Andrew Rosenthal · Jianshe Chen
Editors

Food Texturology: Measurement and Perception of Food Textural Properties

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Preface

The first edition of *Food Texture: Measurement and Perception* was unique among food texture books of the age, in that it provided both theoretical and practical methodology as well as supplying commodity specific chapters, effectively applying the techniques to real foods. Prior to the first edition, many food texture professionals would describe instrumental methods as "*objective*", while denigrating sensory methods as being "*subjective*" and unscientific. However, the book recognized the objectivity of modern sensory methodologies and presented both sensory and instrumental techniques as equals and worthy of scientific respectability. In reality, it has always been the case that sensory methods provide the standards for which the instrumental techniques must be calibrated, for above all else, texture is a sensory phenomenon.

In the long history of food texture research, texturology has been occasionally used in literature. The term texturology has not been widely accepted by texture researchers (texturologists) because of the concern of whether the theories and techniques are broad and strong enough to support texture research as a scientific discipline. During the 25 years since the publication of the first edition, we have seen vast developments in theories as well as the assessment methodology (both sensory and instrumental), and these have shaped our understanding and view of food texture. We are confident that food texture research has grown as an independent and respectable scientific discipline and have therefore changed the title of this second edition to *Food Texturology: Measurement and Perception of Food Textural Properties*.

This second edition is divided into four main parts which provide an introduction and background (*Food Texture, Fundamentals*) to the general area of food texture; a comprehensive coverage of sensory aspects of food texture (*Food Texture, Sensory and Human Interactions*); the application of instrumental methods to assess for texture (*Food Texture, Instrumental Analysis*); and a review of the texture of the key commodity groups from both an instrumental and sensory perspective (*Food Texture, Food Products*).

Food Texture, Fundamentals has four chapters covering some fundamental aspects of food texture. Building on the first chapter of the previous edition, Andrew Rosenthal and Jianshe Chen have written an introductory chapter "Instrumental and Sensory Measures of Food Texture"; here, they set the scene by recognizing the validity of both sensory and instrumental approaches to the assessment of food texture, identifying some of the key attributes. Of course, the texture of foods is fundamentally influenced by the food's structure and in "Food Structure as a Foundation for Food Texture", Pedro Bouchon, Ingrid Contardo and María Teresa Molina consider microstructural aspects of a range of foods, examining how that structure leads to distinctive textures. Taking a somewhat novel approach, Andrew Rosenthal presents a chapter entitled "Texture Maps and Diagrams". Here he explores some of the diagrammatic representations of food textures from both a sensory perspective (e.g. PCA diagrams) and instrumental measurements (e.g. stress:strain diagrams). This chapter explores some of the structural relationships outlined in the previous chapter. We hope that through this chapter, readers will be able to understand food texture from very different perspectives.

As texture is a sensory phenomenon, and as in the case of food texture that phenomenon is predominantly experienced in the mouth, it is essential that the part on Fundamentals includes a review of "Oral Physiology and Mastication". Here Marie-Agnes Peyron delves into oral physiology, control and adaptation of mastication, as well as oral processing and bolus formation.

Food Texture, Sensory and Human Interactions has four chapters considering both consumers and sensory panels. Readers should be aware that a holistic approach has been taken in this book as far as food sensory evaluation is concerned. Unlike the first edition, sensory analysis and practice is no longer the only concern, but a much broader range of sensory-related topics are included. This part starts with a much-needed review of "Psychophysics of Texture Perception". Taking an historical approach, James Makame and Alissa Nolden develop ideas of psycho-rheology, psychophysics of liquid thickness perception, smoothness, grittiness, greasiness and fat perception as well as the soft-hard continuum.

Deciding on the order of chapters can be difficult for editors, and we puzzled over the order of the topics "sensory methodology" and "sensory vocabulary", for which comes first? In "Sensory Scaling and Measuring Techniques", Betina Piqueras-Fiszman outlines the variety of sensory data collection methodologies. Beginning with the classic descriptive methods, she reveals some of the contemporary methods including attribute-based methods, temporal techniques, open-ended questions and holistic methodologies. In the following chapter, the "Meaning of Sensory and Consumer Terminology", Arantxa Rizo and Amparo Tárrega categorize the vocabulary to describe attributes used in sensory testing. While this book is published in English, the authors consider similar classifications in other cultures and languages. In addition to the terms used by sensory scientists, the authors also consider consumer vocabulary.

The final chapter in the part is "Consumer Perception of Texture in Relation to Satiety and Preference". Here Quoc Cuong Nguyen and Paula Varela examine the drives for individuals in consuming foods and the influence of texture on their behaviour. The chapter is helpfully illustrated with two case studies.

We believe that the four chapters in this part on *Food Texture, Sensory and Human Interactions* reflect an up-to-date understanding of the sensation, their perception and measurement of food textural properties.

When inviting authors to contribute to the *Food Texture, Instrumental Analysis* part of the book, we instructed them to focus on instrumentation as opposed to the classification of foods or specific test procedures. Considerable technological advances have taken place in the years since the first edition, so much so that in addition to the texture analysers and viscometers/rheometers examined previously, the newer science of food tribometry is included, as are further novel instrumental approaches. The editors of this book are acutely aware that collected data depend entirely on methodology and that treating an instrument as "black box" is a recipe for disaster. Thus, knowing how instruments work and their limitations is key to good research.

The section begins with an examination of the workings of the much-used "Texture Analyser". From instrument construction, to calibration, force and height verification, to load cell limitations and software, Katie Plummer dissects the workings of the machine as it is now, but also looks at some of the up-and-coming methodologies.

In "Rheometry and Rheological Characterisation", Shona Marsh and Florian Rummel provide insights into appropriate choice of instrument setup for different types of material. The authors take us through correct operation of the instrument so as to gain meaningful data. The chapter acts as an introduction to the next one as some modern rheometers are able to provide tribometric determinations.

As previously mentioned, food tribometry has become a research area in the 25 years since the first edition of this book was published. In "Tribometers for Studies of Oral Lubrication and Sensory Perception", Qi Wang, Yang Zhu and Jianshe Chen provide an introduction to tribology as well as considering the design and operation of conventional tribometers. The chapter goes on to deal with oral tribology, considering its application to creaminess and astringency.

The final chapter in the part on *Food Texture, Instrumental Analysis* considers "New Instrumental Approaches in Food Texture Research", where Miodrag Glumac explores a variety of novel instruments such as oral masticators, modified texture analysers and instruments which use ultrasonic imaging.

As with the first edition, the section on *Food Texture, Food Products* places the instrumental and sensory methodology into context. The first edition only considered limited numbers of food commodities, though now we have been able to increase coverage, to include the texture of dairy products, sugar confectionery, bakery products, fish as well as a chapter on foods for patients with dysphagia.

In "Texture of Vegetables and Fruit", Marc LaHaye focuses on cell wall polysaccharides. Of course, he considers other aspects of plant food texture such as starch and changes in such foods during processing and storage.

In "Texture of Bakery Products", Lucas Westphal and Amy Voong examine the variety of products ranging from bread to pastry to cookies/crackers and cakes. The chapter provides some understanding as to how the ingredients interact to create the structure which translates into product texture.

In their chapter "Meat and Reformed Meat Products", Kim Matthews and Siobhan Slayven take us through the structure of muscle and the factors that contribute to its composition. They consider slaughter and rigor, as well as post-slaughter processing and how it affects the product, moving on to comminuted and reformed meat products. At the end of the chapter, they provide insights into sensory and instrumental ways of evaluating the texture of both meat and reformed meat products.

Closely associated with meat is fish, and in the chapter "Texture of Fish and Fish Products", Xiuping Dong reviews the factors that produce the texture of raw fish. She goes on to consider elements of processing, including products like surimi, dried fish, smoked fish, fermented fish, canned fish and fish snack products – while some of these are less common in the western diet, they are important products from a global perspective and well worth including in this book.

In his chapter "Texture of Dairy Products", Mike Lewis provides a review which starts with cows' milk considering factors that influence its viscosity. He moves on to the texture of other dairy products such as cream, butter and spreads, dairy foams, concentrated milk products, fermented milk products like yoghurt and cheese, milk powders and products containing dairy ingredients including ice cream and chocolate.

Of course, the ever-popular chocolate provides some overlap between the chapters "Texture of Dairy Products" and "Candy Texture (Sugar confectionery)". In the latter, Meredith Cohen and Richard Hartel review the texture of the variety sugar confections. Starting with hard candy, they move to fondants and creams, jellies and gummies, licorice, marshmallows, chewy candies, caramels, fudge and toffee, tablets and lozenges, chewing gum, sugar panned candies and of course chocolate.

In "Starch, Modified Starch and Extruded Foods", our authors Pranita Mhaske, Mahsa Majzoobi and Asgar Farahnaky discuss the composition of starch and changes during heating and storage. There is some discussion of microscopic techniques which cross-references well with the chapter "Food Structure as a Foundation for Food Texture". They also mention specialized viscometric measurements which cross-reference with the chapter "Rheometry and Rheological Characterisation". This chapter goes on to consider the limitation of native starch as well as the benefits of modified starches. The chapter concludes with a discussion of high-temperature, short-time cooker extrusion of starch-based products.

Following on from, and cross-referencing with the chapter on starch, Vassilis Kontogiorgos discusses other "Hydrocolloids as Texture Modifiers". Vassilis discusses gelation, creation of viscous solutions and emulsification before going on to consider specific polymers such as gelatin, xanthan, gellan, cellulose derivatives, galactomannans, carrageenan, alginates, agar, pectin, gum Arabic and starch.

The final chapter is not really a commodity, but rather considers products designed specifically for the needs of special consumers. In "Textural Aspects of Special Food for Dysphagia Patients", Enrico Hadde and Jianshe Chen evaluate and classify the viscosity and consistency of foods as determined by the robust clinical methods advocated by the International Dysphagia Diet Standardisation Initiative (IDDSI) as well as offering some research quality alternatives.

All in all, this second edition is expanded, brought up to date and now fills some of the obvious gaps that existed in the first edition. We thank all contributors for their expert knowledge in putting up excellent chapters on some very challenging topics of food texture. Thanks are also due to Susan Safren and her colleagues at Springer Nature for their assistance and encouragement in producing this book, which we hope will serve as a landmark in the history of food texturology.

Andrew Rosenthal dedicated the first edition of his book to Harry *[Nursten]* who as a family friend and mentor had influenced his interests and choice of career. This second edition is dedicated to our families and friends, who both inspire us and put up with our foibles.

Baiersbronn, Germany — Andrew Rosenthal
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Part I

Food Texture, Fundamentals

Introduction to the Measurement of Sensory and Instrumental Food Texture

Andrew Rosenthal and Jianshe Chen

1 Introduction

Derived from the Latin *textura*, which means a weave, texture originally was taken to refer to the structure, feel and appearance of fabrics. It was not until 1660s that it started to be used to describe 'the feel, appearance, or consistency of a surface or substance' (*Lexico.com*. Oxford University Press, Web. 20 Jan 2022. https://www.lexico.com/definition/texture). Various attempts to define *food texture* have culminated in some international agreement with the development of ISO 5492 (2009), which deals with the vocabulary used for sensory evaluation; it defines texture as:

> all of the mechanical, geometrical, surface and body attributes of a product perceptible by means of kinaesthesis and somesthesis receptors and (where appropriate) visual and auditory receptors from the first bite to final swallowing.

Clearly food texture is about perception, making it above all other things a human experiences. It is about our perception of a foodstuff which originates in that product's structure and how the product behaves when handled and eaten. Furthermore, it incorporates *all* the attributes (mechanical, geometric, surface and body) of the food, suggesting that the experience of texture involves many stimuli working together, synchronously in combination.

Bearing in mind the above definition, is it reasonable to consider that such a complex array of interactions could be measured with a machine? This is a moot point, for while many samples can be subjected to assorted instrumental and chemical testing procedures, on what basis shall we acknowledge that the results produced have any relation to human perception? Prior to the 1940s, it was generally considered that sensory measurements of food texture were purely subjective and as such generally unreliable. Variation in individuals as well as variability of any one person from day to day seemed to make the sensory analysis of food an art and not worthy of serious scientific study. At that time it was inconceivable that an individual's response could be anything other than personal, hedonic and prejudiced by that persons beliefs and biases. Since our scientific ideology was founded on reproducibility, most serious researchers were persuaded to rely on instrumental testing techniques carried out under standardised conditions. Such techniques were considered to be reliable with relatively small inherent variation or error. The attitude in those days was that instrumental tests were *objective* while sensory work was *subjective.* This is no longer the case and the ethos of this book is to treat

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both sensory and instrumental aspects of food texture as objective, complementary sciences.

In these early years of texture measurement, the study of texture focused on the efforts of the rheologist who measured flow and deformation of food materials. In his discussion paper 'Is rheology enough for food texture measurement?', Bourne (1975) suggested that rheological measurements which often focus on a single large deformation, resulting in the sample breaking into pieces, were inadequate in defining food texture. By comparison, when an individual eats a food, the sample is chewed beyond this initial breakdown, and the stimuli which result from each part of process contribute to the overall texture sensation. While the initial bite is an important aspect of texture, providing us with sensations of hardness and fracturability or flow, so too are the subsequent chews along with the mixing of saliva, providing sensation of stickiness and the development of 'cohesiveness of mass' as the consistency of the food changes. Equally important are aspects of the food's appearance, how moist or greasy it might feel in the mouth, the mechanical properties and sounds that occur when it is handled and eaten, as well as lingering sensations after the product has been swallowed. Clearly rheology is not enough to explain all the rich and complex aspects of texture that are experienced by humans.

Attitudes to the objectivity of sensory research began to change shortly after the Second World War. The US army had made a considerable investment into developing nutritious rations for its troops, only to find that many of them did not appreciate what they were being offered to eat. A focused research programme was developed by the US Quartermasters Corps to look at issues of food acceptability and choice. Development of controlled sensory testing procedures, the separation (in peoples' minds) between *sensory* and *affective* tests, along with advances in multivariate statistical techniques, which were made possible by the application of relatively powerful computers, all helped to bring the perception of sensory testing into scientific respectability.

Without doubt, texture plays a key role in our appreciation of food. Our perception of food texture often constitutes a criterion by which we judge its quality and is frequently an important factor in whether we select an item or reject it. We squeeze and prod fruits and cheese to gauge their ripeness; we tilt bottles to estimate the viscosity of their contents (Pramudya & Seo, 2019). Texture can be expressed in the sounds which foods make when handled, to the extent that we listen to foods to estimate their quality, e.g. the sound of a water melon when it is tapped. Familiarity with a product brings knowledge about how its texture and behaviour changes during processing and storage. With continued contact to a specific food, certain individuals have developed great expertise to the extent that they become expert judges of that product's quality. Such individuals (e.g. master craftsmen) often determine the texture of foods with empirical test methods such as prodding, tapping or squeezing. In some food factories, experienced workers can handle or look at a batch on the production line, and while they cannot tell you why, they can say if the batch will be successful (or not). Surely if an individual can assess texture by prodding it, a machine which prods while measuring force might be able to provide an indication of that aspect of texture (and perhaps quality too). By applying suitable calibrations, we have been able to create instrumental procedures which might provide information which formerly only our expert could offer.

Having accepted the idea that a machine might take the place of a human to assess food texture we must remember that before all else, food texture is essentially a human experience which arises from our interaction with food (Szczesniak, 2002). It is worthwhile to be cautious when considering physical test procedures, as data can be collected by subjecting any material to any procedure, but results from the test do not necessarily mean anything in terms of texture. Such a comment is not intended to disqualify instrumental test, which might not relate directly to human perception, for such procedures may be valid for all kinds of other reasons. For example, viscosity of a liquid is frequently measured to gain an idea of resistance to flow and therefore the pumping requirements to push the fluid down a pipe.

However, as we will see later, under some conditions instrumental measurements of viscosity bear little relation to the experience as perceived in the mouth.

2 Texturology

During the 1980s, British Telecom ran a television advertising campaign to encourage people to use their phones. The most memorable was a lad telling his grandmother that he had failed all his exams. When pressed he admits to having passed pottery and sociology. She is delighted saying 'you get an ology, you're a scientist'. While it is a bit facetious, the suffix 'ology' does imply a branch of science.

As has been shown above, food texture is multidisciplinary, cutting across several distinct scientific disciplines and while practitioners perhaps consider themselves with the tags of 'rheologists' or 'sensory scientists', how many, given the opportunity, would better relate the distinctive term 'food texturologist'?

Being multidisciplinary in background, many of the individuals involved in food texture have a breadth of experience allowing them to appreciate complexities and interrelations between the scientific areas they have worked in. The food texture professional is more than the existing tags allow them to be. The idea of the term food texturology as a branch of food science has been talked of but to date has not really caught on. Perhaps with time this perception and self-identification will change.

