Shama and Sherman [143] studied the range of shear rates of liquids for oral processing. The intensity of food sensory perception was found to be related to the time of tongue and upper jaw movements [144]. By comparing mayonnaise processing at different food temperatures and oral temperatures, it was found that the rise in product temperature increased melting and greasiness, but decreased thickness [145]. The comparison of low/high fat mayonnaise revealed that the increase in fat content facilitated a rising creaminess and a declining roughness, and enhanced the sensory experience. The increase in friction was usually accompanied by unpleasant eating sensations such as dryness, roughness, and astringency. Due to the better lubricating effect of grease, the increase in fat content will reduce the coefficient of friction to a smaller value. Smaller droplets may have a larger deformation and will reduce the contact with the friction surface, thus reducing the contact force. The increase in particle size and shape changes within the fluid are also accompanied by a rising friction. These changes can significantly affect oral sensations [79]. The specific relationships are summarized in Fig. 6(b). Saliva has an important role in sensing the textural effects of mayonnaise. There is a correlation between the precipitation and flocculation of salivary proteins and the production of astringency. Giasson et al. [80] found that the properties of solid particles have a large effect on the film properties of

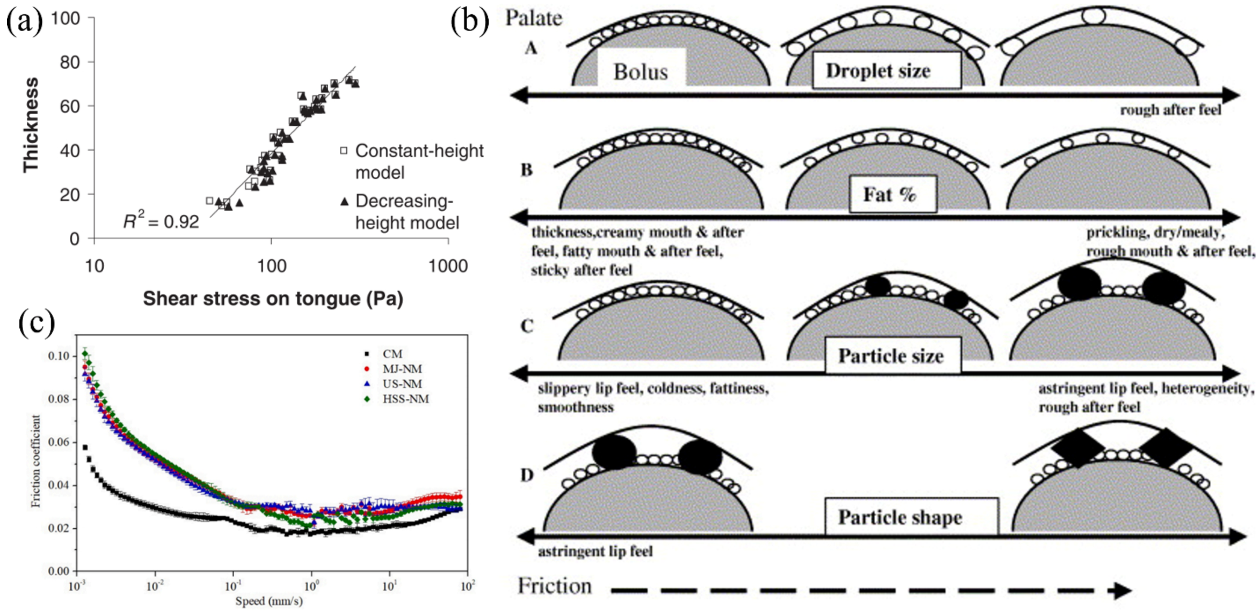

Fig. 6 (a) Correspondence between thickness and shear stress. Reproduced with permission from Ref. [140], © John Wiley and Sons, 2005. (b) The relationship among the physical parameters of mayonnaise, the coefficient of friction, and the variation of oral perception. Reproduced with permission from Ref. [79], © Elsevier, 2005. (c) Comparison of friction variation between new mayonnaise containing apple pomace and commercially available mayonnaise with different preparation methods. Reproduced with permission from Ref. [76], © Elsevier, 2021.

mayonnaise in oral processing. The α-amylase activity in saliva affects the perception of creaminess, which is thought to be related to the adhesion of particles in starch to the oral surface [146].

Health and functionality are goals in the development of new mayonnaise. Egg yolk as a natural emulsifier has an important influence on the texture of mayonnaise. Affected by high cholesterol levels in egg yolks, long-term consumption of mayonnaise may lead to a range of health problems [147]. Apple pomace pickering emulsion as a natural, green emulsifier can replace the role of egg yolk. It performed well in terms of the appearance and stability. However, friction experiments (Fig. 6(c)) showed slightly poor lubricity of the new mayonnaise, which requires further exploratory studies [76]. Modified starch was found to achieve better lubricating properties as fat substitutes while improving the taste [77]. It provides a new option for the development of low-fat mayonnaise. As a green material, pea pods can be processed to powders. It is rich in dietary fiber and micronutrients, which can enhance the functional and sensory properties of low-fat mayonnaise. The emulsion shows a uniform distribution and the droplet diameter decreases as the pea pod powder content rises to 7.5%. This indicates the stabilizing effect of soluble fiber in the emulsion. The aggregation of fat droplets is evident and contributes to the increase of matrix viscosity. In friction tests, mayonnaise with 7.5% pea pod powder content was found to have similar tribological behavior to its commercial counterpart and indicated the possibility of pea pod powder as a functional ingredient [78].

2.6 Red wine

Red wine has been studied more extensively, and this section focuses on the interrelationships and effects of sensory properties, tissue compositions, and frictional behaviors of red wine. As one of the most widely consumed wines in the world, red wine is broadly loved because of its rich taste. Its taste is important in the consumption process. Astringency, bitterness, sweetness, and acidity are usually experienced in the drinking of red wine, and many winemakers want to balance them [148]. Astringency is defined as the complex feeling of contraction and wrinkle of the epithelium affected by substances such as tannin. The interaction of salivary proteins and stimuli produces soluble/insoluble complexes, and this interaction depletes the salivary film and causes an increase in friction, which generates the perception of astringency as shown in Fig. 7(a). Tannins and astringency are usually considered highly correlated in previous studies [149]. Astringency is often described as a dry, rough, and puckering sensation [150]. However, its mechanism is more complex. Watrelot et al. [151] used SFA to study the effects on the frictional behaviors of different types of wines by varying the contact surface properties. And the results showed that the friction behavior of contact surface is greatly sensitive to tannin concentration. In the study of the interaction between dietary tannic acid on oral mucosa and saliva, high concentration (1 mM) of dietary tannins epigallocatechin gallate (EgCG) reacted with salivary protein and produced obvious tannin-protein deposition polymer (Fig. 7(b)) [84]. And the polymer will affect the friction in this area. Figure 7(c) are the local friction images obtained by atomic force microscope (AFM) experiment (the magnitude of friction is expressed in volts). It can be seen that the average friction coefficient (1.313 ± 0.376 V) of 3 mM EgCG (right picture) is more than twice that of the untreated sample (left one) (0.603 ± 0.186 V). This also confirmed that the reaction between tannin and salivary protein would affect the friction response of oral cavity. Proline-rich proteins (PRPs) are highly sensitive to tannins, which limit the concentration of tannins and prevent the development of polymers produced by tannin influence. Moreover, they hinder tannins from interacting with oral mucosa directly, thus providing a protective effect. Only when the tannin concentration is greater than the amount of interaction between PRPs and tannins, can it directly react with the surface mucosa and affects the perception of astringency in the mouth. The presence of PRPs in oral saliva and tannins produces precipitation and flocculation to change the perception of red wine texture [84, 152]. It is thought to be a common cause of astringency [153]. Tannin is a major component of red wine that causes astringency in the mouth. In exploring the relationship between astringency and friction, four mixtures of wine and saliva were prepared for friction experiments [81]. The astringency intensity of the different astringent solutions (tannins, catechins, and four kinds of red wines) showed a significant positive correlation with the friction coefficient (Fig. 7(d)). And the results showed that different frictional behaviors of them (Fig. 7(e)). The experimental data revealed that an increase in the friction coefficient was accompanied by rising tannin contents (Fig. 7(f)). This indicates that astringency is a sensation related to physical perception and closely correlated with tannins. Recent research [154] found the influences of the formed aggregates' properties on the perception of astringency and friction. The difference in harvest date affected the phenolic content of the wine. The polymer of wine and saliva changed from being rough to smooth as the harvest date increased, and the friction data showed a continuous downward trend. The polymer's quantity and physical properties affected the perception of wine and lubrication behaviors in the mouth as displayed in Fig. 7(g). The interaction of polyphenolic compounds with saliva led to lubrication failure [155]. Descriptive analysis showed a good correlation between tannin content and astringency perception [156]. In the wine friction tests with high and low tannin concentrations, an increase in the friction coefficient with rising loads was reported (Fig. 8(a)), and the coefficient of friction was clearly differentiated with tannin concentrations, but there was no significant dependence on speeds. Tannins were easier to interact with salivary proteins and more polymer produced staying in the contact area and increasing friction [82]. Frost et al. [157] found that sour and bitter flavors were significantly influenced by the presence of tannins. EgCG solution increased the coefficient of friction with the lack of lubricating protein in simulating oral processing tests. This obtained consistency with the increased astringency in sensory evaluation. It indicates that there is a correlation between them, but the presence of astringency is not necessarily accompanied by the loss of salivary proteins. And the change in pH with temperature is also a cause of the variation of salivary lubrication [158]. A link between tannin content and boundary friction coefficient was also reported in Ref. [83]. The color of red wine is mainly influenced by anthocyanins. Only anthocyanins have a small effect on astringency intensity, but they significantly alter the perception of astringency and bitterness in the mouth when combined with condensed tannins [159]. The presence of anthocyanins also affects the perception of dryness [160].

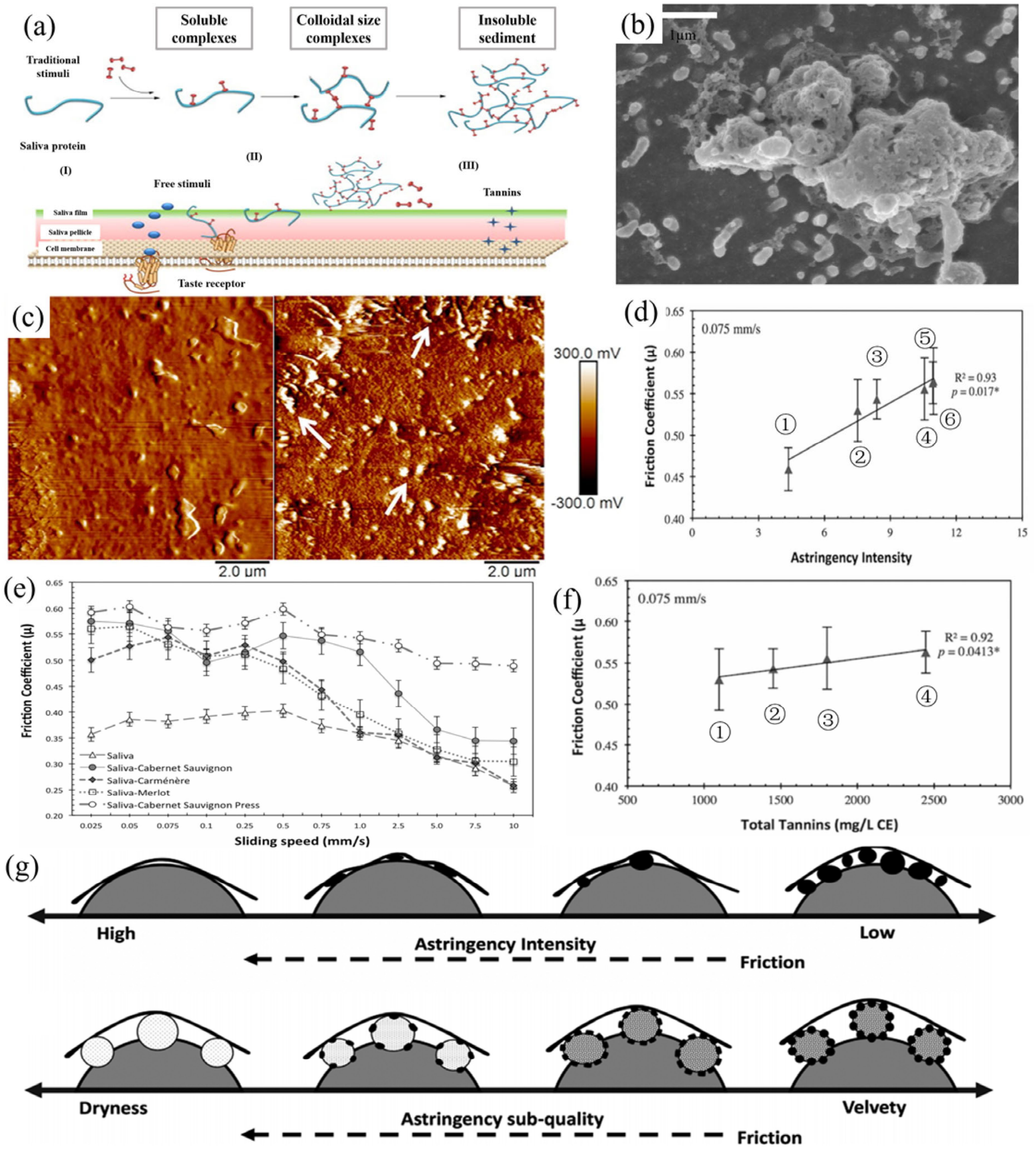

Fig. 7 (a) Diagram of the process of astringency production. Upper: the process of interaction between salivary proteins and stimulants. Lower: (Ⅰ) stimulants and soluble complexes distributed on the salivary surface interact with saliva causing the absence of salivary film and reaction with receptors, (Ⅱ) insoluble complexes and traditional stimulants are deposited on the salivary surface to increase friction, thus causing the production of astringency, (Ⅲ) tannins interact with the mucosal surface. Reproduced with permission from Ref. [149], © Elsevier, 2014. (b) SEM images of mucosa surface with the addition of 1 mM EgCG and (c) AFM friction image of in vitro model without (left) /with (right) 3 mM EgCG added, lighter color means higher friction. Reproduced with permission from Ref. [84], © Elsevier, 2018. (d) Variation of astringency intensity with friction coefficient for six astringent solutions (① Tannic acid, ② Cabernet Sauvignon from Press, ③ Cabernet Sauvignon, ④ Carménère, ⑤ Merlot, and ⑥; (e) variation of friction coefficient with sliding velocities for saliva and four kinds of saliva-red wine mixtures; and (f) relationship between tannin concentration and friction coefficient in red wines (① Merlot, ②, ③ Cabernet Sauvignon, and ④ Cabernet Sauvignon from Press). Reproduced with permission from Ref. [81], © John Wiley and Sons, 2016. (g) Mechanism of action among the properties of aggregates, friction behaviors, and sensory perceptions (astringency, dryness). Reproduced with permission from Ref. [154], © Wiley, 2021.

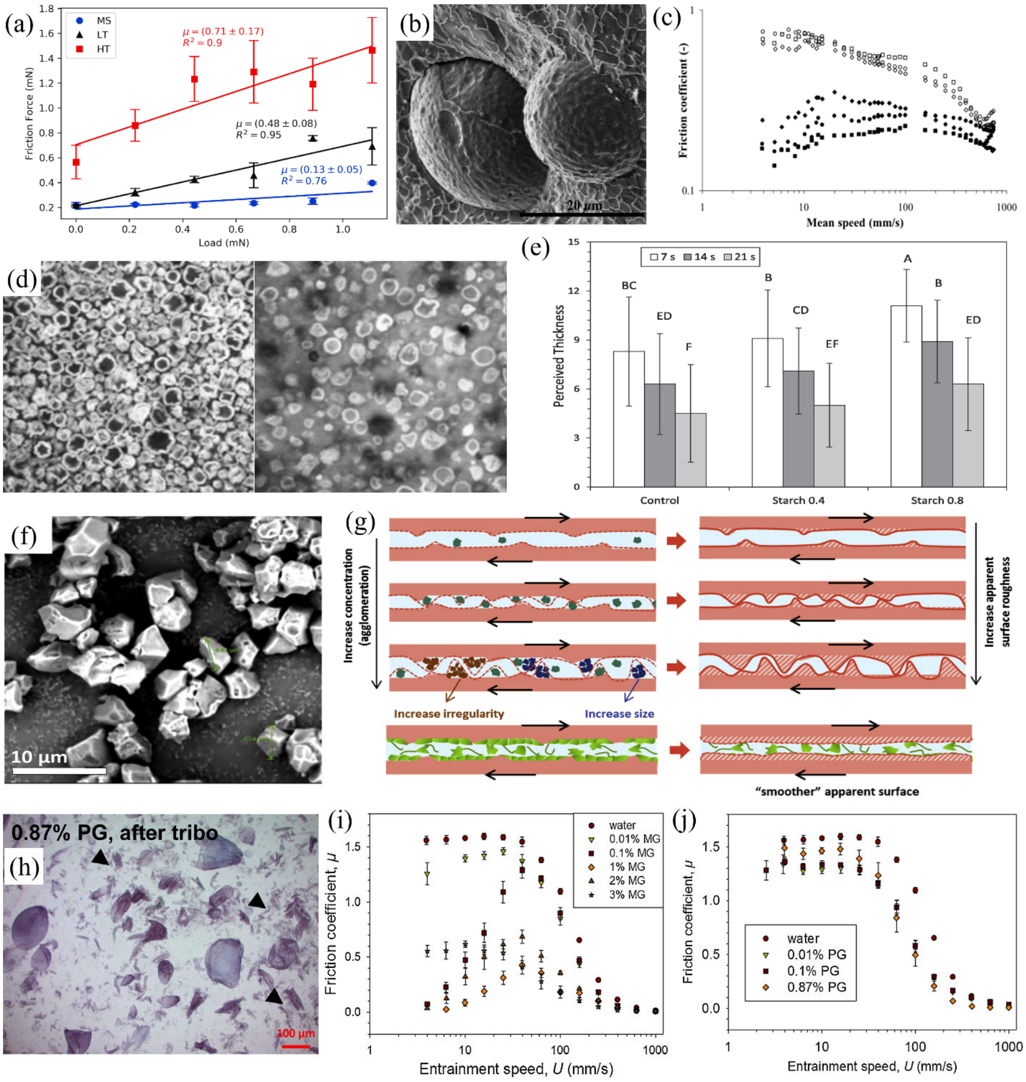

Fig. 8 (a) Variation of friction coefficient with loads for model saliva (MS) and model wine solution with high/low tannin concentration (LT/HT) at a sliding speed of 5 μm/s. Reproduced with permission from Ref. [82], © Elsevier, 2021. (b) Cryo-Scanning Electron Microscopy (Cryo-SEM) images of starch emulsion microgel particles. Reproduced with permission from Ref. [164], © American Chemical Society, 2018. (c) Friction curves of starch paste (SP) and LBG solutions with or without the addition of inactivated saliva or active saliva under 5 N applied load (SP: ■ untreated samples, ● addition of inactivated saliva, ◆ addition of active saliva. LBG: □ untreated samples, ○ addition of inactivated saliva, ◇ addition of active saliva), and (d) CLSM images of starch granules, untreated samples (left), samples treated with the addition of saliva incubation for 10 s (scanning range: 500 nm × 500 nm). Reproduced with permission from Ref. [90], © John Wiley and Sons, 2008. (e) Thickness sensory test results at different oral processing times, pureed carrot, added 0.4% and 0.8% starch-enriched. Reproduced with permission from Ref. [166], © Elsevier, 2020. (f) SEM images of natural rice starch (dry powder) granules, and (g) frictional change process of natural rice starch solution (top) and gelatinized rice starch solution (bottom). Reproduced with permission from Ref. [89], © Elsevier, 2016. (h) Light microscopy images of potato starch granule ghost suspension (PG) after the friction experiment, with arrows indicating starch ghost fragments; (i) variation of friction coefficient with entrainment speeds of MG at different concentrations; and (j) change of friction coefficient of PG with entrainment speeds at different concentrations. Reproduced with permission from Ref. [88] , © Elsevier, 2017.