3 Food Texture and Product Quality

We have seen that we can assess the quality of foods by prodding them with our fingers; interestingly we are not unique among animals in this regard and chimpanzees have also been found to select figs to eat by squeezing them with their digits (Dominy et al., 2016). In many respects, chimpanzees are gauging fig acceptability, and as a parallel to human behaviour, it is important to distinguish acceptability which is normally undertaken by untrained consumers as opposed to trained panels which contain individuals who have been selected on the basis of a highly attuned sensory acuity and often trained to further discriminate between subtle nuances of texture. Both trained and consumer panels have a role to play, yet that role is very different. One should not assume that the measurements of texture which come from a trained panel are similar to those obtained by a consumer panel. It is possible that the consumer may not detect the same detail as the trained assessor, yet it is probably appropriate that the consumer's opinion is the final arbiter in assessing acceptability. In the past, some prestigious research institutes have made an ass-of-themselves with claims that their trained panel identify quality characteristics such as acceptability in a manner identical to the general public.

By way of reminder, the ISO (2009) definition of texture includes 'all of the mechanical, geometrical, surface and body attributes…', though so far we have mainly considered mechanical handling. While we may select some of our foods based on textural behaviour when squeezed in our hands, it is impossible to disassociate such sensations from other cues such as appearance and 70% of consumers make decisions on food purchasing in as little as 0.4 s based on presentation (Milosavljevic et al., 2011). An example of visual influence on texture is the skin colour of bananas, which proves to be an excellent index of maturity. Multiple, parallel changes occur during banana ripening; in addition to changes in skin colour, the flesh softens due to the starchy material being broken down into sweet simple sugars. Another good index of banana maturity is alcohol-insoluble solids (AIS), which measures complex carbohydrates (such as starch, pectin and cellulose) which decrease during ripening.

Other non-mechanical, instrumental measures of texture include moistness and fattiness, which from the ISO sensory point are examples of body attributes. Thus, in some cases, monitoring changes in chemical composition can provide a gauge of food texture and quality. Some indirect indices of maturity include: moisture content of vegetables or free fatty acids in tomatoes. A number of reviews examine these indirect measures of food texture and quality (Szczesniak, 1973; Jack et al., 1995).

Texture-based field measurements and quality assurance tests are essential in selecting produce for sale. When considering correlations between sensory and instrumental measurements, it is appropriate to consider the linearity of the psychophysical response. While Weber's law relates to the magnitude of the just noticeable difference, Fechner's law shows that many stimuli bear a log relation to perception. However, the perception of some stimuli does not follow Fechner's law, and other models have been put forward to explain their behaviour, such as that of Stevens, which essentially follows a power law (Billock & Tsou, 2011). Fitting the right model to a particular stimulus requires an element of preliminary experimentation as each requires that data be collected in a different way (e.g. magnitude estimation for Stevens' model). Elejalde and Kokini (1992) examined the psychophysics of in-mouth viscosity perception. Using magnitude estimation, they showed that perception of viscosity followed a power law relationship which correlated well with shear stress and that shear stress in the mouth is in fact the sensory mechanism for oral evaluation of viscosity, since the slope is very close to unity.

4 Food Texture Perception During Oral Processing

Human perception of food has been described as a cyclic process which starts with an anticipation originating primarily from visual cues, but also flavoured by our prior experiences. Various aspects of appearance such as colour, size and shape as well as aspects of structure (e.g. openness) form visual cues that pre-empt our physical interaction with the food (Kramer, 1973). Though not always associated with texture perception, visual cues provide a gauge of viscosity (Shama et al., 1973) and the 'wobbly' behaviour of semi-solid, jelly-like foods. Our participation leads on to manual manipulation either directly or with tools (e.g. cutting with a knife). The interaction of visual changes while we manually handle the food, inputs to our impressions of the food's texture. Even before the food is in the mouth we have gathered a substantial amount of knowledge about the food's texture from visual, tactile and even auditory stimuli.

Initial perception in the mouth (i.e. without biting) is at a relatively low shear rate. Two categories of sensation have been identified, those due to touch which occur regardless of any shearing and those that require a small amount of deformation. With no shear at all, we gather impressions about the food's homogeneity such as the presence, size and shape of particles or air cells. At slightly higher shear rates caused by movement of the tongue, the food is deformed and flows. Under these conditions, characteristics like elasticity, stickiness to the palate and viscous behaviour are perceived (Sherman, 1969).

During the first few chews much of the structure is broken. Brittle materials fracture, fibrous materials are torn. During these initial chewing cycles, the jaw movement can be irregular and a high degree of shearing is often achieved. A variety of textural characteristics are perceived such as those which relate to physical make-up (e.g. hard, soft), or deformation and breakdown (e.g. brittleness, plasticity, crispness and sponginess) (Chen, 2014). During the subsequent chew-down, the jaw movement is more regular and secreted saliva mixes to form a coherent bolus which is further kneaded prior to swallowing (Hiiemae, 2004). Textural attributes perceived during this chew-down phase are those which relate to the particular nature (e.g. smooth, coarse, powdery, lumpy and pasty), consistency (e.g. creaminess, cohesiveness of bulk and wateriness) and adhesion to the palate (e.g. stickiness).

Following swallowing we perceive a residual masticatory impression which arises from the remains of disintegrated food and any mouth coating materials. Such attributes include mouth coating, creaminess, stickiness, melt-down properties on the palate, greasiness, gumminess and stringy sensations (Sherman, 1969).

Hutchings and Lillford (1988) postulated a model to explain the breakdown path, which holds well for many fresh foods. They reinforced the idea that the breakdown path is a dynamic process occurring over a period of time, and proposed that the key attributes which affect the process are: the degree of lubrication and the structure which the food possesses. During mastication the structure is broken down by mechanical action. Lubrication is due in part to the secretion of saliva during chewing but also arises from the release of fluid components of the food, in terms of moisture and fat, both of which act as lubricants. Changes in structure and lubrication occur until two thresholds are reached at which point the material may be swallowed. In the case of dry foods, after the structure breakdown of the first bite, incorporation of saliva leads to a re-creation of structure and only with continued chewing and saliva secretion (or intake of additional fluids) can the bolus approach Hutchings and Lillford threshold. Hutchings and Lillford's breakdown path holds well for most fresh foods, but in the case of dry foods such as biscuits, crackers, peanut butter, after the initial first bite breakdown there is de novo structure creation prior to entering Hutchings and Lillford's breakdown path (Rosenthal, 2022).

Since eating is a cyclical group of activities, the information gathered during the handling, biting, chewing and swallowing all feed back into our anticipation of the next portion.

5 Comparison Between Instrumental and Sensory Measurement of Texture

5.1 Hardware

Many stimuli contribute to our perception of texture, including visual and auditory cues as well as those related to touch and movement. Visual and auditory cues are gathered through specialised sense organs – the eyes and ears. In contrast, the sensors of material characteristics are spread throughout the body, sometimes being categorised as those sensitive to touch (somesthesis) and movement/position (kinaesthesis). Various skin organelles have been identified such as Pacinian corpuscle, Meissner's corpuscle, Ruffini ending as well as free nerve endings. While some of these organelles have been attributed with the perception of certain attributes (e.g. Pacinian corpuscle being responsible for pressure), it is often thought that the law of specific nerve endings does not apply to skin senses and that all types of nerve ending contribute to our general perception of texture. In addition to the tactile sense organelles in the hard and soft palate, tongue, gums and periodontal membrane surrounding the teeth, there are vitally important nerve endings in the oral muscles and joints. Signals from these nerves provide information on jaw position, muscle tension and length (Chen, 2014).

In comparison to the sensing apparatus of the human body, instrumental testing devices rely on transducers to convert material and physical measurements into visual or electrical outputs which are usually translated into a data stream that can be stored or analysed directly by a computer. Choice of instrument depends to an extent on the physical state of the material being studied – typically solid foods, gels and pastes are examined with a texture analyser (see Chap. 'Texture Analysers'), bulk liquid and semi-solid food properties by rheometer or viscometer (see Chap. 'Rheometry and Rheological Characterisation') and surface interactions between the foods, boli or oral residues and oral surfaces by tribology (see Chap. 'Tribometers for Studies of Oral Lubrication and Sensory Perception'). The innards of such instrument rely on transducers which detect movement, position, force, velocity, etc. Such instrumentation is often in the form of strain gauges and load cells to measure forces, and position or movement detectors. Successful transducers usually have a linear response which, through calibration with standards, can represent defined physical characteristics in terms of absolute units. In contrast, human perception is governed by psychophysical phenomena, which tends to be non-linear. For example, Weber's law states that the magnitude of a *just noticeable difference* is proportional to the intensity of the stimulus already present. Thus, the body adapts to the forces which are exerted, being most sensitive when small forces are applied. Moreover, the response to a stimulus is most noticeable when a change in that stimulus occurs; if the stimulus is held constant the response then lessens with time. The overall consequence is that we are receptive to relative differences and changes, but rather poor at identifying any absolute values.

While a transducer might measure force, interpretation of what that force means depends on the way that the instrument makes contact with the sample. Thus, the geometry of the test cell, the nature of the test, etc. all need to be taken into account by the user. For example, with solid foods we might undertake a test in compression or tension or shear or torsion. We might be using a flat-ended probe or a platen or a shear cell or cone-shaped probe. We might be applying large deformations or small deformations or applying a constant stress. The permutations, while not endless, do need to be considered in interpreting the results. Some researchers have created standard test protocols such as Texture Profile Analysis (TPA) (Friedman et al., 1963). In its original form, TPA squashed the food by 75% using a plunger at 17.8 mm.s^{-1}. However, many researchers have modified this protocol to fit the capability of the instrument and changing speed, or per cent (%) deformation can substantially alter the results obtained (Rosenthal, 2010). While TPA has been widely used almost as a universal method for texture analysis, serious concerns have been raised for the inappropriate applications of TPA method and inappropriate interpretation of TPA results in literature (Nishinari et al., 2019; Peleg, 2019).

5.2 Temperature

Factors like temperature are frequently influential on rheological behaviour and consequently most apparatus for measurement of such parameters will be carefully temperature controlled. Typical instrumental methodology would involve introducing the sample to the device and leaving it to reach a steady temperature before the physical test is applied. How different this approach is to what occurs in the mouth during eating? While the temperature within the centre of the body is fairly constant at 37°C, the mouth is normally a few degrees below that. Food which is introduced is rarely at the same temperature and there then follows a brief change in the temperature of the food, which may lead to a change in its physical behaviour. A well-known example of how this temperature change affects the texture of food is provided by chocolate. As with most triglyceride material, cocoa butter can be crystallised in a variety of polymorphic forms. The desirable V-crystal has a relatively sharp melting point around 33.5°C (Schlichter-Aronhime & Garti, 1988). When chocolate at around 20°C is introduced to the mouth, the temperature starts to rise and the fat crystals commence to melt in the mouth, giving rise to the sensation of dissolving and melting away. Similar sensations are important in ice cream and margarines.

5.3 Saliva

In addition to thermal melting, the presence of saliva within the mouth leads to a dissolution of water-soluble materials. About 1.5 litres of saliva are secreted each day (Humphrey & Williamson, 2001). Saliva behaves as a typical colloidal fluid with specific surface and rheological properties (Zhang et al., 2022). Saliva acts as a lubricant as well as a solvent, allowing food materials to be effectively dissolved and broken down during mastication. Most rheological test equipment does not have any facility to introduce a solvating lubricant on to the sample during testing (Sarkar et al., 2021). More importantly, saliva (and saliva components) can interact with food and food components and significantly changes the properties and microstructure of the food (as well as food bolus) (Mosca & Chen, 2017). For example, the digestive enzyme a-amylase interacts instantly with starch components and can lead to structural breakdown and significant decrease of viscosity (Carpenter, 2013). Salivary mucin can interact with proteins and leads to destabilisation of protein emulsions, which will with no doubt alter mouthfeel of such food systems (Mosca & Chen, 2017). Interaction between food polyphenols and saliva proteins leads to oral precipitation and depletion of salivary protein from the tongue surface, which leads to the sensation of astringency (Brossard et al., 2016). Saliva has also recently been confirmed as a good emulsifier which converts free oil/fat of a food into a stable emulsion (Glumac et al., 2019). Oral emulsification is a very important factor influencing oral sensation of oil/fat. Recently it has been shown that an individual's capability of oral emulsification is directly related to their threshold of the sensation of greasiness (Ma and Chen, 2023).

5.4 Speed of Test

The speed of movement of the jaw and the tongue within the mouth is a critical factor in our perception of food texture. Actually, the speed of the jaw depends on the food being chewed, for example gum chewing is typically 64 mm.s^{-1} while carrot has been reported to be 75 mm.s^{-1}. However the speed of the jaw is not constant during the chewing cycle, slowing down as the sample is crushed followed by a short pause prior to the next bite (Bates et al., 1975). In the case of meat, speeds of 33–66 mm.s^{-1} have been recorded (Tornberg et al., 1985). Such speeds contrast with typical instrumental texture analyser speeds, which rarely exceed 40 mm.s^{-1}. Bearing in mind that only few foods behave as Newtonian liquids, the others will exhibit shear-dependent viscosity and in such a situation the apparent viscosity will depend on the rate at which the liquid is being sheared. Shama and Sherman (1973) examined shear rates in the mouth and identified that they are applied in a range from 0.1 to 1000 s^{-1}. Since most foods are non-Newtonian, their apparent viscosity will depend on the shear rate applied. It is therefore necessary to match shear rates applied in an instrumental test with those which might be experienced in the mouth or else the measured viscosity may not equate to that as would be perceived orally. Shama and Sherman showed that the shear rate applied in the mouth actually depends on the viscosity of the food, such that low-viscosity foods receive relatively high shear rates while high-viscosity foods tend to be sheared more slowly (Fig. 1). Consequently, some iteration is needed to find appropriate shear rates which measure the apparent viscosity such as it would be perceived in the mouth, and the appropriate shear rate may vary from one food to another.

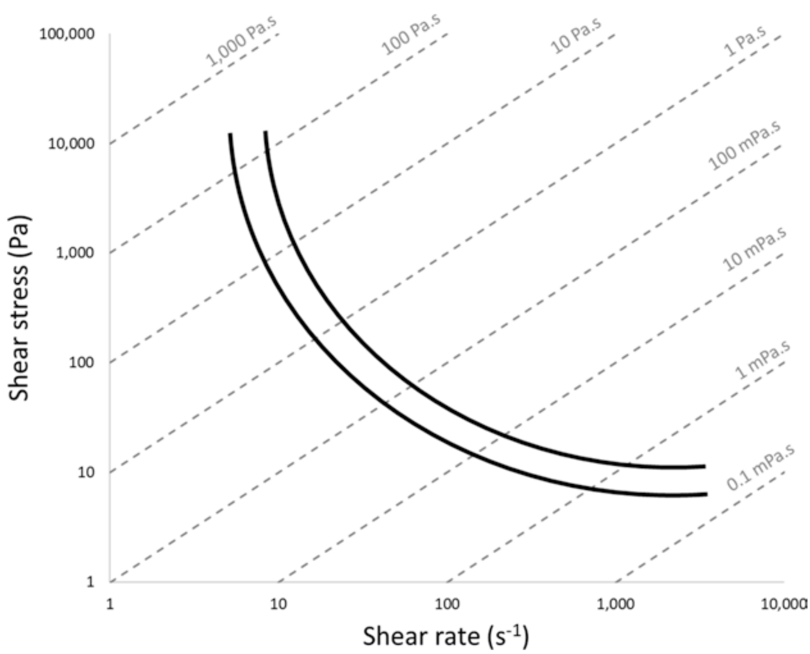

Fig. 1 Shama and Sherman's bounds of shear stress and shear rate associated with oral evaluation of viscosity (Redrawn for this publication)

Takahashi and Nakazawa (1991) studied the swallowing process by introducing pressure transducers into the palate of volunteers. Using a laboratory viscometer at shear rates which occur in the mouth, they determined the viscosity of a variety of carboxy methyl cellulose solutions. Different volumes of these solutions (<25 cm^3) were then offered to the volunteers and the retaining time that the samples were in the mouth, palatal pressure during swallowing and work involved in swallowing were monitored. The swallowing pressure only changed from about 0.1 to 0.2 mPa over a viscosity range of 10–10,000 mPa.s. The time which the sample was retained in the mouth and the work involved in swallowing remained almost constant up to a critical viscosity of 1 Pa.s, above which both the time retained and the work increased markedly. The effect of sample volume varied with solution viscosity, low-viscosity liquids being swallowed in one deglutition (<15 cm^3) while high-viscosity liquids were swallowed in several small volumes. Recently, Chen et al (2021) proposed that an individual's awareness of time is an important factor in influencing their perception of rate-related textural properties. The perception of time varies significantly between different individuals and can even vary for a single individual during different eating scenarios.