2.7 Starch

Starch is widely used in food processing and the texture and properties are influenced by the original plant [161], which has an impact on the perception of starch flavor. Studies of custard desserts with added starch illustrate the effect of lubrication behavior on roughness and creaminess. The surface and volume characteristics of the food also influence oral perception [162]. In a study on starch suspensions [163], it is reported that α-amylase contained in saliva has interactions with starch. The glycosidic bonds in starch undergo a breakage reaction and the mechanical strength of the particles in the starch solution decreases resulting in viscosity declining. Torres et al. [164] discovered that the rising starch content and the addition of α-amylase improved the lubricating behavior of the experimental fluid using starch-based microgel particles (Fig. 8(b)) as biolubricants. This was attributed to the increased particle size of the starch acting as a surface barrier and the starch-α-amylase interaction. In the study of tapioca starch pastes, the friction experiment results (Fig. 8(c)) showed that they had better lubricating behavior compared to locust bean gum (LBG) solutions [90]. The addition of saliva made some of the starch granules to be dissolved (Fig. 8(d)). The friction coefficient was slightly higher but still relatively low because softer starch granules would still be entrained into the contact area to reduce friction, and the decomposition of starch improved the wettability of the contact surface and facilitated the formation of surface lubricant films. The mechanism of action and viscosity change of modified starch was further investigated in the work of Desse et al. [165], where the concentration and hydrolysis of starch and dilution of saliva affected the perception of thickness (Fig. 8(e)) [166]. Liu et al. [89] analyzed the tribological properties of natural/dextrinized rice starch dispersions. Natural rice starch granules are irregularly shaped with uneven edges (Fig. 8(f)), which has enhanced interactions and leads to greater friction than that of spherical granules. The increase of starch concentration will indirectly increase the surface roughness and contact force affected by particle agglomeration and irregular surface, which resulting in high friction (Fig. 8(g)). Gelatinized starch granules are much softer and have a weak resistance to deformation. Starch granules are flattened and serve to fill the surface subjected to shear forces, which will form a thicker starch film on the contact surface and separate the contact surface. However, it will increase the viscosity of the starch dispersion and the adhesion resistance to the relative movement of the surface influenced by the amylopectin flowing out during the heating process, which is not conducive to lubrication (Fig. 8(g)). During the gelation of starch, a residue consisting of amylopectin called "ghost" appears on the outer surface of the granule [167]. In the lubrication study of maize starch/potato starch ghost particle suspension (MG/PG) [88], microscopic observations of the MG granules showed no significant changes in the solution after the friction experiments, while the starch granules in the PG solution were significant broken (Fig. 8(h)), leading to a weakened ability to isolate the two surfaces and higher friction. It was also found that the decrease in the coefficient of friction at the boundary of both solutions was accompanied by an increase in starch concentration, but the MG solution had a significantly lower friction coefficient at similar concentrations (Figs. 8(i) and 8(j)). This seems to be influenced by the structural stiffness of the starch granules. Similar behavior was found in the study of polymer solutions of gelatinized corn starch and carrageenan [85]. Rice porridge, as a paste starch solution, is a common food on the dinner table in many Asian countries. The starch in rice porridge completes the process of pasting and facilitates its absorbing after cooking. In the study of rice porridge with mung bean, it is found that the addition of a certain content of mung bean will not reduce the lubricating performance of rice porridge, and the corresponding sensory experience is better [86]. This showed the value of the combination of tribological and sensory evaluation in improving food taste.

2.8 Carbonated drinks

Carbonated beverages are preferred by consumers worldwide and are consumed in countless quantities. This has contributed to the development of research on the taste properties of carbonated beverages. The perception of carbonated beverages is usually considered to be the response of the nerve endings to carbonic acid in the mouth [168]. Scholars have different opinions about the presence of carbonated taste. Cometto-Muñiz et al. [169] considered that this taste, as a pungent sensation, caused a certain chemical stimulation of the mouth. This was usually due to the presence of nerve fibers in the oral mucosa [170]. Yau and Mcdaniel [171] suggested that pressure fluctuations caused by bubbles generated from carbonation also contributed to this sensation. Subsequent studies also pointed out that mechanical stimuli during oral movements were also important for the perception of carbonated taste [172]. A decrease in the temperature of the beverage enhances the intensity of this sensation [173]. Tingling sensation is also one of the typical characteristics of such drinks, which is usually caused by the stimulation of neurons by carbonic acid [174]. Kappes et al. [175] characterized the perception of commercial carbonated beverages by descriptive analysis. Subsequent work correlated descriptive analysis with changes in the composition of the drink, and yielded opposite trends in carbonation and oral adhesion [176]. The physical properties of saliva change depending on the type of drink to some extent and influence the perception of the drink. The higher viscoelasticity of saliva responded to the stimulation of carbonated beverages is thought to be a self-protective mechanism of the oral cavity [177]. Steinbach et al. [92] compared the friction behaviors of different carbonated beverages and developed Stribeck lubrication curves, and found that the boundary friction coefficient of citric lime beverage was lower than that of cola beverage. Carbonic anhydrase was found to be highly sensitive to the perception of CO_2 [178]. The lubrication mechanism of carbonated beverages has recently started to be studied and their friction coefficients are higher than those of non-carbonated beverages (Fig. 9(a)) [91]. It is caused by a decrease in the local load-bearing capacity of the liquid film due to the

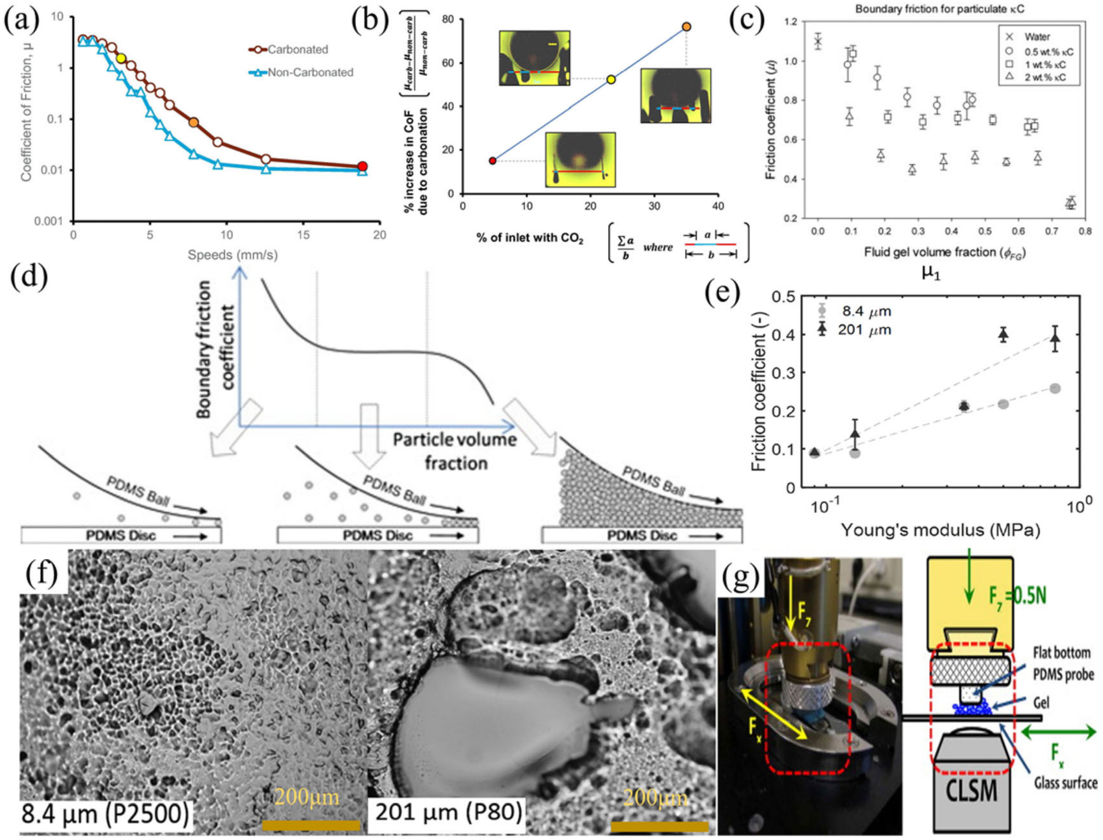

Fig. 9 (a) Variation of friction coefficient with speeds for carbonated and non-carbonated deionized water lubrication, and (b) relationship between the percentage of friction coefficient increased by carbonation and the percentage of contact inlet CO_2. Reproduced with permission from Ref. [91], © Elsevier, 2021. (c) Association between friction coefficient and fluid gel volume fraction for different concentrations of carrageenan particle solutions, and (d) schematic diagram of gel particle entrainment. Reproduced with permission from Ref. [95], © Elsevier, 2013. (e) Sliding speed 20 mm/s, two sandpaper grain size modification of the gel surface, friction coefficient as a function of Young's modulus, and (f) surface topography of the gel modified with sandpaper, the specification of the sandpaper is shown in the lower left corner. Reproduced with permission from Ref. [179], © Elsevier, 2020. (g) OTC structure diagram, the emulsion or gel is applied shear between PDMS and glass, the CLSM image below is able to observe the changes in the contact area. Reproduced with permission from Ref. [180], © Elsevier, 2015.

cavities generated by air bubbles in the beverage. The percentage of water declined gradually with the increase of CO_2 bubbles at the inlet, which resulted in a starved lubrication condition and made the friction coefficient rise as displayed in Fig. 9(b). Carbonated beverages were more capable of consuming salivary films to reduce lubrication conditions and increase friction, which was influenced by the pH of the fluid.

2.9 Food gels

Gels play a wide range of roles in the food field. For example, gel particles can be used as thickeners to improve the texture, viscosity, and stability of food. Carrageenan was also commonly used as a thickening agent for food products, and more carrageenan particles decreased the friction coefficient as shown in Fig. 9(c) [95]. It indicated a certain dependence of the volume fraction on the thickening solution of carrageenan particles at low velocities. The number of gel particles in the friction region might influence this connection, and the constant entrapment and accumulation of particles changed the lubrication behavior in the contact region (Fig. 9(d)). Rudge et al. [179] investigated the frictional behavior of hydrogels with different physical properties. The roughness and morphology of the surface of the hydrogel were changed using different sandpapers as mould substrates during its preparation (Fig. 9(f)), and gelatin concentration was used to adjust the Young’s modulus of the samples. Friction experiments reported an increase in the friction coefficient with the increase of Young’s modulus and roughness (Fig. 9(e)). The morphology was subject to changes in the internal network structure. In the process of shearing with OTC friction apparatus (Fig. 9(g)), the friction coefficient reduced by filling the gel with lipid emulsion because of the aggregation of fat. The fat content also influenced the sensory evaluation [180]. The physical properties of dispersion particles in food can influence the sensory experience [181–184]. The friction characteristics and lubrication behaviors of food gels were studied in order to better use them. The frictional behaviors of gels become complicated owing to the multiple influences (organization, properties of contact surfaces, etc.). Gong [185] proposed a repulsion-contact model to explain the frictional behavior of hydrogels at sliding interfaces. The viscosity of continuous phase affected the lubrication behavior of microgel solution [186]. Hydrocolloids improved the lubricating ability of the base solution [93, 187], which was demonstrated in friction tests with milk protein solutions [188]. The addition of hydrogels to creams had a thickening effect. Added xanthan gum increased the viscosity of the food itself and improved the creaminess and thickness [189]. Alyssum homolocarpum seed gum was also found that the solution friction coefficient decreased with increasing gel concentration [94]. Particle properties had a large influence on the frictional behavior of gel fluids [190], and the elasticity and size of particles were found to affect the frictional response with agar gel solutions [191]. More particle entrapment reduced the direct contact interaction between the two surfaces, thus influencing the frictional behavior of the suspension. The number of water molecules in the hydrogel and the size of the gel network have also been reported to have an effect on the friction behavior [192]. The type of gel also affected the lubricating behavior of the fluid. Nguyen et al. [20] concluded that gelatin significantly improved the lubricating behavior of yogurt and obtained similar sensory evaluation as full fat yogurt adding different gels to yogurt. Moderate gelatin concentration enhanced the lubricating ability of acidic milk [193]. Different concentrations of 7S protein in acidic soy milk gels affected the overall structure and frictional behavior of the gels [194]. The frictional properties of guar gum solutions were found to correlate strongly with the oral perception of smoothness [3]. Chojnicka-Paszun et al. [195] found that the size of dispersed particles in polysaccharide gels influenced the perception of powdery sensation in the mouth. The xanthan gum hydrogel with 10 wt% sunflower oil and κ-carrageenan gel with natural oil bodies could be used as fat substitutes [196, 197].