5.5 Modality and Concurrency

As a human response, it is worth remembering that texture can arise through a combination of stimuli occurring concurrently, for example, creamy mouthfeel is associated with viscous oral consistency and smoothness on the tongue (Chen & Eaton, 2012). Such multimodal interactions are generally difficult to reproduce instrumentally in real time, perhaps requiring multiple measuring instruments, such as a rheometer and a tribometer, providing simultaneous outputs on the same sample while it undergoes changes akin to chewing and secretion of saliva!

The actions of mastication and secretion of saliva combine in the breakdown path until the bolus is suitable for swallowing (Hutchings & Lillford, 1988). Clearly this is a time-dependent process and one in which the nature of the food, and hence its texture, is changing. Few instrumental tests consider this kind of broad time frame. While a considerable amount of the structural breakdown may occur during these early parts of mastication, other sensory attributes experienced closer to the time of swallowing, frequently do not get evaluated instrumentally. Moreover, some sensory attributes such as 'cohesiveness of bulk' do not exist in raw food as they are in effect properties of the bolus. The texture perceived during oral processing changes along the oral trajectory and, therefore, exists as snapshots in a transient time frame.

6 Selected Terms Used in Instrumental and Sensory Texture

In this section we consider selected mechanical texture attributes which might be measured with both sensory panels and mechanical instruments such as rheometers or texture analysers. We have based the classification of terms on the International Organisation for Standardisation's 'Sensory Analysis – Vocabulary' (ISO, 2009). While the ISO includes 'all of the mechanical, geometrical, surface and body attributes of a product perceptible by means of kinaesthesis and somesthesis receptors and (where appropriate) visual and auditory receptors from the first bite to final swallowing', here we have focused on the mechanical properties such as hardness, cohesiveness, viscosity, elasticity and adhesiveness.

Fundamental to the measurement of texture of solid foods is the application of stress and the measurement of the resulting strain. Rosenthal and Chen (2023) proposed a conceptual model in non-technical, everyday language to understand the dimensions of food texture.

6.1 Hardness

The ISO (ISO, 2009) defines hardness as the 'mechanical textural attribute relating to the force required to achieve a given deformation'. The term 'hard' is often considered to be an extreme on a sensory continuum with 'soft' forming the low-end anchor point. The ISO (2009) also identifies standards as: 'cream cheese' at the low end, 'olives' as a moderate level of hardness and 'boiled sweets' (hard candy) at the high end.

The term 'firm' is related to hardness, though it is associated with the application of small forces such as in squeezing fruit. In physical sciences such small compressive forces are used in the measurement of the elastic modulus. Moduli are expressed as the stress (force per unit area) divided by the strain (deformation as a ratio of the original dimension). Measurement of moduli employs such small stresses that the material returns to its original state when the stress is removed. As with hardness, the low-end anchor for 'firm' is 'soft'.

Despite the idea of small deformation tests, many researchers consider hardness to relate to the maximum force required to break the product whether in the sensory situation between the teeth or in a texture analyser. That breakage might be due to penetration of the probe into the surface or collapse of the material – either way we are looking at catastrophic material collapse. Some typical instrumental force–time curves for large-deformation single-compression tests are exemplified by Fig. 2. The smooth curve in Fig. 2a is typical for many gels or doughs where the force increases to a maximum until the compression is halted or reversed; Fig. 2b typifies materials that rupture during compression such as a batter-coated food product, and Fig. 2c is typical of a brittle food. In all cases, the hardness is taken as the stress at the maximum height.

Fig. 2 Typical shapes of curves obtained from large-deformation measurements of hardness: (a) non-breaking sample, (b) simple fracture, (c) brittle food

TPA has a term called 'hardness', which relates to the force measured during a 75% compression at 18 mm.s^{-1}. When TPA was originally described, Szczesniak et al. (1963) undertook correlations with real food samples and had nine named foods which they rated by sensory panel and TPA with the General Foods Texture Analyser. These include 'cream cheese', 'egg white', 'frankfurters', 'cheese', 'olives', 'peanuts', 'carrots', 'peanut brittle' and 'rock candy'. As has been pointed out earlier many researchers have modified the TPA protocol, which invalidates correlations with such sensory standards (Rosenthal, 2010).

While forces may be applied in compression, tension and shear, hardness is associated with compression. Perhaps the shear and extensional equivalents (i.e. the resistance to bending or stretching) might be 'stiffness' and 'taut', respectively. However, neither of these is in common use.

6.2 Fracturability, Brittleness

As seen in Fig. 2, some foods undergo fracture during compression. The stress at the point of fracture gives an idea of the strength of the weakest part of the structure. Fracture is often a feature of cellular materials. While we illustrated fracture during compression, another common geometry to examine it from an instrumental point of view is with three-point bending. Fracture can occur at flaws or weak points in the structure, stress concentration can occur and it can lead to crack propagation. Brittleness has sometimes been quantified by counting the number of mini-peaks in addition to the actual force at which they start.

From a sensory perspective it is considered to be defined as 'force necessary to break a product into crumbs or pieces' (ISO, 2009) and is assessed by suddenly compressing the food between the incisors or fingers.

The degree of fracturability can be described by a number of adjectives ranging from 'pulverulent', where the material immediately disintegrates into powder, to 'cohesive', which exhibits no fracture but undergoes plastic flow on deformation (Fig. 2a). Intermediate adjectives describing mid-levels of fracturability include ‘crumbly’, ‘crunchy’, ‘crisp’ and ‘brittle’.

Some of these terms, especially ‘crunchy’ and ‘crisp’, are associated with chewing sounds which add to the overall eating experience and even help discriminate between sensory descriptors (Vickers, 1982; Dacremont, 1995).

While ‘cohesiveness’ is used as a description for a non-fracturing food, it is also considered to be an attribute in its own right.

6.3 Cohesiveness

Cohesiveness has been defined as the ‘the strength of the internal bonds making up the body of the product’ (Szczesniak, 1963). Despite simple definitions like this, the term does not seem to be universally understood (Rosenthal & Thompson, 2021) and while Szczesniak (1963) created standard reference scales to enable the training of sensory assessors and correlation between sensory and instrumental measures, she did not provide such standards for ‘cohesiveness’. The ISO (2009) resolves this by treating it as a zero level of fracturability rather than an attribute in its own right. They do however say that it relates ‘to the degree to which a substance can be deformed before it breaks’.

Rosenthal and Thompson (2021) identify some of the misunderstanding in the use of the term ‘cohesiveness’ to the anomalous value of the term in TPA – where it is derived algorithmically by dividing the strength under the second compression by that at the first. While this provides a value, it is probably a measure of recovery rather than ‘the strength of the internal bonds making up a product’. Friedman et al. (1963) went further to derive the other texture terms ‘chewiness’ and ‘gumminess’ from calculations involving the anomalous value derived from their measure of cohesiveness. The term ‘chewiness’ does seem valid in its own right, though does not need to be entangled by this peculiar definition of ‘cohesiveness’.

6.4 Cohesiveness of Mass

Cohesiveness is mainly used to describe a textural property of foods, yet all foods undergo changes through oral processing with the ultimate formation of a swallowable bolus. The term ‘cohesiveness of mass’ was coined by Civille and Liska (1975) to describe the cohesiveness of the oral contents after 5–10 chews. They considered the oral processing of a cookie which starts oral processing as a crumbly brittle (low cohesive) material, though disintegrates during chewing and with the adsorption of saliva results in a sticky, cohesive mass.

6.5 Adhesiveness, Stickiness

If cohesiveness is the ‘the strength of the internal bonds making up the body of the product’, then adhesiveness is the strength of the bonds between the product and adjacent surfaces. In the case of sensory measurements, it is ‘the force required to remove material that sticks to the mouth or to a substrate’ (ISO, 2009). When the ISO uses the term ‘substrate’, they refer to the palate, lips, teeth or neighbouring particles. While from a sensory point of view this separation is normally thought to be in the mouth, it can also refer to a separation from an implement such as a spoon. Instrumental measurements of stickiness follow the idea of measuring the force to separate the material from a surface. Various forms of tack test have been documented in the literature (Adhikari et al., 2001). Normally a probe of fixed dimensions is used and, in the case of a tack test, that probe is brought into contact with the sticky material, before being pulled away at a defined speed.

TPA has a term referred to as adhesiveness, which is obtained by measuring the area under the curve of the negative peaks between the two bites. Of course with Bourne’s TPA protocol (Bourne, 1966), where the sample is sandwiched between a platen and the base of the instrument, the area of contact is poorly defined. Another problem with the measurements from TPA is that the value of adhesiveness is normally reported on a force–time curve, whereas it makes more sense to take account of the speed and plot values on a force–distance curve (where the units are work).

Kazemeini and Rosenthal (2021) examined the factors that influenced tack testing of liquid foods like syrups and realised that while highly reproducible for any particular testing protocol what they were seeing was the texture analyser pulling syrup apart at a speed greater than its viscosity allows it to flow. The results are thus entirely artefacts of the test protocol, being snapshots in time of non-equilibrium processes.

A number of adjectives are commonly used to describe the degree of stickiness, ranging from 'sticky' for products like toffee to 'tacky' for foods like marshmallow.

6.6 Viscosity

Viscosity crops up in rheological measurements in a number of contexts. Traditionally it is considered to be the resistance to fluid flow at a given rate, though it occurs in other contexts too. A number of viscometers are available for measurement of viscosity, though the non-Newtonian nature of most foods does limit the use of some of these. Increasingly, rotational viscometers are the instrument of choice though cost and precision are a balance for laboratory managers.

From a sensory perspective, viscosity is defined as that textural attribute relating to resistance to flow and corresponds to 'the force required to draw a liquid from a spoon over the tongue, or to spread it over a substrate' (ISO, 2009). Assessors may be trained with various materials and complementary adjectives such as water being 'fluid', or olive oil being 'thin', and double (heavy) cream being 'creamy or unctuous'.

As is apparent, the non-Newtonian nature of many foods verges on viscoelastic (or even elastoviscous) behaviour and when rheological modellers attempt to explain the flow behaviour of such materials they talk about viscous elements to describe a retarded rate of flow and use the idea of such viscous elements to explain the unrecoverable deformation which occurs when a fixed force is applied for a period of time (a creep test). Margarine is an example of a solid material which displays plastic behaviour, which flows when a yield stress is overcome – such materials do not recover their original shape when the deforming force is removed.

6.7 Elasticity, Springiness, Resilience

Elasticity, springiness and resilience are defined as the rapidity (and degree) of recovery of a material from a deforming force (ISO, 2009).

The rheological modellers mentioned under viscosity above describe this as elastic behaviour and often liken it to a spring. Highly elastic materials recover their original dimensions when the deforming force is removed. In reality, few foods are purely elastic in their behaviour.

Instrumentally, elasticity is determined from recovery of the linear dimension which was deformed (e.g. under compression or tension).

TPA had a term 'elasticity', but this was replaced with 'springiness' because of possible misunderstandings with physical science definitions. 'Springiness' was extracted from a TPA curve as the time taken from the start of the second peak to its maximum (Bourne, 1978). Another TPA term 'resilience' was introduced by texture analyser manufacturers as a measure of remaining strength in the sample after the first compression. It was determined by measuring the area under the curve to the right of the first peak maximum divided by the area to the left.

6.8 Gumminess and Chewiness

Gumminess and chewiness are well-defined attributes in sensory lexicon; however they are seldom used as instrumental terms outside of TPA, which derives them from the dubiously defined term 'cohesiveness' (see Sect. 6.3 above). The ISO (2009) defines gumminess 'as the effort' and chewiness 'as the work' needed to break up the food ready for swallowing.

While it is of course possible to undertake a formulaic calculation with any set of data, Szczesniak (1998) pointed out that gumminess and chewiness (in TPA) are mutually exclusive where gumminess is intended for semi-solids while chewiness for solid foods only.

6.9 Non-mechanical Texture Attributes

6.9.1 Chew Count

The chew count is widely used in oral processing studies as a measure of how many chews are needed to chew the sample until it is ready to be swallowed. Of course, chew count relates to the assessors as opposed to the food.

6.9.2 Denseness

From both sensory and instrumental point of views, density is a measure of the compactness of the food. From a sensory point of view scale, extremes range from suet puddings to whipped desserts. Instrumentally it can be determined by dividing mass by volume – the determination of volume being more problematic. Various methods exist for volume determination such as seed displacement.

6.9.3 Granularity

Granularity relates to size and shape of particles in the mouth. Of course the limit of detection in the mouth dictates what we can perceive, and some products like ice cream or chocolate can become gritty if particles such as lactose or cocoa solids exceed 6–10 μm (Hough et al., 1990; Engelen et al., 2005). Common adjectives used to describe the degree of granularity include 'smooth', 'powdery', 'grainy', 'coarse' and 'lumpy'.

6.9.4 Conformation

Conformation describes shape and orientation of particles. For example, cellular particles are spherical and thin walled, while angular particles are normally described as 'crystalline'. Long, parallel particles are 'fibrous' and layered structures 'flaky'.

6.9.5 Moistness

At the low end of the moisture spectrum, we have adjectives like dry, which are used to describe products like biscuits or crackers. In contrast, the high-moisture end is exemplified by foods like oysters. As a body attribute, moistness relates to composition and while water can be determined by a variety of methods, the sensation of moistness might arise from other substances such as oil or glycerol.

7 Conclusion

ISO 5492 (2009) defines food texture as: 'all of the mechanical, geometrical, surface and body attributes of a product perceptible by means of kinaesthesis and somesthesis receptors and (where appropriate) visual and auditory receptors from the first bite to final swallowing'. In this chapter, we explore the key food texture attributes from both a sensory and an instrumental point of view. We recognise that food texture manifests from how we interact with foods, with oral processing being one of the crucial interactions. Yet food processing is a dynamic process and our perception of texture changes from initial handling to first bite, and on to chewing down, before the bolus is finally swallowed. Even after swallowing, some residual elements of texture may still be apparent. Textural changes during oral processing mean that data from both sensory and instrumental techniques are snapshots in time of a transient process.

The book provides an update to *Food Texture: Measurement and Perception* (Rosenthal, 1999). In this second edition, we have updated the sections which deal with the methodology of instrumental measurement and perception; we have also broadened the scope of commodity chapters. As an introduction to the book, we cross-reference with the specialised chapters which follow.

Acknowledgement Andrew Rosenthal's 'Relation Between Instrumental and Sensory Measures of Food Texture' (Rosenthal, 1999), from the first edition of this book, formed the basis of this chapter, though it has been substantially restructured, rewritten and updated.

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Food Structure as a Foundation for Food Texture

Pedro Bouchon, Ingrid Contardo, and María Teresa Molina

1 Introduction

The majority of textural characteristics associated with food are detected through the oral process of mastication. This complex process involves the grinding of solid food, which is subsequently mixed with saliva to form a bolus that can be comfortably swallowed, which is heavily dependent on food structure. This structural aspect of food impacts several attributes, such as the crispiness of snacks, the smoothness of ice cream, the snap of chocolates or the undesired grainy sensation in confectionery products. Additionally, the sounds produced while biting a food are related to the perception of its texture, and hence a comprehensive understanding of food structure, particularly at the micro level, is relevant. This chapter will address some pertinent concepts and techniques that may help to establish a right microstructural approach to food texture.

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2 Food Microstructure

A shift in food engineering has been obvious over recent years, from emphasising processes and unit operations to developing and designing products that offer convenience, health benefits and sensory enjoyment. Food design requires a proper understanding of the structural elements that make up a food and contribute to its structure, texture, stability and functionality during processing, storage and consumption. Indeed, foods represent some of the most complex examples of soft matter due to their complexity of components, the co-existence of multiple phases and the multitude of relevant characteristic time and length scales.

2.1 Food Development Trends

In recent decades, the food industry has been challenged with new tasks. Consumers have high demand of food products that can contribute to their wellness and health but are not willing to sacrifice organoleptic enjoyment. Sensory attributes such as flavour (taste and aroma), texture

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and appearance remain crucial criteria for product acceptance. In this context, product consistency is a critical factor to the overall success of the food business. Providing consistent, high-quality foods allows customers to know what to anticipate every time they purchase a product. Consumers expect consistent food products from batch to batch, and failure to meet such expectations impacts on repeat purchases. Moreover, customers instantly disseminate their dissatisfaction through various social media platforms. In addition, new living styles impose a challenge to developing convenient and ready-to-eat foods with desirable sensory attributes. This has led researchers and producers to study novel techniques, processes and ingredients to develop new food structures to fulfil consumers' demands, at the interface between health, pleasure and convenience.