2.10 Drugs

Drugs, as a special “food”, have an important impact on the elimination of diseases and the maintenance of health. A large proportion of the elderly, children, and even adults have a low level of acceptability of oral medications to varying degrees [198–200]. In addition, the symptoms caused by some diseases can also lead to the occurrence of dysphagia [201]. These phenomena can affect the swallowing of medications and their effectiveness [202]. Increasing the acceptability of drugs has become a challenge for the medical industry. Regarding solid tablet drugs, the acceptability is related to the tastes during oral processing [203]. By covering the surface with a coating, the taste of the drug body can be masked to facilitate taking medicine [204]. Smaller tablets also demonstrate better palatability [205]. A comparison of swallowing evaluations of tablets with and without coatings revealed that the texture properties of the tablets (surface characteristics, stickiness, and smoothness) influenced their oral behaviors, and smoother tablets exhibited were easier to swallow [206]. The intervention of tribological methods allowed a better understanding of the lubricating behavior of drugs in the mouth, which was beneficial to improve the swallowability of drugs. Tribological tests indicated that drugs wrapped with different coatings exhibited different lubrication behaviors (Fig. 10(a)), and a correlation was the set up between the tribological data and oral evaluations including slipperiness and stickiness [96]. In addition to coated tablets, many drugs were also made in suspension form. Batchelor et al. [97] selected several suspension drugs with different microstructures (Fig. 10(b)) and particle properties, and friction experiments showed that they have different lubrication behaviors due to the excipients in the drug and the production method.

2.11 Other foods

In addition to the tribology research of common foods described in the above sections, there are some food types with relatively few tribological studies, which will be briefly stated in this section and not

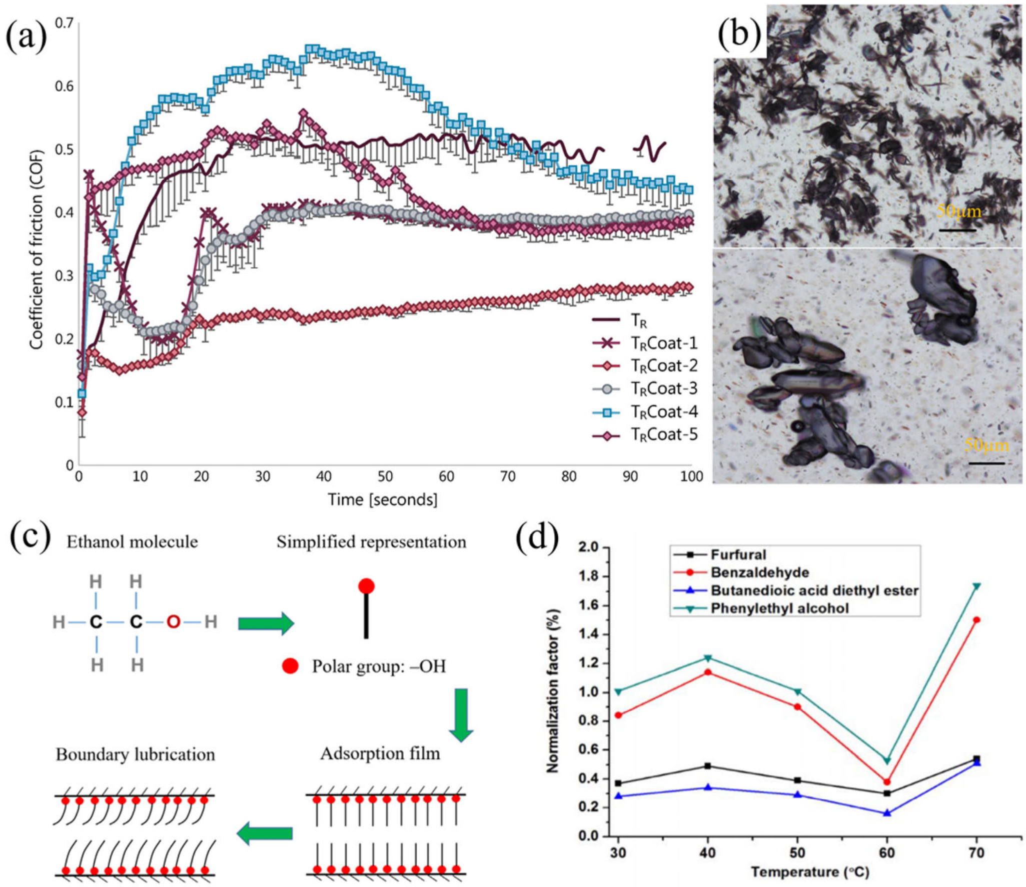

Fig. 10 (a) Variation of friction coefficient curves with time for plain tablets and coated tablets. Reproduced with permission from Ref. [96], © Elsevier, 2021. (b) Microscopic images of drug suspensions. Reproduced with permission from Ref. [97], © Elsevier, 2015. (c) The chemical structure formula of ethanol and a diagram of its lubricating effect and (d) variation of flavor-influencing compounds with temperature in Chinese rice wine (CRW). Reproduced with permission from Ref. [98], © Wiley, 2021.

be introduced separately. Chinese rice wine (CRW) is made from cereal grains and has high nutritional values [207–213]. CRW usually gets better flavor after heating. Friction experiments and other evaluations were applied to investigate the effect of heating temperature on the taste of CRW. It was found that CRW tasted best when heated to 60 °C with the best lubricity. CRW's lubricating mechanism and the changes of four key compounds were shown in Figs. 10(c) and 10(d), respectively [98]. As a substitute for coffee creamer, the glycosylation-modified fish gelatin was able to improve the stability and brightness of the emulsion and increase the lubricity of the coffee solution [99]. Chong et al. [100] found a significant correlation between the sweet aftertaste perception of tea solutions and the friction coefficient at low velocities by comparing the friction experiments of tea adding saliva with its sensory analysis. This association was obvious in the sensory experiments with the sensitive group. Park and Yoon [101] prepared mashed potatoes with different particle sizes. Bigger particle size corresponded with the larger coefficient friction and reduced the smoothness perception. Kim et al. [102] evaluated the frictional behaviors of apples using a rotational/reciprocating friction experiment and found that the transient frictional behavior was more consistent with the oral perception. And the friction data achieved a good correlation with the texture perception of apples.

3 Food models

The establishment of appropriate food models is of great help to accurately comprehend the friction behavior and lubrication mechanism of foods. For example, different concentrations of aqueous glycerol solutions substituted for different types of fat products [214]. Hydrogels prepared with different gelatin concentrations were used as semi-solid food models [169, 215]. Oil in water emulsions were similar in the structure of emulsion foods [18, 216]. This method allows to exclude some unimportant factors and to objectively evaluate the physical parameters that influence the lubrication behavior. The study of these parameters can better guide the development of food products, and enhance the food experience based on the food oral tribology approach.

Friction coefficient (μ) is often used as an important physical parameter in food oral tribology [18, 100, 130, 168, 192, 217]. It is given by the equation ($F_f = \mu F_N$). F_f represents the friction force, F_N is the normal load [218]. The Stribeck curve, a common tool for lubrication theory analysis [219], divides the lubrication behavior of fluids into three states generally based on the value of μ as shown in Fig. 11. Boundary lubrication regime: The fluid is almost extruded out of the contact area and cannot play the role of bearing pressure and improve lubrication conditions. The two friction surfaces are in direct contact, and the friction is mainly affected by the interaction of surface roughness peaks. The curve remains constant in this stage. Mixed lubrication regime: Part of the fluid begins to enter the friction region and fill the gap to the rough surface as the flow speed increases. The fluid partially separates the two contact surfaces and replaces the contact surface bearing pressure. At this time, the lubrication behavior is controlled by both the interaction of the two surfaces and the fluid. The lubrication effect of the fluid continues to increase and the surface interaction weakens with the rising speed. Thus the lubrication situation is improved and the friction coefficient decreases rapidly. Hydrodynamic (or elastohydrodynamic, EHL) lubrication regime: The hydrodynamic force is further enhanced and the two friction surfaces are completely separated by the fluid. The lubricity is dominated by the overall properties and viscosity of the fluid.

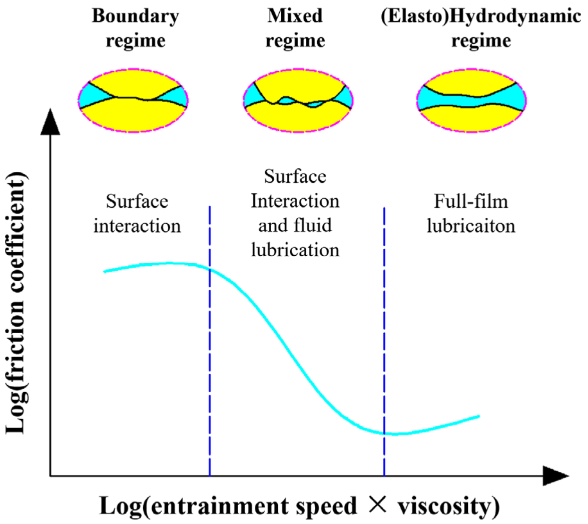

Fig. 11 Classical Stribeck curve, friction coefficient as a function of the combination of viscosity and entrainment speed.

Usually oral surface is considered to be soft and the fluid in mouth is in iso-viscoelastic state. Therefore, researchers are often interested in the prediction and modeling of iso-viscoelastic soft lubrication associated with oral contact. The elastic deformation of soft contact pairs affects the thickness of the film in the contact area, which has an impact on the lubrication behavior. The lower pressure in the iso-viscoelastic state does not cause significant changes in fluid viscosity [220]. Point contact is usually considered to be the contact form for oral tongue–upper jaw movement [221–223]. Vicente et al. [224] studied the frictional behavior of a Newtonian fluid model of corn syrup solutions with different concentrations using a MTM. The authors proposed a prediction equation for the friction coefficient under full submergence based on Poiseuille flow and Couette flow [224]:

$$\mu_{\mathrm{Total}\circledcirc}=1.46U^{0.65}W^{-0.70} +\mathrm{SRR}\left(3.8U^{0.71}W^{-0.76}+0.96U^{0.36}W^{-0.11}\right) \tag{1}$$

$$U=U\eta/E'R' \tag{2}$$

$$W=\mathrm{W}/E'R'^2 \tag{3}$$

$$1/E'=1/2\left[(1-v_1^2)/E_1+(1-v_2^2)/E_2\right] \tag{4}$$

$$1/R'=1/R_1+1/R_2 \tag{5}$$

where η is the effective viscosity, U is the entrainment speed. E' and R' are defined by Eqs. (4) and (5). Where R_1, R_2, E_1, E_2, v_1, v_2 are the radii in the flow direction, Young's modulus, and Poisson's ratio of the two friction bodies. Comparing the solved friction coefficients with that of having been measured could obtain a better fit in the EHL regime. The prediction formula was used to study lubricating properties of polysaccharide and microgel solutions and verified the accuracy of the model [85, 186, 225]. de Vicente et al. [226] proposed two schemes for the prediction of the friction coefficient under soft contact: (1) The approximate method, and (2) the full soft EHL solution. Scheme (1) is based on the friction coefficient prediction equation proposed by Couette flow theory [220, 227] as shown in Eq. (6) [226]:

$$\mu=K(\eta U)^{0.34} \tag{6}$$

$$K=0.8(\mathrm{SRR})R^{-0.09}W^{-0.12}E^{*-0.22} \tag{7}$$

$$\pi a^2=2.6\left(RW/E^*\right)^{0.67} \tag{8}$$

$$\mathrm{SRR}=2\left(u_{\mathrm{D}}-u_{\mathrm{B}}\right)/\left(u_{\mathrm{D}}+u_{\mathrm{B}}\right) \tag{9}$$

where W is the applied load, R and E^* are obtained from Hertz theory (equation 8), SRR is the slip-roll ratio and is defined by Eq. (9), u_{D} and u_{B} are disc/ball speed of contact body.

Scheme (2) used the forward iterative method [223] to solve the two-dimensional Reynolds equation and the elasticity equation respectively in Eqs. (10) and (11) [226]:

$$\partial/\partial x\left(h^3\partial p/\partial x\right)+\partial/\partial y\left(h^3\partial p/\partial y\right)=12U\eta\,\mathrm{d}h/\mathrm{d}x \tag{10}$$

$$\omega(x,y)=1/4\pi E^*\iint_A p\left(x',y'\right)/r\,\mathrm{d}x'\mathrm{d}y' \tag{11}$$

where p denotes the local pressure at (x',y'), ω represents the total elastic deflection at the point (x,y). The undeformed spherical surface is approximated as a paraboloid, which is given by Eq. (12) [226]:

$$S(x,y)=x^2/2R+y^2/2R \tag{12}$$

The finite difference method was used as the solution method [226]. From Fig. 12(a), it can be seen that the second method achieves better consistency.

Cowap et al. [214] used different ratios of aqueous solutions of glycerol to build food model fluids to simulate the frictional behaviors of milk, cream, and edible oil during soft-hard contact. They found that the total friction coefficient was influenced by adhesion friction, velocity, and hysteresis friction. And a prediction model for the friction coefficient was derived in Eq. (13) [214]:

$$\mu_{\mathrm{Total}}=0.83(\mu_{\mathrm{Hysteresis}})-0.18(V_{\mathrm{Speed}})+\alpha+\beta(\mu_{\mathrm{Dry\ adhesion}}) \tag{13}$$

where $\mu_{\mathrm{Hysteresis}}$ is the hysteresis friction coefficient, V_{Speed} is the sliding speed, $\mu_{\mathrm{Dry\ adhesion}}$ is the dry adhesion friction coefficient, the specific values of α and β in the equation are from Ref. [214]. Good agreement was achieved between the predicted friction coefficient and the actual value.

In addition to predicting the coefficient friction, researchers want to establish quantitative relationships among the rheological properties, texture of food

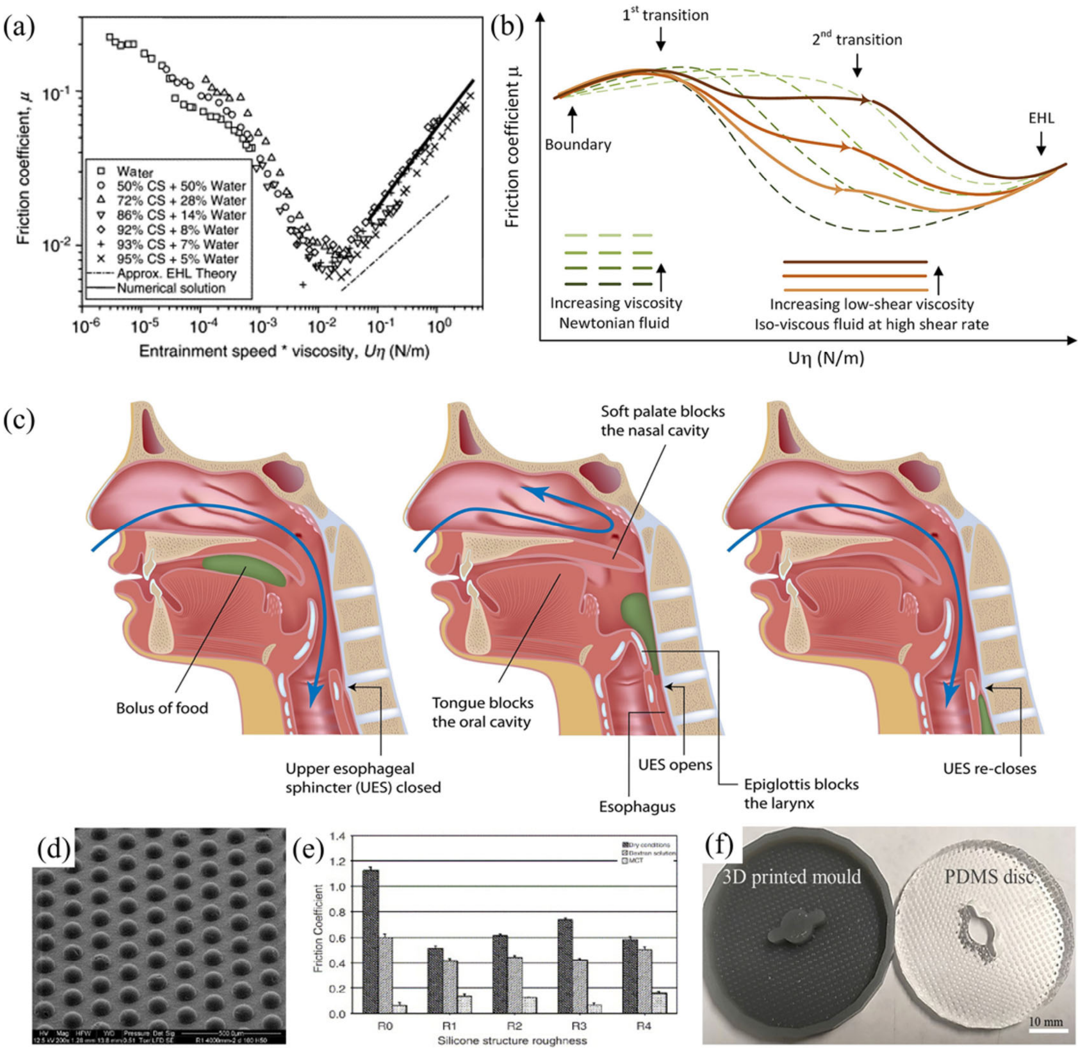

Fig. 12 (a) Stribeck curves of corn syrup solutions versus approximate solutions/full film EHL solutions. Reproduced with permission from Ref. [226], © Elsevier, 2006. (b) Non-Newtonian fluid Stribeck curve variation diagram. Reproduced with permission from Ref. [217], © Elsevier, 2020. (c) The whole process of human swallowing. Reproduced with permission from Ref. [246], © Public Library of Science, 2018. (d) Spherical regular array of friction surface morphology and (e) effect of different silicone surface roughness on friction coefficient (R0: untreated surface, R1–R4 hemispherical surface with different parameters). Reproduced with permission from Ref. [33], © Elsevier, 2006. (f) PDMS friction pairs and dies with cylindrical arrangement of surfaces. Reproduced with permission from Ref. [253], © Elsevier, 2020.

products, and the friction coefficient [105]. A correlation between thickness and tongue shear stress was reported in the study of Newtonian fluids and is given by Eq. (14) [105, 228]:

$$\text{Thickness} \propto \text{shear stress}\, \tau = \eta^{1/2} W^{1/2} V \left(4t/3\pi R^4\right)^{1/2} \tag{14}$$

where η is the coefficient of Newtonian viscosity, W is normal force between tongue and palate, V is tongue movement speed, t is time, R is the radius of the tongue. A relationship between thickness and fluid viscosity is established from this formula, which provides a relatively accurate method for improving the sensory evaluation of thickness. For some non-Newtonian fluid foods that exhibit power-law behavior (juice, cream, etc.), the numerical model for thickness is given by Eq. (15) [104, 105]:

$$\text{Thickness} \propto \text{shear stress on the tongue} = mV^n[1/h_0^{(n+1)/n} + \left((F/R^{n+3})\cdot(n+3/2\pi m)\right)^{1/n}\cdot(n+1)/(2n+1)t]^{n^2/n+1} \tag{15}$$

where h_0 is initial gap between tongue and palate in the presence of fluid, all remaining parameters in Eq. (15) are given by Ref. [104]. There is a significant relationship between thickness and shear stress values. Smoothness can be quantitatively related by physical parameters as the thickness. Previous studies [104, 123] reported that smoothness might be significantly influenced by frictional forces. The relationship between friction coefficient and smoothness is further corroborated by friction experiments of chocolate samples mixed with saliva [67]. The quantitative relationship is given by Eq. (16) [104, 105, 123]:

$$\text{Smoothness} \propto 1/\left(\mu F_{\text{Tongue}}\right) \tag{16}$$

where μ is the coefficient friction, F_{Tongue} is normal force of the tongue on food. Creaminess was found to be closely related to the evaluation of thickness and smoothness, and its mathematical model is given by Eq. (17) [123]:

$$\text{Creaminess} \propto (\text{thickness})^{0.54} \times \text{smoothness}^{0.84} \tag{17}$$

It was found that creaminess was closely related to softness in addition to thickness and smoothness, and a quantitative relationship was established between creaminess and these three sensations in Eq. (18) [229]:

$$\begin{aligned}\text{logCreamy} = {} & 0.52\text{logthick} + 1.56\text{logsoft} \\ & - 0.32\text{logslippery}\end{aligned} \tag{18}$$

The numerical predictions achieved a good fit with the experimental sensory evaluation scores.