As depicted in Fig. 1, specific opportunities arise to target three core demands: convenience, health and pleasure. If sensory experience is included, high-quality guilt-free indulgence products will be the consumers' option in future food supply.

Besides, environmental aspects with respect to food production are also relevant. This imposes the need to develop sustainable agricultural and food processing systems, with an adequate food resource management and supply. This includes climate change mitigation and adaptation, energy efficiency, water management, pest management and control of genetic resources, among others. These requests are translated into consumer demands, which ask for clean food labels, with identifiable or 'generally recognised as safe' (GRAS) ingredients, as well as the use of readily recyclable or reusable packaging. In addition, increased social awareness demands for the end of hunger by achieving food security and improving nutrition and providing access to safe, nutritious and sufficient food globally, as defined by sustainable development goal (SDG) number 2 (United Nations, 2022).

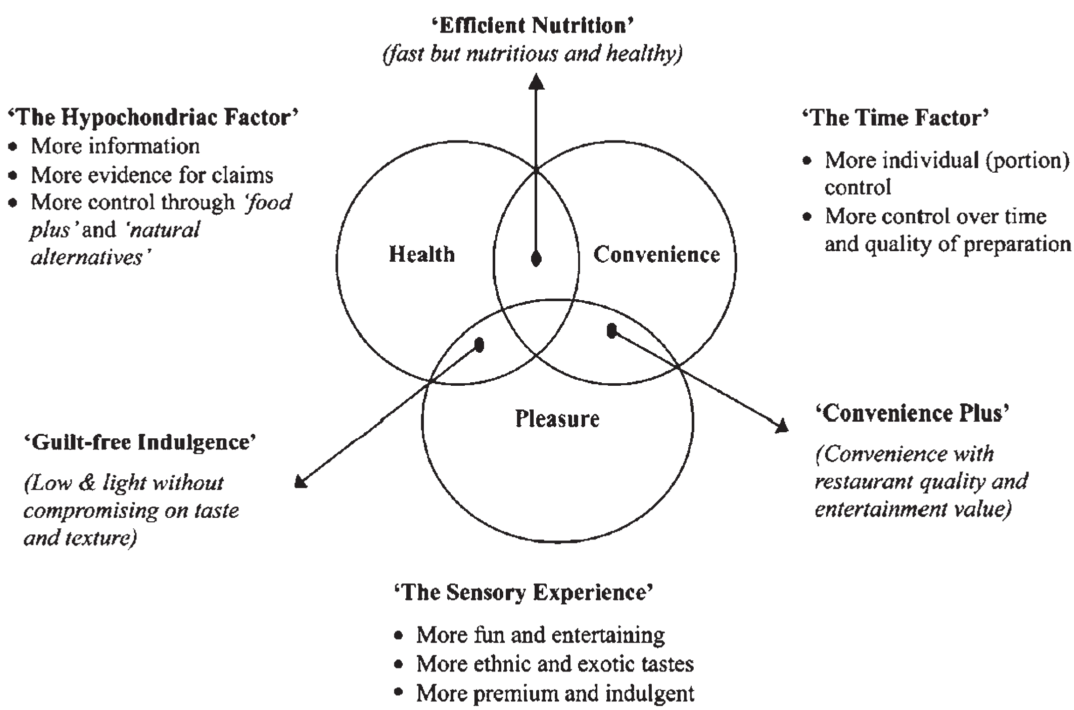

Fig. 1 Contemporary food megatrends. (Extracted from Gray et al. [2003])

2.2 Food Product Design

The food industry of the twentieth century was characterised by its ability to successfully scale up artisanal processes into high-volume production lines. This resulted in the consistent production of high-throughput safe, nutritious and appealing foods, which was a significant accomplishment. However, consumers' growing concerns on health and well-being impose a challenge to the food industry to develop new products or modify existing ones to meet their needs. This *product-driven process engineering era* required controlled structure-building and therefore, a proper understanding of the functionality of the structural elements prior to or formed during processing (Aguilera, 2006), as shown in Fig. 2.

Since dietary habits are hard to change in the short and medium term, redesigning common foods to be healthier offers a subtle approach. A proper understanding of the structural elements that compose the food and contribute to their structure, texture, stability and functionality is essential. With respect to health, there is increased evidence that the microstructure of foods affects its nutritional value (Parada & Aguilera, 2007; Contardo et al., 2016, 2018). Certainly, to address complexity, an interdisciplinary approach is needed, where different and complementary perspectives can interact. For instance, in recent decades, there have been remarkable advancements in material science that have resulted from a thorough comprehension of material structure and its correlation with its properties; in addition, the techniques to modulate these properties have been successfully applied to food development.

2.3 Food Building Blocks and Their Relevant Scale

To understand the link between the roles of different constituents, product microstructure and transport phenomena, the study of microstructural changes during processing is essential. Transport phenomena and physical properties depend on the architecture formed within a matrix where most of recognisable elements are in micro- or even nanoscales, that is, most important changes are invisible to the naked eye, and,

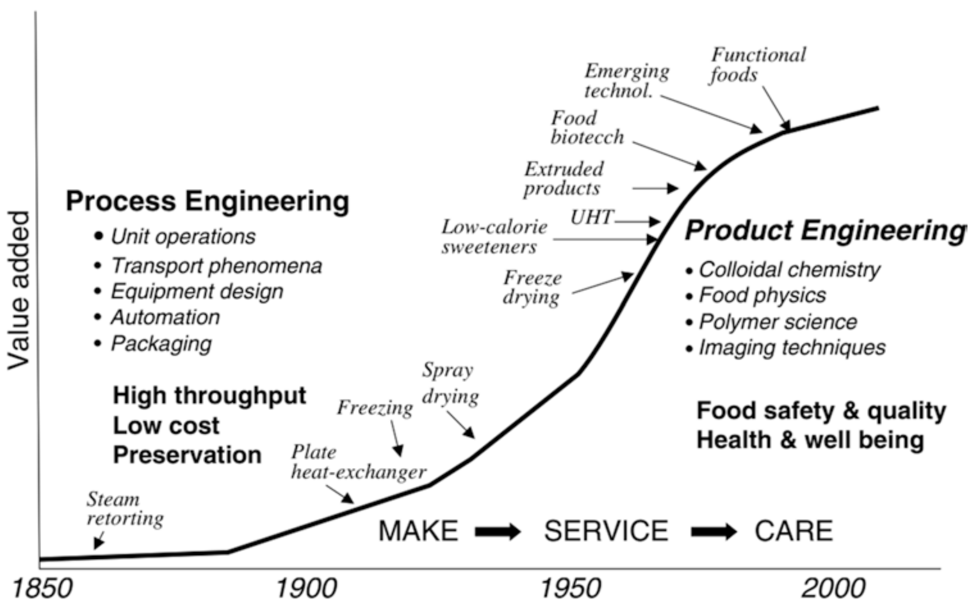

Fig. 2 Evolution of the food industry in terms of value added to products and shift in emphasis from process engineering to product engineering, together with a change in the supporting concepts and techniques. (Extracted from Aguilera [2006])

consequently, integration of microscopy techniques is vital. A variety of substances can be found among them, such as plant cells and cell walls, meat fibre, starch granules, proteins, protein bodies, crystals, oil droplets, gas bubbles and colloidal particles, among others (Aguilera, 2005). These are referred to as food building blocks since they correspond to the structural elements within foods.

Wheat gluten, for example, is a protein complex derived from the storage proteins of the wheat grain and is a food building block of great importance. When mixed with water, these storage proteins transform into a cohesive and viscoelastic dough with distinct rheological characteristics that can retain gas bubbles. These unique properties enable wheat to be used in a variety of food products, such as breads, noodles, pasta, cookies, cakes, pastries and more (Day et al., 2006). The two major protein components of gluten are glutenin and gliadin, which differ substantially in their chemical and physical characteristics yet contribute to gluten's viscoelastic properties. Glutenins consist of multiple, high-molecular-weight chains. When isolated from wheat gluten, glutenin displays considerable resilience but limited extensibility, making it responsible for gluten's elastic properties. In contrast, gliadin consists of about 50 single-chain proteins with relatively low molecular weights. When isolated from wheat gluten, gliadins are highly extensible and sticky, providing gluten with its cohesive and extensible properties (Kulp & Ponte, 1990; Gazmuri & Bouchon, 2009).

Another relevant food building block is starch, the main carbohydrate in human nutrition, which occurs in the form of granules ranging in size from 2 to 150 μm (Coultate, 1996; Bertolini, 2009). They are composed of an essentially linear polysaccharide called amylose, and a highly branched polysaccharide known as amylopectin (Pérez & Bertoft, 2010). The amylose molecule is essentially a linear chain of (1➔4)-linked α-*D*-glucopyranosyl units that give sufficient mobility to form a coil left-handed with six residues per turn helix (Enrione, 2005). Amylopectin is present in all starches, constituting about 75% of most common starches. Some starches consist entirely of amylopectin (≈95%) and are called waxy starches. This highly branched molecule is formed through chains of α-*D*-glucopyranosyl residues linked together mainly by (1➔4) linkages but with (1➔6) bonds at branch.

In terms of how these polymers structure themselves, it has been shown that double-helix strands of amylose can form crystallites named A and B types (Wang et al., 2014). Single amylose helices can form a structure called V-type in the presence of linear alcohols and fatty acids. Since the internal helix is hydrophobic, the enclosed molecule has also to be lipophilic in nature (Becker et al., 2001). In the case of amylose–lipid complexes, it is assumed that the aliphatic part of the lipid lies inside the amylose helix, while the polar group lies outside, being too large to be included (Buléon et al., 1998). The presence of these 'guest' molecules complexed with amylose can have a stabilising effect affecting the crystallisation process of the amylose molecule over time (Gelders et al., 2004). Accordingly, starch confers particular textural attributes to foods, favouring product expansion and/or crunchiness, as well as modulating some specific transport phenomena, such as oil absorption during frying (van der Sman & Broeze, 2013; Sobukola et al., 2013). Most of these properties are triggered when starch is heated in the presence of liquid water. Under these circumstances, the crystalline structure of the granule is disrupted, allowing amorphous regions to become more accessible to water and swell, a process known as starch gelatinisation (Biliaderis et al., 1980; Blazek & Gilbert, 2011). Interestingly, the degree of starch gelatinisation is linked to starch digestibility (Torres et al., 2019). For instance, Contardo et al. (2016) were able to substantially reduce starch gelatinisation through vacuum frying, promoting an increase in the unavailable glucose fraction with a simultaneous reduction of the available fraction. In addition to starch, important building blocks may include modified starches (e.g. pregelatinised, acetylated, crosslinked) with various technological attribute points (for more information on starch, see Chap. 'Starch, Modified Starch and Extruded Foods').

Fat is another key building block, whose applications depend on its physical and chemical properties. Additionally, the nutritional properties of fats are defined by the composition of fatty acids and the stereochemistry of their triacylglycerols (Gunstone, 2006). Scientists have modified fats using fractionation and blending to enhance their technological applications and to retain or improve their sensory quality, but hydrogenation remains a preferred method to achieve the desired semi-solid consistency (Ribeiro et al., 2009). However, when hydrogenation is incomplete, the creation of harmful trans fatty acids (TFAs) can arise (Hunter, 2006). While fractionation and blending are still possible, interesterification presents an alternative to modify the physical characteristics of fats while maintaining the original fatty acid profile and degree of saturation, without generating unwanted trans fatty acids (Rodrigues & Gioielli, 2003); this can be useful in creating a semi-solid spreadable product. Interesterification is a chemical process, catalysed either chemically or enzymatically, which achieves redistribution of fatty acids within triacylglycerol molecules (Idris & Dian, 2005). The resulting stereochemistry alters the physical–chemical characteristics and nutritional properties (Klinkesorn et al., 2004). The position of each fatty acid within the triacylglycerol determines whether it will be absorbed (Farfán et al., 2013). A better knowledge of lipid metabolism and the effective use of interesterification provide the ability to synthesise lipids to improve their nutritional or functional properties (Osborn & Akoh, 2002). These new fats have been defined as structured lipids (López-Hernández et al., 2005). It is important to note that lipids in most processed foods are present as emulsions, which can be end-products or part of a more complex food system (Singh et al., 2009). The aforementioned principles can also be applied to emulsions, to modify their physical and/or nutritional properties (Farfán et al., 2015).

Lipids also play a critical role in confectionary products, particularly in chocolates, where proper tempering is critical to obtain the appropriate fat crystal polymorphism (form V or β2), giving rise to the gloss and snap upon breaking. Key attributes appreciated by customers (and desired by confectioners) arising from this are the feel and sound of breaking chocolate, by hand or bite, resulting from the macroscopic resistance that depends on the internal microstructure (Beckett, 2000; Altimiras et al., 2007). Interesterification is widely used to mimic cocoa butter behaviour in chocolate substitutes (for further information on chocolate confectionery, see Chap. 'Candy Texture: Sugar Confectionery').

Improvements in the quality of existing foods and creation of new products, to satisfy growing and demanding consumers, are largely based on interventions at a microscopic level. Food building blocks and their interactions during processing operations constitute the basis of food structure. Such structure can be classified under three scales of length, as shown in Fig. 3 (Day & Golding, 2016):

1. Molecular level (from 1 Å to 1 nm), where chemical structures of food building blocks can be found, such as minerals, vitamins, flavour components, fatty acids, lipids and protein monomers.
2. Microscopic level (from 1 nm to 100 μm), where aggregation of molecules, colloids, polymer networks and supermolecular structures (e.g. casein micelles, milk fat globules) are categorised here.
3. Macroscopic level (greater than 100 μm), characterised by structures that consumers perceive. At this level, microstructural parameters play an important role in influencing textural properties and sensory attributes perceived during oral processing.

Table 1 shows a classification of parameters, properties and attributes, and their definitions, mostly studied in food science.

3 Microscopy Techniques to Understand Food Structure

To understand the link between the roles of different constituents, product structure and transport phenomena, the study of microstructural changes during processing is essential. Standard

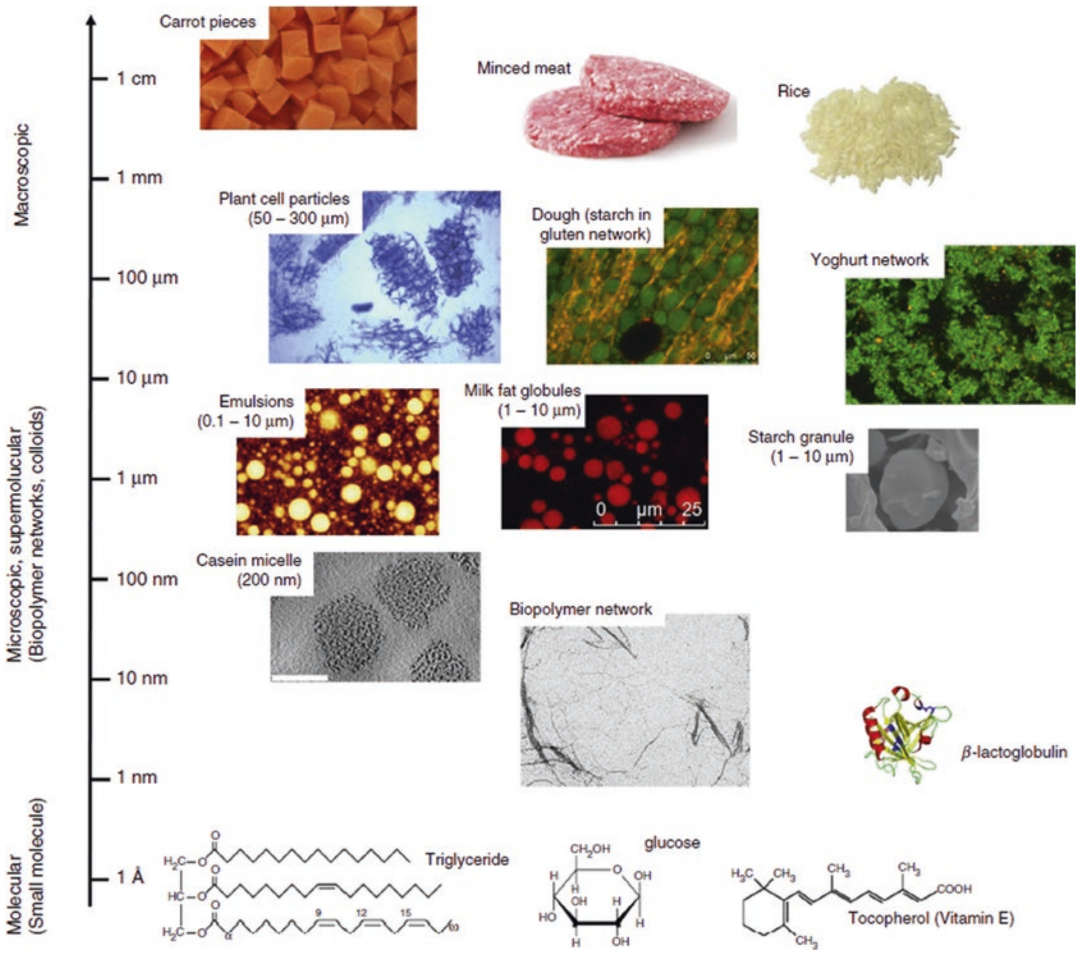

Fig. 3 The length scale of structures and examples of representative molecules, food components, networks and food structures. (Extracted from Day and Golding [2016])

microscopy techniques may produce artefacts in samples, such as swelling of the interiors by solvents or structure destruction due to sectioning. Ways of minimising these detrimental effects are the use of several microscopy techniques in parallel and to have recourse to less invasive methods of microstructural observation. This, together with laboratory procedures (Bouchon et al., 2003), modelling (Bouchon & Pyle, 2005a) and use of experimental data (Bouchon & Pyle, 2005b), can help understanding the phenomena.