In addition to focusing on mathematical and physical modeling, many scholars have also constructed conceptual food systems to represent corresponding real foods. This allows an in-depth investigation of the lubrication behavior of foods with similar structures, which is important for the study of the food oral processing. Food emulsions often exhibit non-Newtonian properties and exist as shear-thinning fluids (e.g., milk, yogurt, etc.). There are many sensory attributes associated with food emulsions, such as creaminess, smoothness, and thickness, which are often related to the texture, rheological properties, and frictional behavior of the emulsion [230]. Oil in water emulsions were prepared with sodium caseinate as the emulsifier. And the correlation between rheology and oral perception was examined by adjusting the fat content, oil droplet size, and viscosity. A significant association was found among η_{50}, thickness, and creaminess. Droplet size did not reflect a significant difference in rheological behavior [216]. Fat usually led to changes in the perception and lubrication behavior of emulsions. The presence of fat decreased the friction coefficient, which was attributed to fat-induced agglomeration to form oil films improving lubrication conditions. The increase in friction on hydrophobic surfaces was thought to be correlated with the concentration of proteins as a result of their adhesion to the contact surface [231]. The addition of saliva also significantly reduced the friction coefficient of the emulsion, but it changed by the presence of surfactant and fat (which was related to their interaction) [232]. The adhesion and diffusion of emulsion droplets on the contact area decreased the friction of the emulsion owing to the droplet and contact surface wettability, electrostatic and spatial interactions [233]. Protein microbubbles, as the substitute for fat in emulsified foods, could enhance the creaminess of foods [234–236]. The tribological technique was used to compare the frictional properties of food systems containing emulsified droplets with those containing microbubbles. The lubrication behaviors were similar, and microbubbles did not significantly enhance the lubrication behavior of the model liquid [237, 238]. The possibility about its replacement of fat needs to be further explored. The frictional behaviors of whey protein model foods were examined by different motion patterns (linear/elliptical). The elliptical motion was found to be closer to the real motion of the tongue. The mode of motion was also found to affect the friction coefficient of the model food (ellipse < straight line) [239]. The frictional properties of water in oil solutions under soft friction conditions were also researched [219]. The volume of the aqueous phase dispersed in the solution influenced the lubrication behavior of the emulsion through changing effective viscosity. The friction coefficient in the boundary/EHL region was affected by the phase volume affected and varied by the load.

Oral processing surfaces are considered to be soft, and the lubricity under soft friction is important for modeling oral processing. de Vicente et al. [240] studied the lubrication properties of different polymer solutions. They usually showed non-Newtonian behaviors, and the viscosity value of the solution at high shear rates was taken as the scale factor of the Stribeck curve transverse coordinate. The polymer concentration affected the friction coefficient in the mixing region, while it has almost no effect on the boundary region. The friction coefficients of xanthan gum and guar gum solutions were higher than that of pure water under hydrophobic conditions. It is due to the physical properties of polymer particles that are not entrained into the contact area and do not improve the lubrication behavior of the contact area. For the friction coefficient in the EHL regime of polyethylene oxide solutions, the experimental and numerical solutions had a good correlation [240]. Myant et al. [30] examined the frictional behaviors of three fluids (water, glycerol aqueous solution, and corn syrup solution) under soft–soft contact. Effects of elasticity of the frictional materials and the load were also investigated. It was found that the increase in the friction coefficient was accompanied by the decrease in the load and elastic modulus of the friction bodies. The measured and theoretically predicted friction coefficients were relatively consistent in both sliding and rolling modes under I-EHL conditions. Polymer solution concentration and friction coefficient appeared an opposite trend and friction behavior was affected by surface wettability. Gabriele et al. [241] reported the effects of different concentrations, physical properties of particles (stiffness, size) on friction behaviors using agarose liquid gels as model fluids. The friction coefficient was found to be proportional to the concentration and inversely proportional to the particle size. The hardness of the particles affected the magnitude of the transition velocity of the Stribeck curve. Nanocrystalline cellulose (NCC) has the advantages of small size, easy flow, and low interference effects. Xu and Stokes [217] obtained a non-Newtonian fluid model with shear thinning properties by mixing NCC with aqueous glycerol solution. And a secondary curve transition not seen in previous Newtonian fluid curves was found in the generated Stribeck curves (Fig. 12(b)). The transition was more obvious when the contact surface was rougher. Microscopic local EHL and the interaction between the fluid and the rough surface were thought to be responsible for the appearance of the second transition.

4 Simulation of oral processing based on tribology

Food is subjected to squeezing and shearing movements in oral manufacturing by tooth–tooth, tooth–tongue, and tongue–palate interactions. This complicates the study of the lubrication behavior of food in the oral cavity [242]. The tongue in the mouth is capable of producing complex combinations of movements, which affects the gap between the tongue and palate. A tight arrangement of different types of papillary receptors makes up the surface of the tongue. It is rough and hydrophobic, but the wettability is greatly improved when saliva is adsorbed on its surface. Lingual papillae are usually divided into four categories with filamentous and fungal papillae in the front and lobulated and pinnate papillae in the back. Their presence allows the tongue to receive mechanical and chemical stimuli from different foods [243–245]. Chewing and swallowing of foods are affected by the properties of the food mass itself (volume, viscosity, and hardness), oral pressure, salivary decomposition, and tongue movement. The swallowing process is illustrated in Fig. 12(c) [246]. Many scholars have examined the chewing and swallowing behaviors and mechanical properties of different foods by instrumental techniques as well as swallowing models through finite element methods [247–250]. Current tribologists are mainly concerned with the behavior of the tongue–upper jaw movement in the mouth. As the food moves in the mouth, its thickness gradually decreases to a thin film layer and the length scale changes during the movement. Then the film shape plays a major role instead of the bulk properties [251, 252]. Therefore, tribological methods can provide a good explanation for the oral movement of food [80]. And frictional behavior plays an important role in the perception of food texture [3]. To understand the real processing laws, it is necessary to explore friction materials with similar charac on the tongue and upper jaw. It is important to examine the factors affecting the lubrication behavior by changing the physical properties (stiffness, wettability, roughness, and surface texture) and motion patterns (pure sliding/sliding + rolling) of the friction pairs. Thus *in vitro* simulation of oral environment better fitting the real oral conditions is essential to accurately grasp the laws of food oral processing. Researchers have been studying various tongue and palate materials to mimic oral conditions as listed in Table 3.

De Hoog et al. [28] reported the tribological results of food emulsions with different friction pairs including metal, rubber, and glass. The measured friction coefficient decreased under soft materials with rising loads, but it was more stable under hard materials. This phenomenon was caused by the differences in surface roughness and hardness. Sadowski and Stupkiewicz [259] also reported that surface morphology and rigidity affected the transition of lubrication. Chojnicka-Paszun and de Jongh [266] investigated the friction behaviors of polysaccharide solutions under different rubbers and found that softer and flatter friction surface reduced the coefficient friction. Carpenter et al. [262] used silica and PDMS as simulated tongue–upper jaw friction to research the lubricities of saliva and water. Material stiffness affected friction behavior and film thickness was in the EHL regime. The charged groups of PDMS allowed the adhesion of proteins in saliva [267]. And there was a strong

Table 3 Friction materials and experimental conditions used for *in vitro* friction experiments.

Contact form	Tribopairs		Movement mode	Physical modification	Reference
	Upper pair	Lower pair			
Ball on disc/plate	PDMS ball	PDMS disc	Rotation	Surface roughness, wettability	[34]
	Steel ball	PDMS plate	Rotation	Surface roughness/texture	[253]
	Steel ball	Silicone disc	Rotation	—	[254]
	Steel ball	PDMS plate	Rotation	Added saliva	[255]
	PDMS ball	PDMS disc	Rotation	Added saliva	[256]
	PDMS ball	PDMS disc	Rotation	Coated mucin	[257]
	PDMS ball	PDMS disc	Rotation	Surface roughness, added saliva	[258]
	NBR^a ball	NBR disc	Rotation	Surface roughness	[259]
	PP^b ball	HDPE^c plate	Rotation	—	[260]
	Steel ball	Silicone plate	Straight line	Surface roughness/texture, wettability	[33]
	Steel ball	Pig's tongue	Straight line	Added saliva, wettability	[261]
	Hydrogel ball	Hydrogel plate	Straight line	—	[192]
	PTFE^d ball	ZrO_2^{e} disc	Rotation	—	[74]
	Steel ball	Polyurethane plate	Rotation	wettability	[71]
Pin on plate/disc/flat	Silica pin	PDMS plate	Rotation	Added saliva	[262]
	PDMS pin	PDMS disc	Rotation	—	[27]
	PDMS pin	PDMS disc	Rotation	—	[263]
	PDMS pin	PDMS disc	Rotation	Wettability	[264]
	PDMS pin	Glass flat	Straight line	—	[43]
	PDMS pin	Glass flat	Straight line	—	[169]
	Stainless steel pin	DMAA^f disc	Rotation	—	[265]
Plate-plate	Pig's tongue	Pig's esophagus	Rotation	—	[28]
	Silvered mica plate	Silvered mica plate	Straight line	Added saliva, wettability	[151]
Ring on plate/disc	Steel half ring	surgical tape plate	Rotation	—	[125]
	Neoprene o-ring	Silicone disc	Rotation	—	[266]

a: nitrile butadiene rubbe; b: polypropylene; c: high density polyethylene; d: polytetrafluoroethylene; e: Zirconia; f: poly-dimethylacrylamide.

association between friction coefficient and protein signal, which was observed by the fluorescence microscopy. The adsorption behavior of mucins on PDMS surfaces was influenced by pH as well as competing functions of themselves [27]. Bongaerts et al. [34] examined the friction behaviors of different Newtonian fluid solutions using modified PDMS friction surfaces. They were treated through oxygen plasma and sandblasting to alter the surface wettability and roughness. It was found that the decrease in the boundary friction coefficient was caused by the reduction in the contact angle and surface flatness. However, the frictional behavior in the EHL regime was not affected by these two factors. In their subsequent work, friction experiments were performed for different treated human whole saliva and surface roughness enhanced the friction coefficient of saliva. Different handling methods affected the rheological properties of saliva and hydration was found to be important for lubrication by comparing dry saliva with moist saliva [258]. Porcine tongue has also been widely used for *in vitro* oral friction experiments as a tribopair material with similar characteristics to the human tongue. The surface of porcine tongue showed hydrophobicity, but the wettability was improved significantly after the application of saliva. This suggested that saliva could significantly improve lubrication and it was essential when simulating oral processing [261].