Light microscopy (LM) utilises visible light to observe small objects and is widely used in food research. The compound microscope, available in various configurations, is frequently used to examine food samples due to its affordability, ease of operation and simple sample preparation, though this may require tedious steps. Despite the emergence of electron microscopy in biological research, the compound microscope has retained its utility in structural studies. Nevertheless, novel technologies, such as the confocal laser scanning microscope (CLSM), offer significant potential to explore the internal composition of food products through non-invasive 'optical sections'. Extensions of LM may provide non-invasive approaches, such as through miniaturisation, a technique that allows us to follow changes in real time with minimal intrusion (Bouchon & Aguilera, 2001). Electron microscopy has also evolved greatly, including devices that require minimal sample preparation (e.g. environmental

Table 1 Microstructure parameters, texture properties and sensory attributes mostly studied in food science, and their definitions

Attribute	Definition
Microstructure parameters	
Porosity	The fraction of the void volume of air with respect to the total volume of the structure.
Pore size distribution	Cumulative or relative distribution of air pores by size along the food structure.
Tortuosity	Ratio of the path length of a flow channel connecting two pores to the straight-line distance between the two pores.
Cell wall thickness	Thickness of the structural layer surrounding pores or cells of the food structure.
Expansion (extrusion)	Cross-sectional diameter of the extrudate divided by the diameter of the die opening.
Crystalline density	The mass of solid divided by the volume occupied by the particle.
Texture properties (instrumental)	
The force–displacement curve that is obtained from instrumental measurement reflects the resistance of the food material against deformation and can be used to interpret some major mechanical textural features	
Hardness	Maximum force upon compression (Hard → Firm → Soft).
Fracturability	The first significant peak upon compression (Brittle → Crunchy → Crumbly).
Cohesiveness	The ratio of the area under the curve of the second bite to that of the first bite in texture profile analysis (Crumbly → Crunchy → Brittle).
Elasticity	The property of a solid material that it gains its original shape and size after applying a compression force (Elastic → Plastic).
Adhesiveness	The force required to remove the material that adheres to a specific surface. After the sample is subjected to pressure deformation, if the surface of the sample is sticky, a negative force will be generated (Sticky → Tacky → Gooey).
Sensory attributes	
Grittiness	The presence of small solid particles which tend to scrape off the tongue.
Hardness	Force required to break the food structure after the first bite with incisors.
Crispiness	High-pitched sound produced when the teeth crack the product during mastication.
Crunchiness	Low-pitched sound produced on food fracture during mastication.
Crumbliness	Disintegration into crumbs at the first bite.
Chewiness	Mouthfeel sensation of laboured chewing due to elastic resistance from the food.
Dry mouthfeel	Feeling of dryness in the mouth.
Fat mouthfeel	Feeling of film of fat or oil in mouth.
Sweetness	Level of perceived sweetness during chewing.

Based on Zambrano et al. (2022), Contardo et al. (2020), Molina et al. (2021), Zhao and Takhar (2017), Devi and Khatkar (2016), Ma et al. (2015), Akhtar et al. (2014), Chen and Stokes (2012), Brookfield Engineering (2023) and Stable Micro Systems (2023)

scanning electron microscope [ESEM] and variable pressure scanning electron microscope [VPSEM]), or the ability to work under cryogenic conditions (e.g. cryo-transmission electron microscope [cryo-TEM] or cryo-scanning electron microscope [cryo-SEM]) (Aguilera & Bouchon, 2008). X-ray micro-computed tomography (micro-CT), a non-destructive method, has been also increasingly used in food research, as will be discussed later.

3.1 Process Miniaturisation Using Hot-Stage Polarised-Light Microscopy

Food process miniaturisation is a concept first introduced by Aguilera and Lillford (1996) and refers to the transfer of a food process to a stage mounted under the lens of a microscope. The stage allows temperature ramps (heating or cooling) as well as isothermal periods to be programmed and controlled. Additionally the control of pressure, among other variables, is possible. A video camera attached to the microscope captures images in real time, which are later analysed, providing numerical data. The system can be mounted under a stereomicroscope, a light transmission microscope or even under a confocal microscope. The system has been used to miniaturise several unit operations such as frying (Bouchon & Aguilera, 2001), powder caking (Saragoni et al., 2007) and lactose crystallisation (Arellano et al., 2004), allowing real time, in situ experimentation. Other configurations may be set up under the microscope lens. For instance, a microfluidic device can be coupled to the microscope to analyse bubble formation under different flow regimes (Skurtys et al., 2008).

Accordingly, several structure parameters of food components can be quantified, including the loss of birefringence and degree of gelatinisation (DG) during the heating of starch granules, using polarised microscopy (Tao et al., 2018; Molina et al., 2016) (Fig. 4). Process miniaturisation enables us to better understand some fundamental relationships between formulation, processing and microstructure that may help explaining what occurs at a macro level under real processing conditions (Li et al., 2022; Ovalle et al., 2013). Molina et al. (2016) analysed the effect of freezing on starch gelatinisation during subsequent heating by means of polarised-light, video-microscopy. The degree of gelatinisation (DG) was measured by following-up the gradual loss of birefringence, which was quantified through image analysis. They showed that the DG was delayed when native starch granules were immersed in water and subjected to freezing. This process roughened the surface of native starch granules, making them more accessible to hydration and water redistribution within, as reflected by atomic force microscopy (AFM). This provides relevant information to understand what happens at the macro scale when a dough is subjected to freezing before heating, as examined by Xu et al. (2022). Here the authors observed structural disorganisation of starch during freezing-thaw cycles, which led to higher swelling capacity during heating as well as accelerating the intra- and inter-molecular rearrangement during cooling. This was related to the inferior quality of steamed bread, where the specific volume decreased, while the hardness and chewiness increased in frozen-thawed doughs.

Interestingly, Ovalle et al. (2013) used a vacuum hot-stage mounted in a polarised-light microscope to understand the effect of low pressure on the microstructural changes in starch granules during heating. Under atmospheric conditions, they observed that the gelatinisation process was retarded (i.e. the gelatinisation onset temperature increased) when the heating rate raised from 5 to 15 °C/min. In contrast, at low pressures such as 6.5 kPa (where water boils at 38 °C), no starch gelatinisation occurred due to the rapid water evaporation occurring before the gelatinisation temperature was reached. However, at 30 kPa (where water boils at 69 °C), partial gelatinisation was observed at 90 °C. These results confirmed that enough liquid water had to be present to induce starch gelatinisation and that through pressure control it was possible to control the extent of gelatinisation. This microstructural approach has helped to explain the high oil absorption of starchy products when vacuum fried (Contardo et al., 2016). Similar results have been observed when vacuum frying starchy doughs at 6.5 kPa, which suppresses starch gelatinisation to 28%; this is accompanied by a higher oil absorption compared to their atmospheric pressure counterparts where 99% starch is gelatinised. These results were explained by the development of weaker and crackier structures during frying, with more oil infiltration during vacuum frying (Contardo et al., 2020). Gelatinisation is a crucial process in determining the texture creation such as hardness and crispness of starch-based foods. Gelatinisation is affected by water content; food constituents such as lipid, protein and fibre; air content; and the microscopic network and pore arrangement.

This technique has also been used to study lactose crystallisation kinetics in situ, to understand the effect of storage temperature and lactose

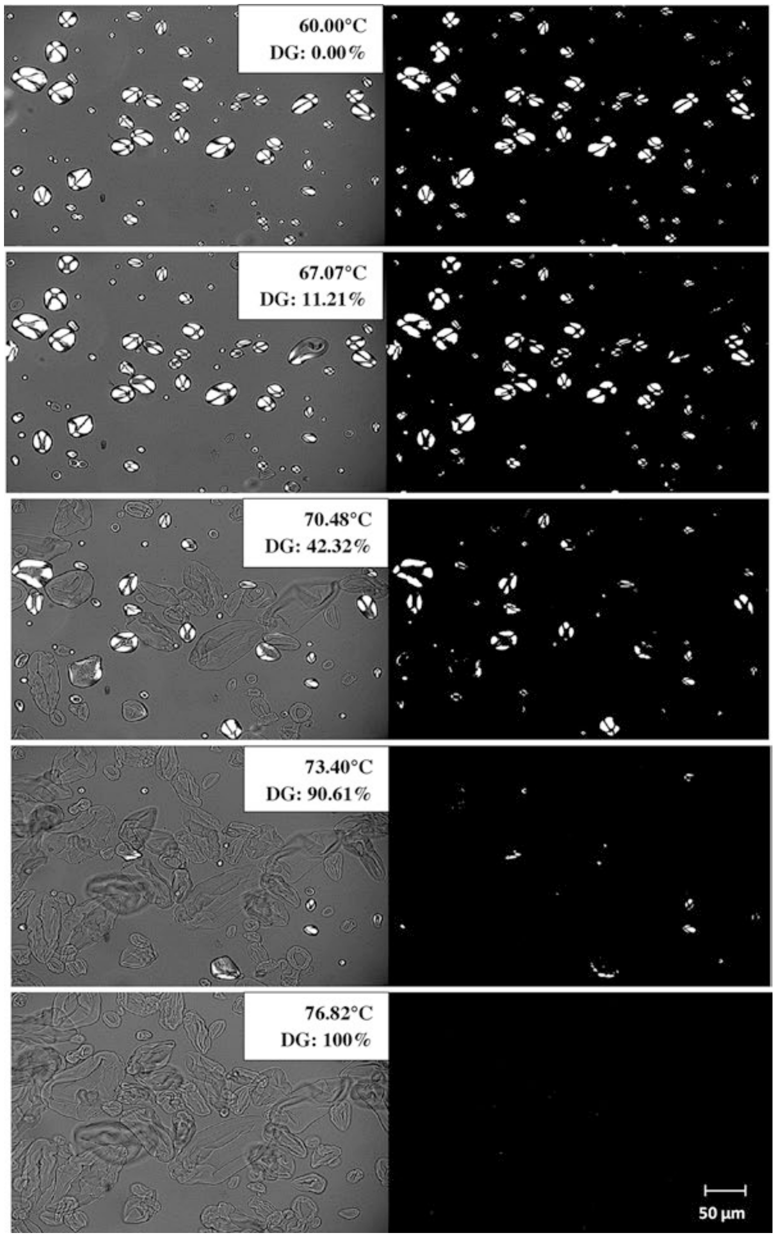

Fig. 4 Gelatinisation process of potato starch granules immersed into water-carrageenan system, observed through hot-stage polarised-light microscopy (left column), showing the loss of birefringence after image processing (right column). DG degree of gelatinisation. (Extracted from Molina et al. [2016])

supersaturation on crystallisation with high accuracy. This information is relevant as the quality of certain food products, such as sweetened condensed milk and ice cream, depends on the control of crystallisation during processing and storage. Even minor variations in external conditions can lead to unwanted changes, such as graininess, which can negatively impact their quality and acceptance (Arellano et al., 2004).

3.2 Confocal Laser Scanning Microscopy (CLSM) to Visualise Food Microstructure

CLSM is an optical imaging technique, where a laser beam is focused onto a small area of a sample, causing fluorescence or scattering of the light, which is used to scan and capture images of a sample at various depths. A big advantage of this technique is that the microscope only captures images in a single focal plane at a time, increasing optical resolution and contrast, by means of a spatial pinhole (to block out-of-focus light), and produces a series of two-dimensional images that can be reconstructed into three-dimensional structures, a process known as optical sectioning (Vodovotz et al., 1996). Accordingly, CLSM provides visualisation of microstructural changes that may be linked to textural properties (e.g. stiffness, hardness, brittleness, strength) in food products due to their ability to produce images with a strong contrast and high resolution, differentiating food components (e.g. oil, protein, carbohydrates) from empty pores. This technique allows optical sectioning to be carried out, avoiding any physical damage of the specimen. To do so, either autofluorescent compounds must be present or fluorescently labelled components must be added. In food matrices, the selection of fluorophore depends on its affinity to the food component of interest, its emission spectra and its behaviour in the food matrix (Sharif et al., 2020).

CLSM can be used to analyse component distribution within the food, aggregates, physical integrity and starch granules as well as their gelatinisation behaviour. For example, Lyu et al. (2022) determined the water distribution in maize starch (MS) and pea protein isolate (PPI) within composite gels using CLSM and were able to quantify the volume fraction of each phase. Water competition between MS and PPI limited starch gelatinisation. The degree of swelling of the starch influenced the final volume fractions of starch and protein in the composite gels, with starch granules becoming dispersed in the protein network. CLSM can be used to predict water distribution within gels, which influences the gel stiffness, hardness and brittleness. In another study, Gu et al. (2022) used CLSM to examine the effects of roasting (160 °C, 0–60 min) on oat kernels and whole oat flour from microscopic, nutritional, functional, structural and digestive perspectives. Changes in starch integrity, cell wall, aggregation and lipid distribution were evaluated. The lipid distribution became denser with continued roasting indicating that some of the lipids were released during the heat treatment. Modest roasting produced a modified starch with lower pasting viscosities, higher gel strength and higher relative crystallinity.

CLSM has been used to study how food processing can improve the textural characteristics for food components. For example, Pu et al. (2021) evaluated the effects of annealing during ultra-high pressure (UHP), finding that the treatment partially disrupted the ordered structures of native and annealed starches, indicating that UHP can delay the gelatinisation process. In another example of improving food constituents, Moll et al. (2023) used CLSM and rheological characterisation to evaluate the impact of homogenisation of pea proteins on the stickiness of pea protein–apple pectin mixtures. A reduced particle size of pea proteins resulting from homogenisation led to an increased stickiness of the biopolymer matrix, which resulted in improved adhesion and cohesion, attributed to an increased reactive surface area.

CLSM has also been used as a complementary technique to visualise the effect of frying on different matrices and the influence on their textural properties (Bouchon, 2012). Contardo and Bouchon (2018) examined the resulting oil distribution in starch–gluten matrices and the influence of microstructure on texture. Compared to atmospheric frying, vacuum frying resulted in a larger amount of oil take-up with an even distribution across the matrix. Some cracks were also visualised on the surface of vacuum-fried samples, although a clear differentiation of the pores was difficult to ascertain in samples processed under vacuum using CLSM (see Fig. 5). The technique was based on that developed by Moreno and Bouchon (2013), who added heat-resistant fluorescent dyes during dough preparation, before frying, to avoid post-labelling and, therefore, to reduce artefacts. Interestingly, vacuum-fried matrices showed a much lower starch gelatinisation, which resulted in a more brittle structure, enhancing oil infiltration and significantly reducing the hardness.

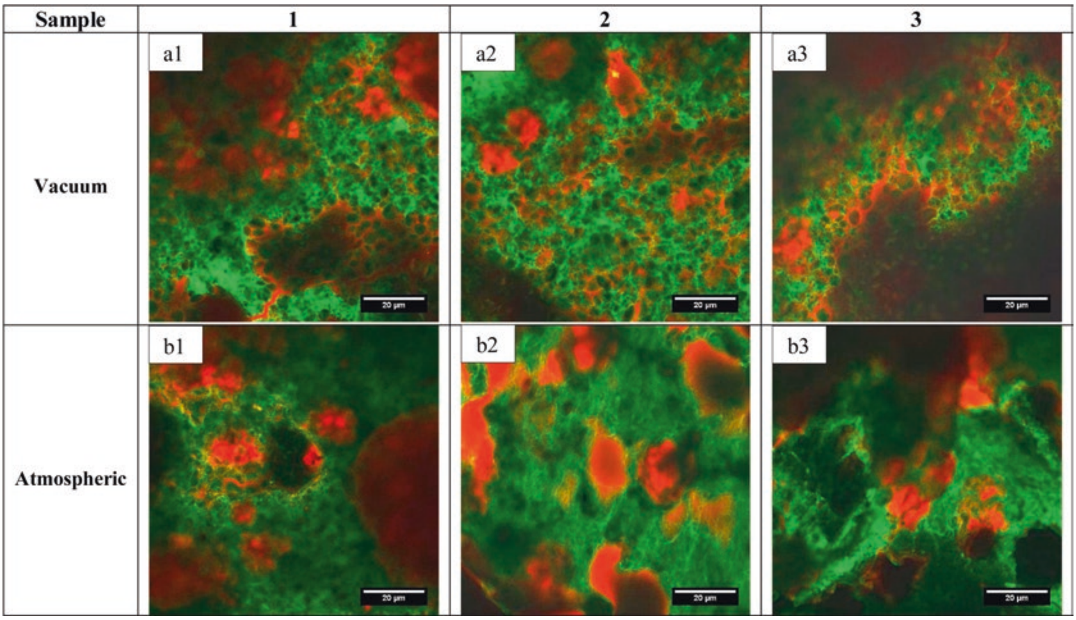

Fig. 5 Confocal micrographs of fried dough samples with similar degrees of starch gelatinisation (~60%), using Acridine-Orange and Nile Red. Three different samples are shown in the inset figures: (**a**, 1−3) vacuum-fried samples (115 °C, 9.9 kPa); (**b**, 1−3) atmospheric-fried samples (170 °C). Barr represents 20 μm. Green area = starch–gluten matrix; red area = oil; and black area = air. (Extracted from Contardo et al. [2020])

3.3 Electron Microscopy in Food Studies

As thoroughly discussed by Aguilera and Bouchon (2008), SEM is more widely used in food studies than TEM. This is due to the scale of components being examined as well as overcoming many of the limitations imposed by TEM. SEM uses electrons to scan the surface of a sample to create high-resolution images. When the electron beam strikes the specimen, various signals are generated that can be utilised for imaging purposes. Secondary electrons and backscattered electrons are the two most used signals to produce SEM images. X-rays, which are also produced due to the interaction of electrons with the sample, may be detected to gather compositional information. SEM allows us to produce a 3D image of the material surface with high resolution and a great depth of field, and the preparation of samples is simpler than required for TEM, as it does not require fixation and sectioning. However, SEM conventional equipment has some weaknesses related to sample preparation, including the need to maintain high vacuum, which requires total dehydration of the sample and the requirement to coat non-conductive materials with a conducting metal.

High moisture content of samples is a significant challenge in food microstructure imaging. Water plays a crucial role not only as a dispersion medium for various components, but it also determines the specific structures of macromolecules such as proteins and membranes. In conventional SEM, adequate drying of samples is necessary, with few exceptions like low-moisture or powdered foods (such as snacks or milk powder). Examination of various food samples in their natural state without the need for dehydration or metal coating is now possible with low vacuum scanning electron microscopes (VPSEM and ESEM). These new techniques significantly expand the range of food materials that can be studied. They enable minimal intrusion imaging of moist vegetable tissue, emulsions, food gels, dispersions and more. Interestingly, these technologies also permit miniaturisation of food processing, and processes such as dehydration,

hydration, freezing, freeze-drying, crystallisation and melting can be observed in real time by modifying the chamber conditions. Cryo-SEM is another technique that can be utilised to observe wet samples. Additionally, with the appropriate detector, X-ray analysis is also possible. Other analytical electron microscopy capabilities may include electron energy loss spectrometry and Raman scanning electron microscopy.

3.4 X-Ray Micro-Computed Tomography (Micro-CT) to Quantify Food Microstructure

CLSM is a valuable technique which enables observation of the inner structure through optical sectioning. However, the technique involves the use of fluorescent labels which may lead to some artefacts. The penetration depth of the laser only allows a maximum thickness of ~300 μm, which limits the volume of observation. SEM, on the other hand, permits a wide surface characterisation of a food sample, with a high field of observation. Even though it is still possible to use SEM to reveal inner characterisation if the sample is physically fractured, differentiation and quantification of different components are challenging. Because of these limitations, micro-CT has been widely adopted in food studies, particularly for non-invasive observation and analysis of porous structures (Contardo et al., 2020).

The operating principle of micro-CT relies on the contrast observed in the image of a sample produced by the variations in the intensity of the X-ray attenuation, and, therefore, the technique is particularly suitable to characterise porous materials (Zambrano et al., 2022). Samples are normally placed inside the micro-CT equipment on a holder and rotated to generate successive X-ray images, out of which 3D images can be generated. The use of micro-CT involves great advantages over conventional techniques, due to minimal sample preparation, high-resolution and possibility to perform 3D quantitative image analysis of the internal structure. Through micro-CT analysis it is possible to quantify dimensions, expansion, porosity, pore diameters, pore size distribution, pore connections, cell wall thickness, specific gravity, specific volume, percentage crystallinity, compact arrangement of molecules, and nutrients (e.g. oil) or mineral (e.g. calcium) distribution, as well as other parameters which influence the textural properties of food (Mishra et al., 2023). Accordingly, this technique has been used to study microstructure of food products during various processing operations, including frying, drying, baking, freeze-drying, freezing, 3D-printing, extrusion.

With respect to food microstructural analysis, a low imaging contrast between food components is expected when using micro-CT, due to the low X-ray attenuation differences among food components (e.g. water, polysaccharides, proteins or lipids) (Sikorski, 2002). The incorporation of agents may modify X-ray attenuation, as has been done in the medical field, where iodine and barium have been successfully applied to raise the atomic number or confer selective opacity to specific components (Ritman, 2002). Interestingly, Contardo et al. (2020) reported successful differentiation of the oil fraction within a starchy matrix, through the application of fluorescent labels. Image segmentation allows us to examine the same sample by means of micro-CT and CLSM. Using micro-CT, Contardo et al. (2020) found that vacuum-fried dough samples had less air porosity than those fried at atmospheric pressure, though no differences were found with respect to total porosity (Fig. 6). These microstructural characteristics (uniform distribution of ungelatinised starch and external cracks on the surface) were linked to lower hardness with a weaker structure, more oil infiltration and lower starch digestibility. When analysing deep-fat frying, Alam and Takhar (2016) found a significant change in the pore size distribution of potato discs, as a function of frying time. A linear inverse relationship was observed between porosity and tortuosity, where tortuosity decreased with the increase in porosity, and oil content increased with the decrease in tortuosity. In another study, Parikh and Takhar (2016) showed microstructural differences in the properties of French fries prepared with microwave or

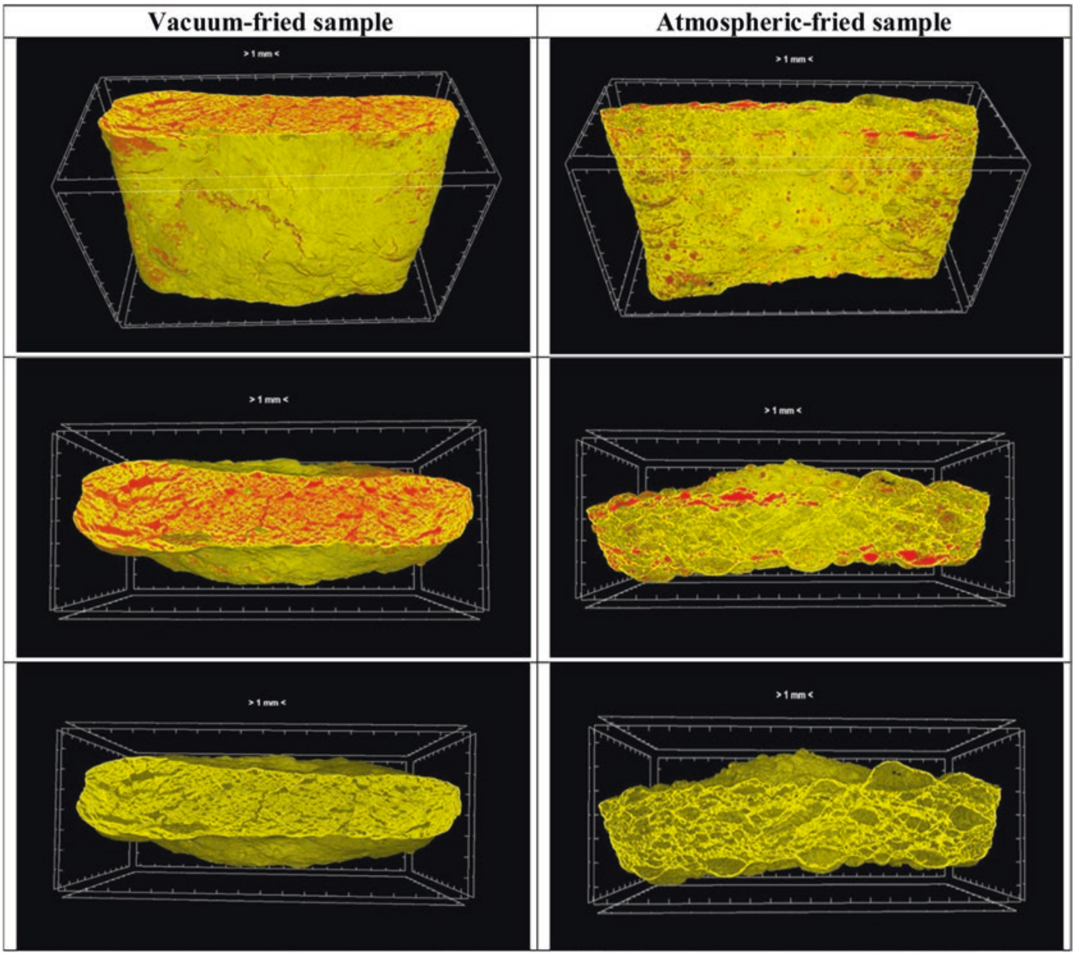

Fig. 6 3D representation of the porous structure of vacuum (115 °C, 9.9 kPa) and atmospheric (170 °C) fried samples with the same degree of starch gelatinisation (~60%). The images show two perspectives (front and cross sections, in the first and second rows) and differentiate (i) the starch–gluten matrix (in yellow), (ii) the pores filled with oil (in red), and (iii) the empty pores (no colour). In the last row, the images show the matrix without the oil, to depict the whole porosity within the structure of the samples (using CTVox software, version 3.3.0). (Extracted from Contardo et al. [2020])

conventional frying. The 3D images obtained by micro-CT showed that the crust of samples processed by microwave frying was less compact compared to conventional frying, probably due to moisture evaporation uniformity.

The characterisation of the internal porous structure of starchy matrices may give critical information about the infiltration and distribution of functional ingredients such as oil, as well as void spaces based within the sample (Schoeman et al., 2016). Oh and Lee (2020) evaluated the effects of soybean oil–candelilla wax oleogel on the rehydration of hot air-dried noodles during cooking. The oleogel noodles showed higher thermal conductivity that could be correlated with a softer texture compared to the non-oleogel noodles. These results were attributed to the more porous microstructural characteristics of the oleogel noodles. The 3D micro-CT analysis showed that the use of oleogel allowed cooked noodles to become less dense, facilitating rehydration during cooking. Additional studies with respect to oil penetration have been undertaken by Zhang et al. (2021), who analysed the effect of ultrasound pre-treatment on starch properties, pore characteristics and oil absorption in potato slices, and by Voong et al. (2020), who examined the physical and mechanical properties of three types of deep-fried battered and breadcrumb coatings (fine, medium and coarse) using micro-CT analysis. Dehghannya and Ngadi (2021) made a summary of recent advances in microstructural characterisation of fried foods and highlighted the potential of micro-CT as a non-destructive and non-invasive method to quantify fried food microstructure.

Olakanmi and co-workers (2023) prepared a comprehensive review of the application of micro-CT to study the unique aerated structure of extruded foods. Zambrano et al. (2022) used micro-CT to investigate the effect of extrusion temperature and feed moisture on the microstructural properties of rice-flour pellets as an intermediate product prior to microwave heating. They found that low water content and the high extrusion temperature led to the greatest pellet volume with the thickest walls, which went on to the greatest expansion after microwave heating. In other research, micro-CT has been used to evaluate the impact of processing conditions on extrudate microstructure. Working with red lentils, Luo et al. (2020) demonstrated that nitrogen injection during extrusion has a great potential to modulate extrudate expansion, microstructure, and texture, showing that extrudates produced with 300 kPa nitrogen injection pressure resulted in the greatest expansion compared to other nitrogen pressures, such as 400 and 500 kPa, whose inner structures are shown in Fig. 7. Nitrogen injection at 300 kPa had a different microstructure with lower extrudate density (across all feed moistures and screw speeds). Extrudates with nitrogen injection had numerous, evenly distributed small cells. A further observation was that increased moisture in the feed resulted in harder, less crisp extrudate.

Considerable research has applied micro-CT to examining structure and structural changes in fruit and vegetables. For example, cell deformation and collapse during drying of apples, kiwis, raspberries, mango, beetroot, potatoes and bananas (Khan et al., 2020; Prawiranto et al., 2019; Siebert et al., 2019). Visualising 3D ice recrystallisation in frozen vegetables and fruits exposed to temperature fluctuations during the storage (Vicent et al., 2019; Zhao & Takhar, 2017; Ullah et al., 2014). Vicent et al. (2019) examined the volume of ice crystals in frozen carrots over a two-month period, showing distinctive crystal growth, as shown in Fig. 8. The ice recrystallisation decreased the air pore size of frozen carrots, suggesting that the larger specific volume of ice compared to water led to shrinkage of the cell walls. The enlargement of ice crystals damaged the cell structure resulting in undesirable quality changes such as drip loss, softening and surface dehydration of frozen foods (Zhao & Takhar, 2017). Convective dehydrofreezing using cold air has shown promise; initially, air convection partially removes cellular water before the freezing is carried out (Tumer & Tulek, 2023; Schudel et al., 2021; Anmella, 2015). Schudel et al. (2021) showed that convective dehydrofreezing resulted in a 52% firmer bell pepper and 35% firmer carrot compared to their conventional frozen counterparts; furthermore, there was a reduced drip loss observed indicating lesser cell damage in dehydrofrozen samples.

3.5 Super-Resolution Microscopy (SRM) in Food Materials

The super-resolution fluorescence microscopy, sometimes called nanoscopy, was developed by Eric Betzig, Stefan Hell and William E. Moerner, who were jointly awarded the Nobel Prize in Chemistry in 2014 for their work (Van Noorden, 2014). They identified the scientific limitation of optical microscopes to reveal molecular structures at nanoscale in living cells (Betzig et al., 2014). SRM refers to fluorescence microscopy techniques that use innovative approaches to selectively tune fluorescence emission, extending the diffraction limit of light (to about 10 nm), thus overcoming resolution limit defined by Abbe's diffraction equation and achieving the visualisation of fine structures (Gallegos-Cerda

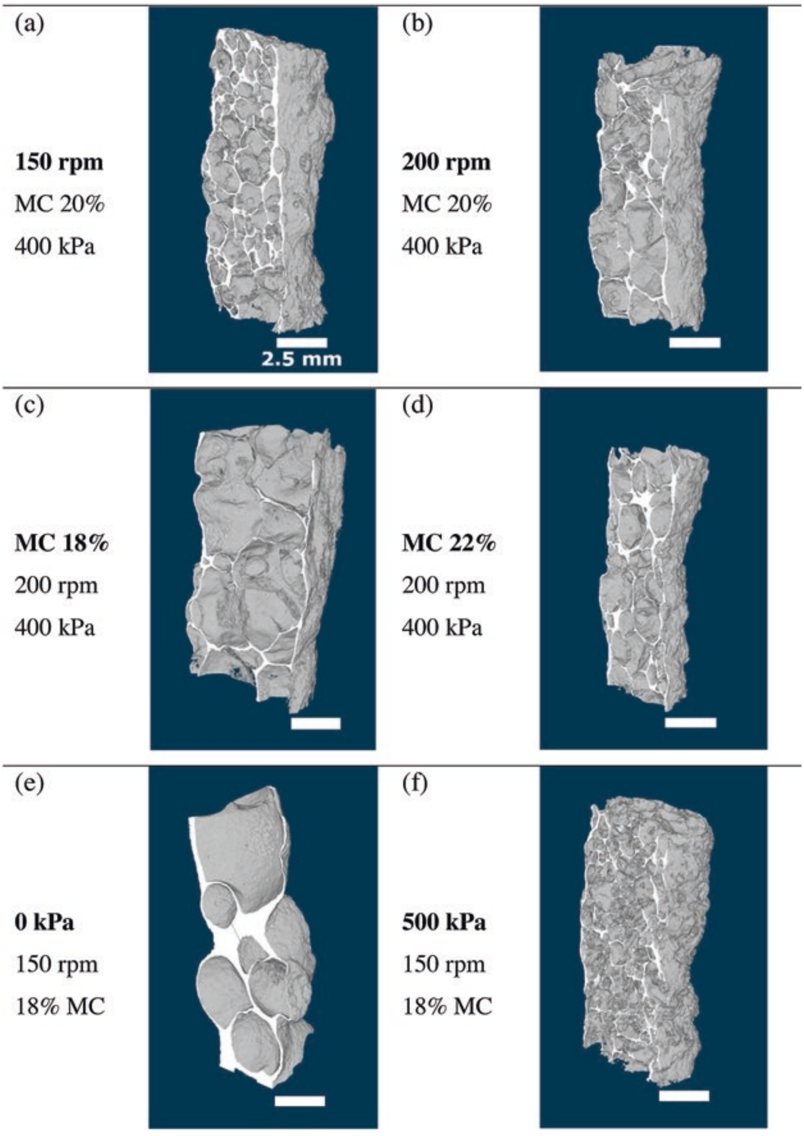

Fig. 7 3D cross-sectional microstructure of red lentil extrudates at (**a**) 150 rpm and (**b**) 200 rpm, at the constant feed moisture content (20%) and constant nitrogen injection pressure (400 kPa); at (**c**) 18% moisture content and (**d**) 22% moisture content, at constant screw speed (200 rpm) and constant nitrogen injection pressure (400 kPa); and at (**e**) 0 kPa and (**f**) 500 kPa nitrogen injection pressure at constant screw speed (150 rpm) and constant moisture content (18%). The scale bar in (**a**) is 2.5 mm and is applicable to all images. (Extracted from Luo et al. [2020])

et al., 2023; Bonilla & Clausen, 2022). SRM techniques have only recently been applied to the field of food, where they have been used to visualise the structure of casein micelles in dairy gels (Li et al., 2023; Glover et al., 2019a, 2020), study protein and fat localisation in milk gels (Glover et al., 2019b), and observe garlic skin, cellulose and agave fibres (Hernández-Varela et al., 2021) as well as egg-white protein denaturation (Bonilla & Clausen, 2022). The application of SRM for the study of food materials presents a new opportunity to visualise and quantify food structures at the nanoscale level and to gain a better understanding of food building blocks and their interactions across multiple length scales. SRM can be used in conjunction with other microscopy techniques such as TEM or atomic force microscopy (AFM), which allows surface protuberances measurement and analysis, potentially revealing food nanostructures.