The above studies did not consider the effects of the texture as well as the arrangement on the friction surface, but in fact the tongue surface is a combination of rough and arranged papillae. Thus it is necessary to investigate the influences of the tribopair texture. Ranc et al. [33] used a mold to fabricate a soft material with a hemispherical array on the silicone rubber surface (Fig. 12(d)) and performed comparative experiments by adjusting the size and density of the hemisphere. Water and medium chain triglycerides (MCT) oil were used as lubricating fluids. The fabricated friction materials were closer to the real condition of the tongue surface and the experimental results showed that the frictional behavior of the fluid was strongly influenced by the contact surface topography. The friction coefficient of the treated surface was significantly lower than that of the untreated surface (Fig. 12(e)), which seemed to be influenced by the contact surface texture. In the case of dry friction, the friction coefficient became bigger with the rising density of the surface hemisphere, while the opposite trend was in the presence of lubricant. This was considered to be the result of the surface protrusion interfering with the fluid flow. The effect of surface morphology on flow behavior was also found in Ref. [253]. They prepared PDMS friction pairs with cylindrical arrays (Fig. 12(f)), and fabricated different surfaces by adjusting the size and density. Friction experiments of suspensions containing round particles showed that friction decreases when the particle size was smaller than that of the surface cylinder and vice versa. The effect of tongue texture on friction behavior was also studied in the work [26]. They replicated the surface state of real tongues through rubber and plaster. Tongue surfaces mostly exhibited symmetry with the roughness increasing from the posterior to anterior. The tongue surface contours usually showed irregular arrangements and shapes, which posed a challenge to simulate real food machining situations. Andablo-Reyes et al. [268] used two polymer materials covering the tongue to collect surface contours and obtained morphological data by software scanning analysis. Afterwards, the surface morphology was generated by Poisson surface reconstruction algorithm. Finally, the friction materials were manufactured using 3D printing. The prepared friction materials greatly reproduced the real tongue surface and provided a new method to simulate the oral environment.

5 Friction equipment

Friction devices, as commonly used *in vitro* test instruments, are essential tools for probing the lubricating behaviors of foods in mouth, because it is hard to conduct *in vivo* experiments from technical and ethical perspectives. Friction devices applied on food have made great strides in recent years in various aspects as listed in Table 4. Olsson et al. [275] used a sliding tribometer to test the lubricating behavior of oral mucosal surfaces and found the lubricating effect of saliva. Friction test equipment was used by de wijk and Prinz [79] to study the friction characteristics of

Table 4 Overview of tribological equipment applied to the food industry.

Equipment name	Contact form	Flash point	Reference
Friction tester	Cylindrical–strip	Simple and convenient operation, stable measurement	[79, 162, 269]
Customized friction device	Cylindrical–flat	Easy to use, low cost, dynamic/static friction of the material can be measured	[28]
SFA	Plate–plate	The friction material is easy to replace, can simulate shear and squeezing movement, and can observe the change of contact area.	[44]
CSM tribometer	Pin–disc	Easy installation for rotary movement and temperature control	[73]
HFRR	One ball–one disc	Constant load reciprocating shearing motion can be realized, and the experimental temperature can be adjusted	[35]
Friction equipment (based on texture analyzer)	Plate–plate; Three balls–a plane	Close to tongue and upper jaw contact, easy to operate, cheap, better measurement accuracy	[45, 46]
New friction device (based on rheometer)	A ball–three flats; Two balls–a flat; Three balls–a plane; Ring–a plat	Friction pairs can be replaced flexibly, with a wide range of temperature/load/speed. More accurate measurement data	[32, 92, 270–272]
OTC	A probe–a flat	Flexible material changes, actual changes in the shearing process can be observed	[43, 169]
MTM	One ball–one disc	Wide range of use, large adjustable load/speed range, sliding, rolling, and mixed modes can be adjusted. The most accurate experimental data.	[3, 273]
Bionic friction equipment	Plate–plate	Shearing motion can be realized and the force in the direction of three axes can be measured with high accuracy	[274]

semi-solid foods (creamy desserts and mayonnaise). It is an early and relatively simple device, which consists of a rubber band connected to a weight sensor and a drive roller (Fig. 13(a)). The lubricated sample is placed between the rubber band and roller driven by a motor. The equipment is inexpensive and easy to operate, but the surface material is consumed quickly and the range of materials available is small. The ability to simulate oral processing is limited and the accuracy of the motion needs to be improved. de Hoog et al. [28] also developed a friction device with a similar motion pattern. It is made of a rotating shaft and a slide bar, and the mucous membrane material is fixed on both surfaces. The adjustment of the load is achieved by adding weight and the friction force is recorded by a sensor connected to the slide bar. The OTC is also commonly used as an *in vitro* friction device to explore the behavior of oral lubrication, which consists mainly of two mutually rubbing surfaces and CLSM [43, 169]. The upper friction pair is replaceable and the lower end is a glass surface. The device can perform shear motion on the test sample under constant load conditions. The changes of the sample structure in the friction region can be observed through the CLSM assembly under the glass. However, the adjustable ranges of load and speed are small, which limits its use.

Due to the advantages of the rheometer itself (large velocity range, controllable load, and temperature setting function, etc.), friction instruments have been made based on it. Heyer and Läuger [272] installed a friction measurement attachment on the rheometer. It consists of a ball and three plates and plates are placed in a vessel at the same angle of inclination. The test sample is put in the vessel and the ball makes a rotational motion. The high resolution as well as the flexible adjustment of the motion parameters proved the potential of this type of experimental apparatus. In addition, two ball–disc (Fig. 13(d)) and three ball–plane configurations have been applied in rheometer-based friction devices [92, 270], which increases the stability of the device and facilitates more accurate data recording. Godoi et al. [271] used a ring-plane structure (Fig. 13(e)) in their experiments. The upper tribo-pair is connected to the rotation device by a coupler to achieve rotation, the lower surface

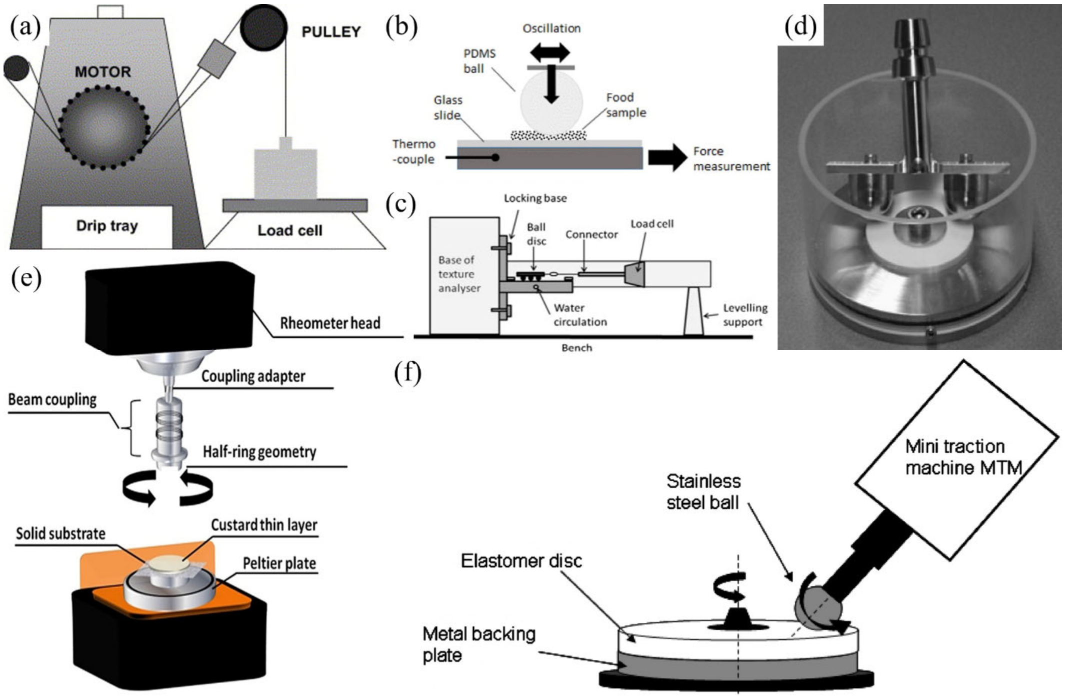

Fig. 13 (a) Schematic diagram of friction equipment. Reproduced with permission from Ref. [79], © Elsevier, 2005. (b) Sketch of HFRR device. Reproduced with permission from Ref. [35], © Elsevier, 2016. (c) Experimental device based on texture analyzer. Reproduced with permission from Ref. [46], © Elsevier, 2014. (d) Friction device based on rheometer. Reproduced with permission from Ref. [270], © Elsevier, 2010. (e) Tribo-rheometer experimental equipment. Reproduced with permission from Ref. [271], © Elsevier, 2017. (f) Equipment diagram of MTM. Reproduced with permission from Ref. [30] , © Elsevier, 2010.

is prepared by 3M surgical tape and a Peltier plate is installed below it to control the experimental temperature.