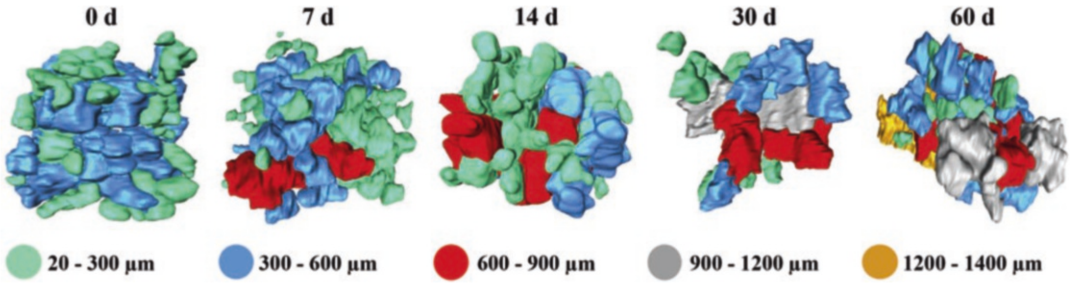

Fig. 8 3D volume renderings of the isolated ice crystal data of the same carrot tissue sample stored under dynamically changing temperature scenarios over a two-month storage period. Ice crystals were subsequently and individually labelled based on their equivalent diameters to describe the different size classes. The 3D models represent 240 × 240 × 240 voxels at a voxel size of 8.9 µm^3. (Extracted from Vicent et al. [2019])

4 Microstructural Approach to Understand the Impact of Ingredient Reformulation on Food Texture

As explained, in recent years, there has been a shift in consumer trends towards healthier, functional, sustainable and clean label food products (Aschemann-Witzel et al., 2021). This includes a preference for products that are low in sugar and fat, high in fibre or fortified with micronutrients that have positive effects on human health and well-being, as highlighted by Alongi and Anese (2021). Additionally, consumers are gravitating towards plant-sourced products and alternative ingredients to gluten and animal-sourced proteins (Giacalone et al., 2022). These choices have posed new challenges to the food industry such as reformulating products while maintaining the same sensory experience (texture and flavour) provided by the original product. It is therefore important for the industry to conduct further research into the possibilities of such reformulations, taking account of the relationships between ingredients, properties at the macro- and microstructural levels, as well as sensory and texture attributes.

4.1 Soluble Fibre to Replace Sugar

Sucrose is the most important sugar used in confectionary and bakery products, and it plays an important role in food structure and texture. Sucrose increases the boiling point of water, modifies the thermal transitions of starch and gluten proteins, gives sweetness and the presence of sugar crystals provide grittiness to the final texture (van der Sman & Renzetti, 2019). Replacing sucrose with alternative ingredients, such as soluble fibre, has been challenging because other ingredients rarely mimic sugar functionality, which has knock-on effects on the textural properties of food matrices. Molina and co-workers (2021) demonstrated that aeration, hardness and grittiness were detrimentally affected in sucrose-reduced biscuits. Micro-CT image analysis showed that biscuits with lower levels of sucrose resulted in a microstructure with smaller air pores and thinner biscuit walls (Fig. 9), which probably relates to a lower level of grittiness and hardness during the first bite. Reducing sugar also raised the degree of gelatinisation from 6 to 40%, suggesting the antiplasticising effect of sucrose water retarded the thermal transitions of starch and gluten. Consequently, the mobility of dough was limited during baking, restricting the expansion during baking of reduced sugar dough, resulting in smaller dimensions and lower levels of aeration in the baked biscuit. It seems that the sucrose particle size was a key variable to modulate the vertical expansion of biscuit doughs. Biscuits that were formulated with powdered sucrose and more than 30% of added sucrose reached an expanded, brittle and non-collapsible structure (Molina & Bouchon, 2021).

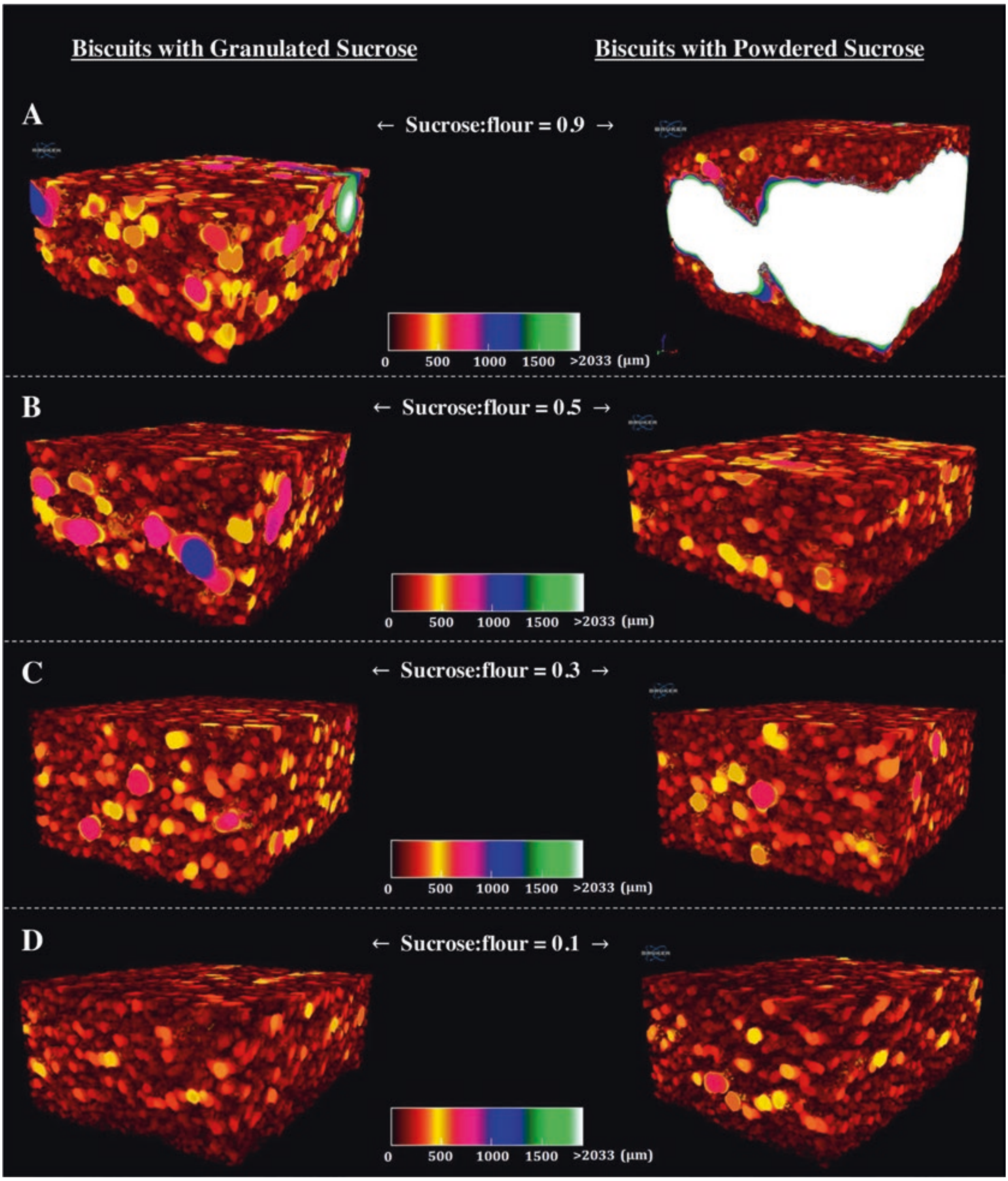

Fig. 9 3D microtomography images of the air pores distributed within biscuits prepared with either granulated (*left*) or powdered sucrose (*right*) using sucrose:flour (g/g dry basis) ratios of 0.9 (A), 0.5 (B), 0.3 (C) or 0.1 (D). The air pore sizes are represented according to the colour-bar legend, where dark red to orange colours represent the smallest air pores (<500 µm), whereas white colour represents the biggest air pores (>1905 µm). (Extracted from Molina et al. [2021])

Soluble fibre is an interesting alternative as a bulking agent instead of adding flour to the biscuit formulation when sugar is reduced; this is due to their lower water-holding capacity compared to flour. Rodriguez-Garcia et al. (2022) analysed the effect of four soluble fibres (Nutriose and Promitor as dextrin-types; Orafti and Fibruline as inulin-types) on dough viscoelastic properties and final biscuit attributes, where 30% of sucrose was replaced with each fibre. Dextrin-type fibre had similar viscoelastic behaviour to that of the full-sugar dough, while inulin fibre presented a more elastic response due to their hygroscopicity and ability to immobilise water. Regarding instrumentally measured texture, all fibre-enriched biscuits showed lower breaking strength compared to full-sugar control biscuits; however, all of them were firmer at the first bite during sensory analysis compared to the control. While the results show promise in terms of elevating the fibre content of biscuits and lowering their sugar content without compromising the desired sweetness profile, additional research is necessary to comprehensively grasp the impact of fibre substitution on the ultimate structure and its correlation with sensory texture. In cakes, Tsatsaragkou et al. (2021) replaced 30% of sucrose with two types of inulin (Orafti and Fibruline), which differed from each other in the degree of polymerisation (DP). They examined the impact of incorporating fibre on batter viscosity, a crucial parameter for cake quality since it is responsible for retaining air bubbles during baking. The lower DP of Orafti inulin allowed the batter to have similar apparent viscosity and viscoelastic properties that the control, while the higher DP of Fibruline produced higher values. Regarding aeration of the final structure, control and Orafti cakes showed similar mean cell size and cell circularity, and Fibruline cake had bigger cells and compact areas in the crumb. Despite instrumental texture measurements showing that Fibruline cake was the firmest, these differences were not detected by the sensory assessors. These findings emphasise the value of comparing both methodologies, as sensory panels may not detect the sensitivity of instrumental techniques. Soluble fibre may offer an alternative for reformulating sweet bakery products, but it is crucial to understand the impact of structural parameters of fibre, such as the degree of polymerisation, solubility and hygroscopicity, on the viscoelastic properties of the dough and their subsequent influence on the final structure, texture parameters.

4.2 Oleogels and Bigels as Fat Substituents

Fat influences the overall texture of many products because it provides tenderness, mouthfeel and a lubrication during chewing. The solid fat content (SFC) is considered a key parameter, if not the most important one, to evaluate the functionality of fat in foods such as flavour release, the melting profile, spreadability and plasticity (Grossi et al., 2022). This is defined as the ratio of solid to liquid fat at a given temperature, and depends on the composition of the fatty acids, as shown in Table 2. However, the growing health concern over high levels of saturated fatty acids (SFAs) and trans fatty acids (TFAs) in the diet has promoted the partial or total replacement of fat with vegetable oils or structured lipids (see Sect. 2.3). Among the replacements, oleogels and bigels appear to be promising candidates (Pușcaș et al., 2020; Quilaqueo et al., 2022; Silva et al., 2022).

Oleogelation is a technique used to entrap liquid vegetable oils in a solid-like gel structure using oleogelators, namely crystalline particles (e.g. waxes, fatty alcohols), self-assembled networks (e.g. ricinelaidic acid, tocopherol + lecithin), polymer networks (e.g. ethylcellulose, κ-carrageenan) and emulsions or foams (Flöter et al., 2021). The main difference between

Table 2 Physicochemical properties of some fats and oils

Property	Palm oil	Coconut oil	Peanut oil	Sunflower oil	Cottonseed oil
SFC (%) at 21.1 °C	14.0	26.6	–	–	–
Melting point (°C)	37.5	25.5	3	–17	13
Saturated fatty acids (SFAs, %)	50.4	92.0	18.4	12.4	25.7
Unsaturated fatty acids (UFAs, %)	49.6	8.0	80.3	87.6	74.3

Based on Devi and Khatkar (2016) and Akhtar et al. (2014)

oleogels and bigels is that the former are gels in which the continuous liquid phase is oil, while bigels are biphasic systems where both the lipid and the aqueous phase are structured in the form of an oleogel or hydrogel (Kanelaki et al., 2022). These structures have been used to reduce fat in different food products, such as biscuits (Quilaqueo et al., 2022; Onacik-Gür & Żbikowska, 2020), meat products (Oh et al., 2019; Gómez-Estaca et al., 2019) and chocolates and ice creams (Moriano & Alamprese, 2017; Ceballos et al., 2016). Moriano and Alamprese (2017) used sunflower oil oleogels enriched with antioxidant compounds as milk-cream substitutes in artisanal ice creams, where two levels of fat were considered (4 and 8%). At 4% of fat, with 12 g of gelator, the flow behaviour of the mix was slightly affected. Milk-cream containing ice cream mixes showed higher viscosity than oleogel ice cream mixes at shear rates below 200 s^{-1}, yet similar values were obtained after this threshold. The apparent viscosity of ice cream mixes at 290 s^{-1} differed only in 2 mPa.s between milk-cream and oleogel, showing the structuring effect of the sunflower oil oleogel. However, at 8% fat, ice cream mixes containing milk-cream showed higher viscosity than oleogel ice cream mix over the whole shear range. Despite these results, the overrun and the shape retention index increased in oleogel ice cream compared to the milk-cream ice cream, confirming the good performance of the sunflower oil oleogel in entrapping air and maintaining the final structure of ice cream, as can be seen in Fig. 10.