Chen et al. [46] performed friction experiments using a modified texture analyzer, which is a three ball–plane configuration with three balls arranged in a triangle to improve the stability of the measurement (Fig. 13(c)). A water bath system below the flat surface is used to ensure the test temperature. The experimental device can simulate tongue and upper jaw processing in pure sliding friction. They have also used 3D printing technology to improve the connection between the tribology pairs and the sensor used in this instrument, further improving the accuracy of the experiment [276]. Moreover, there are several other sliding friction devices applied in the food field. For example, Tsui et al. [35] used the HFRR apparatus (Fig. 13(b)) for reciprocal sliding friction experiments on yogurt. It used a ball-on-disc configuration. The experimental parameters were adjusted by a program in the computer. A sensor under the disk was used to record friction data. The reciprocating friction device BTM in pin–disk contact was applied to the lubrication behavior of chocolate [31]. SFA was used to measure the frictional force of a fluid using a plane–plane configuration where the frictional pair is connected by two vertically oriented springs moving in a linear motion. The interaction force between the two surfaces was measured by the deflection of the connected springs. The deformation of the contacting surfaces could be observed by optical interference techniques [44]. Srivastava et al. [274] have recently developed a novel bionic friction device which was a plane–plane contact. The lower cavity could be placed into the bionic tongue friction substrate and the test sample is coated on the tongue surface. The device could conduct transverse shear motion. It had high stepping accuracy and could better simulate the tongue–upper jaw contact motion.

MTM (Fig. 13(f)) has been also widely used in the oral food tribology, where it can provide automatic traction mapping. It is a ball on disc contact and can flexibly replace the friction pairs. The experimental sample is usually placed on the surface of the disc connected to the vertical axis, and the ball is connected to the rotation axis. The lower disc is rotated by a motor with high accuracy and a wide speed range. Force sensors placed on the ball are used to measure the traction force. The setup can be set in sliding, rolling, or mixed mode well simulating the real tongue and upper jaw situation [3, 30]. However, the equipment is expensive, which may limit its application in the food industry.

6 Food testing

Food safety has always been the most important issue in food industry and it is related to people's daily diet and health. Some unscrupulous businessmen added some cheap or even harmful ingredients in food to achieve greater benefits. Established methods such as mass spectrometry or chromatography [277–279] are capable of performing effective food composition tests to detect whether food products are adulterated. However, their use requires professional operators, more time, and high cost to handle, which limits the spread of these techniques. Therefore, a simple and efficient method to detect food adulteration is currently needed. Tribology technique has been applied to food safety test recently and it is easy, quick, and effective. Different components in food may result in different frictional behaviors, which provides a basis for detecting food adulteration. Melamine-adulterated milk has been detected by oral tribology [19]. The addition of melamine can increase the nitrogen content according to its chemical structure (Fig. 14(a)) and be misdiagnosed as the protein by Kjeldahl nitrogen determination [280], and it is hard to be detected. Nevertheless, in the friction experiment, it was found that the friction coefficient of melamine-adulterated milk was significantly greater than that of normal milk for the same protein content (Fig. 14(b)). Subsequent wettability tests revealed that the adulterated milk was less hydrophilic and more difficult to form a film to improve lubrication in the frictional contact area. Later the authors also tested rice syrup adulterated

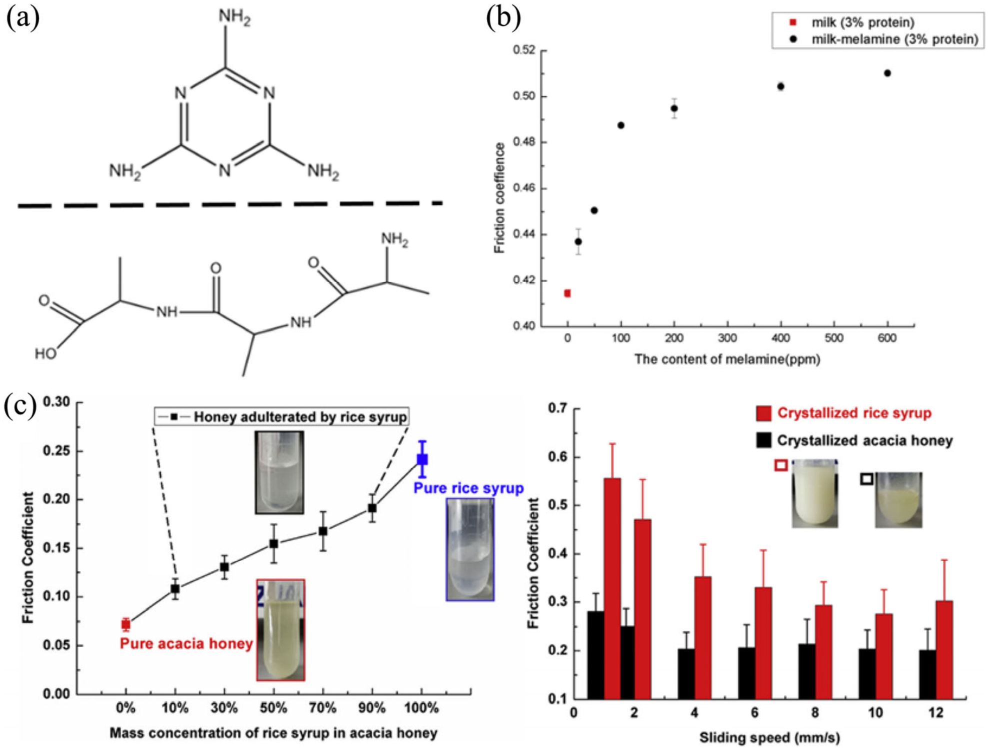

Fig. 14 (a) Chemical structure formula ((top) casein; (bottom) melamine) and (b) change in friction coefficient between regular milk with 3% protein content and melamine-added milk. Reproduced with permission from Ref. [19], © Elsevier, 2018. (c) Left: Comparison of coefficient of friction between liquid acacia honey and rice syrup mixed with different concentrations; Right: Coefficient of friction between crystallized acacia honey and crystallized rice syrup at different speeds. Reproduced with permission from Ref. [50], © Elsevier, 2019.

acacia honey using tribological methods [50]. Tribological experiments were conducted on liquid honey adulterated with different concentrations of rice syrup and crystallized honey/rice syrup under simulated oral environment (Fig. 14(c)). Adulterated liquid acacia honey was found to increase the friction coefficient rapidly with rising concentration of rice syrup. The friction coefficient of liquid acacia honey was in the EHL regime while the adulterated honey was in the boundary region based on the Stribeck curve. The difference between crystallized acacia honey and adulterated honey was more pronounced at low velocities. These studies extend the application of tribological methods in the food industry and it should fulfill its potential at food safety in the future. For instance, oral tribology can be a simple and quick pre-detection method for suspicious foods before complicated tests.

7 Conclusions and outlook

Food oral tribology has played an important role in addressing the faced challenges in food industry. Relevant research has been conducted extensively over the past few decades, and this review provides a new perspective by summarizing the studies of tribology on oral lubrication behavior and the relationship between friction and sensory perception of foods. In addition, research progress has been concluded in this paper, including conceptual models of foods, the prediction of frictional behavior, the quantitative relationships among physical properties of foods, oral perception, and frictional/rheological behaviors, etc. Friction devices have also made great strides in recent years, and all these factors will contribute to the further development of tribology in the food field. However, due to the diversity of food types and the complexity of oral processing behavior, there are still many unknown aspects of food oral tribology that need to be explored. The following are the author's suggestions on the current challenges and future development of food oral tribology:

1) Simulating the complex oral environment remains difficult. For example, the movement of tongue is complicated because it is controlled by multiple muscles. And the tongue's stiffness changes dynamically with movement. However, current friction experiments mainly use two modes of motion, reciprocating and rotating movements. The dynamic property of the tongue cannot be fully reproduced. In addition, some components of food (tannins, anthocyanin, etc.) can react physically and chemically with the tongue surface to affect the oral lubrication behavior. But it is difficult to simulate similar reactions for some conventional friction materials (rubber, steel, etc.). And there is a degree of instability in the preparation of biological friction materials such as pig tongue. A reliable and reproducible biological friction material has not yet been found. In addition, more research results have been obtained on the friction behavior of fluid and semi-solid foods, but research on hard solid foods is still lacking. In a recent sensory study using tribology [102], transient friction behavior instead of steady state corresponds to the perception of hard food. This is a significant difference from previous studies on fluids and soft foods. Therefore, it needs further investigation by researchers in this area. What's more, the teeth, as the first procedure of food oral processing, can break down food and reduce the particle size by biting, which can assist in swallowing. However, the conditions of teeth will get worse by bad chewing habits, lower water content, less saliva adhesion, higher food hardness, and erosion of acidic drinks [281–285]. It will gradually lose the role of the tooth itself and affect the subsequent oral processing behavior. There is a clear correlation between dental tribology and food oral tribology, and its development should also receive attention. These aspects of research can help explore the real oral processing laws, play a role in guiding food processing, and improve the food manufacturing process.

2) Healthy, green, and nutritious food is one of the future goals in the food industry. Many researchers in the field of food and tribology have made a lot of exploration and developed some low-fat, low-sugar, and high-nutrition food. However, some of them have destroyed the original food taste properties and affected the eating experience. The intervention of food oral tribology technology can examine such problems and improve its taste according to the test results. This not only meets the requirements of healthy diet and environmental protection but also increases the

acceptability of such food. The current application of tribology in this field is limited compared to the rich variety of foods, and more scholars are needed to further extend the application to more food products.

3) The development of functional foods and easy-to-swallow medicines cannot be ignored. For vulnerable groups such as the elderly with weak chewing ability, swallowing difficulties, and dry mouth syndrome patients, the eating experience is poor, which is detrimental to the absorption of nutrition and medicinal effects. The ease of swallowing for such people is more important than the taste of food, which puts forward higher demands on the lubricity of food. In the future, it is worthwhile to investigate whether the lubricity of food or pharmaceutical products can be significantly raised by adding ingredients to foods and covering solid tablets with coatings to improve their swallowing abilities. This would greatly enhance the quality of life and well-being of specific vulnerable groups who suffer from swallowing problems.

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Wenhu XU. He received his Ph.D. degree in mechanical engineering from Tsinghua University in 2011. From 2011 to 2016, he worked at the Research Institute of China National Offshore Oil Corporation, China, as a mechanical engineer. Since 2016, he has worked at Nanchang University and his current position is a professor. His research areas cover chemical mechanical polishing, friction material, food oral tribology, etc.

Min ZHONG. She received her Ph.D. degree in mechanical engineering from Tsinghua University in 2010. From 2010 to 2013, she worked at China National Building Material Group Co., Ltd. as a technology director. Since 2016, she has worked at Nanchang University and her current position is an associate professor. Her research interests include food oral tribology, chemical mechanical polishing, self- lubrication material, etc.