Martins et al. (2019) demonstrated that the textural behaviour of hybrid gels is influenced by oleogel-to-hydrogel ratio. An increase in the oleogel-to-hydrogel ratio presented a decrease of firmness, spreadability, gel adhesivity and cohesiveness. This textural response was a consequence of the disaggregated structure, stemming from the disruption of the hydrogel network, through the inclusion of increasing amounts of oleogel. Oh et al. (2019) utilised foam-structured hydroxypropyl methylcellulose (HPMC) to structure canola oil, to use as an animal fat replacer for reduced saturated fat meat patties. Beef tallow was replaced with 4% HPMC oleogels at two different levels (50 and 100%, w/w), where the ratio of saturated to unsaturated fat decreased from 0.73 to 0.18. When burger patties were subjected to cooking, inevitable weight loss was observed mainly due to fat melting and evaporation of water. Patties prepared with HPMC oleogels were softer and had significantly better

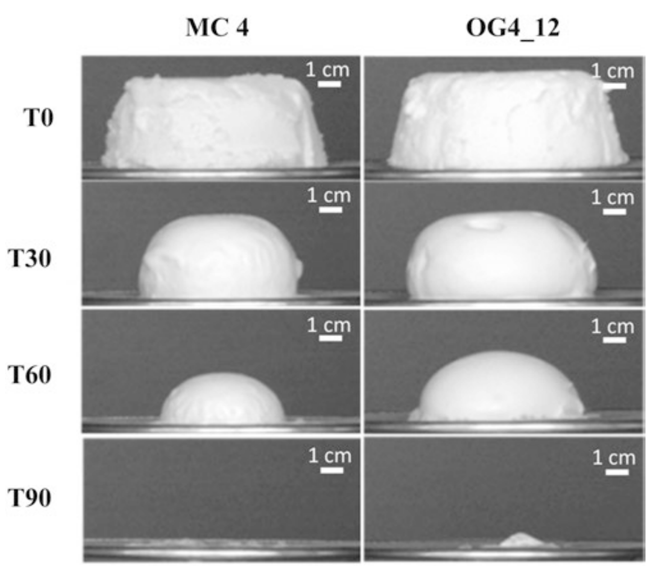

Fig. 10 Examples of pictures taken during melting test of ice creams containing 4 g/100 g fat, produced with milk-cream (MC4) and organogel with 12 g/100 g gelators (OG4_12). The pictures were taken at the beginning of the test (T0) and after 30 (T30), 60 (T60) and 90 (T90) minutes. (Extracted and adapted from Moriano and Alamprese [2017])

weight retention compared to patties made with beef tallow, possibly due to the greater water-holding capacity of HPMC.

The sensory evaluation of patties with oleogel replacements had similar visual appearance, colour, flavour and taste. The highest overall acceptability was attained at 50% replacement level, highlighting the score in juiciness and tenderness. This study showed that saturated fat-reduced patties can be made with HPMC oleogel, without sacrificing the sensory attributes. Quilaqueo et al. (2022) created cookies in which the buttercream was totally replaced with a bigel. This bigel was made from a beeswax/canola oil oleogel with sodium alginate or carboxymethylcellulose hydrogels. The relatively high levels of water in the bigel meant that the final cookies had a three times higher water content than conventional cookies. However, the hardness of all the cookies (bigel and conventional) were similar to each other, though the fracturability of bigel cookies increased more than three times compared to the buttercream ones.

4.3 Alternative Proteins to Replace Gluten and Animal Proteins

Over the past few years, there has been a growing interest among consumers in reducing their meat consumption and opting for plant-based alternative proteins. There are two main factors contributing to these behaviours. Firstly, growing concern for greenhouse gas emissions, as water usage and land usage associated with animal food production are major drivers, as highlighted by Aschemann-Witzel et al. (2021). Secondly, the popularity of gluten-free diets may be linked to the diagnosis of silent and subclinical coeliac disease cases, as well as increased awareness and understanding of coeliac disease, gluten allergy and gluten sensitivity (Demirkesen & Ozkaya, 2022).

Meat alternatives can be classified as plant-based (e.g. soy, pea, microalgae), cell-based (also known as in vitro, cultured or lab-grown meat) and fermentation-based (mycoproteins) (Sha & Xiong, 2020). Gluten alternatives can be also plant-based, including glute-free cereal flours (e.g. sorghum, rice, millet) and pseudocereals (e.g. amaranth, chia, quinoa) (El Khoury et al., 2018). Although researchers from different disciplines have worked together to successfully mimic the complex microstructure of animal-based products, there are still challenges for the industry, namely the process scaling-up, the sensory acceptance and the nutritional profile (Aguilera, 2022). Samard and Ryu (2019) used extrusion to texturise (i.e. to produce a fibrous structure) a combination of texturised vegetable proteins (TVPs) (soy and gluten proteins), to then compare its microstructure and texture with beef, pork and chicken meats using an integrity index. This index is an important texture parameter in analogue meat, and it refers to the texture of meat (or meat analogue) residues after the sample is hydrated, pressurised, dispersed and dried. They found that TVP meat had the lowest integrity index value, followed by chicken, pork and then beef, as well as the lowest cutting strength among the samples. Through scanning electron micrographs, they explained these differences due to the amount and shape of air cells, where TVP showed a fibrous structure with non-uniform air cells compared to meat products.

Regarding the cultured cell-based meat, one of the biggest challenges is the production at large scale, which includes the following steps: (1) cell line development, (2) serum-free media development, (3) bioreactor design and (4) scaffold development for cell alignment and proliferation yielding a multicellular tissue (Xiang et al., 2022). Scaffolds are essential components in cell-based meat production, but they are often animal-derived and their production is expensive. Xiang et al. (2022) developed porous scaffolds using glutenin from wheat gluten to support mammalian cell culture. They observed that 3D glutenin scaffolds have aligned fibrous structures, where 2.5% glutenin scaffold presented aligned fibrous structures whereas 5% glutenin scaffold showed aligned sheet structures (Fig. 11). In addition, they confirmed that muscle cells adhesion, proliferation and differentiation occurred in glutenin scaffolds without incorporating an exter-

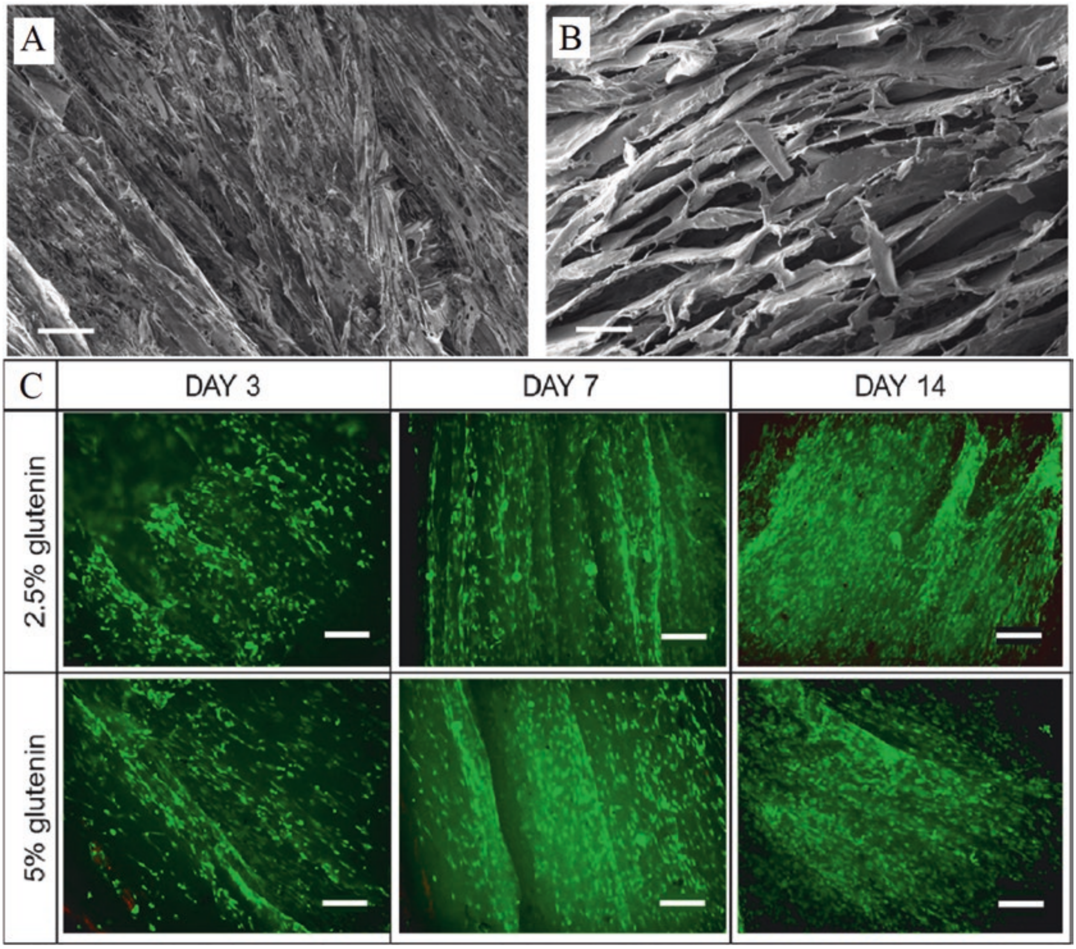

Fig. 11 SEM images of aligned fibrous scaffolds prepared with glutenin concentrations of 2.5% and 5% (**a** and **b**; scale bars: 50 μm) and viability of bovine satellite cells on 2.5% and 5% fibrous glutenin scaffolds at days 3, 7 and 14 (**c**; scale bars: 200 μm). Colour codes: *green*, calcein-AM, live cells; *red*, ethidium homodimer-1, dead cells. (Extracted from Xiang et al. [2022])

nal coating to the scaffold (Fig. 11), showing a promising solution for scaffolds in cultured meat applications.

Godschalk-Broers et al. (2022) studied possible relationships between structure, textural characteristics, consumer acceptance and sensory evaluation of commercially available meat analogues, concluding that only some textural attributes could be explained by structure. Other factors may also be relevant, such as the water-holding capacity of the protein structures, the specific hardness of the fibrous areas, the size of the oil droplets, the oil-binding capacity, etc. Samples with more added fibres had a harder and chewier texture but were less cohesive. Sensory evaluation revealed lower levels of hardness and chewiness in products with more fat. Fat content showed a clear correlation to perceived fattiness. A lower sensory hardness was found to be related to the presence of small air pockets. However, liking was related to other factors, such as meaty flavour and juiciness, which were not directly linked to compositional or textural features. Juiciness was not directly related to the moisture content of the products, indicating that this attribute is rather complex and probably involves a combination of characteristics.

5 Conclusions

Due to the rising demand among consumers for food products that offer convenience, sensory quality and health benefits, there is a growing focus on food product design in both research and industry. An ample body of evidence supports the notion that the microstructure of food plays a critical role in determining the desirable properties of food products. This is partly due to the advent of new microscopy techniques that produce minimal artefacts and enable quantitative information to be obtained through image analysis. In response to this evidence, there is an increasing emphasis on precise interventions in food production that target key structural elements. Such interventions require a multidisciplinary approach, as the challenge is to establish connections between phenomena at the microscale and the resulting properties of food products, including their texture.

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Food Texture Diagrams and Maps

Andrew Rosenthal

1 Introduction

Diagrams are used to represent information in a graphical form, and diagrams that show the spatial relationships between features are referred to as maps. A common use of maps is to show geographical information, yet spatial relationships between other items may also be plotted. In this chapter, we aim to look at ways of discriminating and classifying attributes of food texture through graphical representations. Unlike graphs, which traditionally have one independent and one dependant variable, in the case of maps both axes are independent of each other. Sometimes maps show clustering of products or related textural characteristics; they may also show contours of similarity along which common items may be found. Some of the diagrams in this chapter (particularly Sects. 4 and 5) allow us to predict texture changes by moving from one locus to another.

We cannot consider texture in isolation of structure, yet structure alone does not give us texture. For texture is a human response; it is about *our* interaction with foods when handled, bitten, chewed, mixed with saliva and swallowed. Research into food texture follows two distinctive routes: work with human subjects and instrumental biophysical techniques. The literature in both these areas provides us with maps and diagrams which enable us to understand how textural characteristics relate to each other.

Spatial relationships encompass both the proximity in terms of how close food textures are to each other, and spatial discrimination as a means to separate closely associated food textures. By their nature, maps are diagrammatic and while traditional cartographic maps have scaled distance to form the axes, in this chapter different constructs based on composition and physical properties are used.

2 Non-map Diagrams

The images in this section are not really maps as they do not have unrelated axes allowing a spatial arrangement of textural properties; however, as diagrams they are useful in depicting distinction of textures within the subject matter.

2.1 Butchery Diagrams

Some of the early food illustrations come from culinary roots, before food was treated as a science, and such illustrations can provide an understanding of how we might expect the texture to be; thus, we have the butchery diagrams (e.g. Fig. 1),

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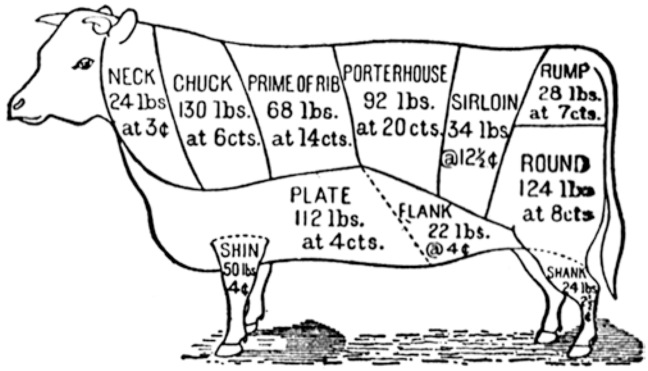

Fig. 1 A butchery diagram. (From Warren, G.F. [1913]. *Elements of Agriculture*. London: MacMillan)

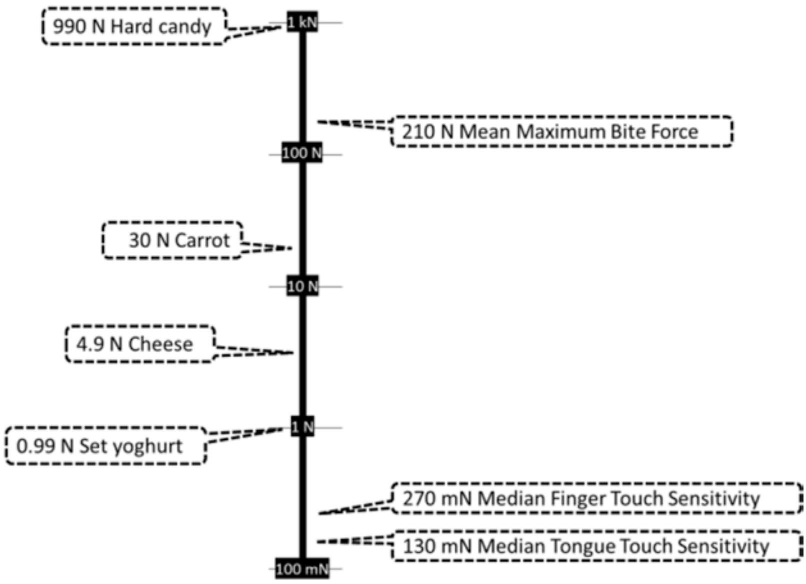

Fig. 2 Scale of hardness in food

which imply expected tenderness/toughness of different cuts. While not really maps, such diagrams do relate textures and monetary value and can be associated with cooking methods to tenderise and enhance palatability.

Butchery diagrams are derived from culinary experience, yet there are scientific principles involved; for example, the amount of connective tissues associated with different cuts, which might influence the levels of tenderness/toughness of the meat (see Chap. 'Meat and Reformed Meat Products' for more information on the tenderness of meat), though even cuts with more connective tissue can still be softened through long cooking time stewing, which enables hydrolysis of collagen.

2.2 Scales

Maps have at least two axes, yet there are diagrams which instruct us about texture based on a single linear dimension.

2.2.1 Scale of Food Hardness

Figure 2 shows the diversity of forces reported in the food texture literature. As texture directly relates to our perception (ISO, 2009), it is appropriate to limit it to the range of forces that we can perceive. The right-hand side of the scale provides physiological values relating to the limits of detection of force (Aktar et al., 2015) and mean maximum bite force (Paphangkorakit &

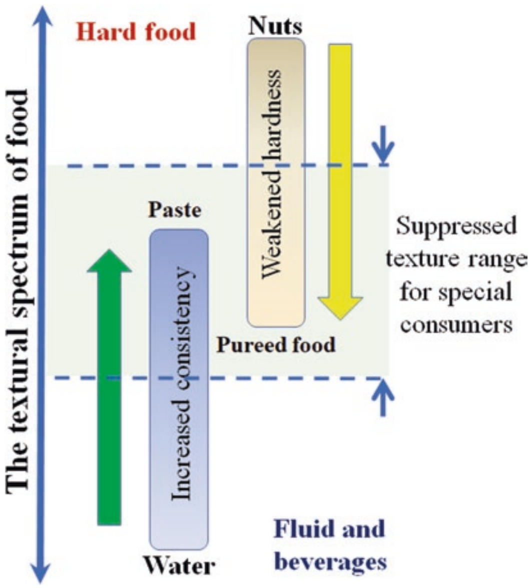

Fig. 3 Scale of the textural spectrum of foods. (Created by Jianshe Chen for this book)

Osborn, 1997). Of course, as a mean, there will be some individuals who achieve higher bite forces, which is why the scale extends to 1 kN.

The left side of the scale shows examples of the hardness for selected foods. The hardest food material with a citation is hard candy (McNulty & Flynn, 1977), which exceeds the maximum bite force; however, as Szczesniak (1998) points out, hard candy is generally sucked, yet we know that sometimes it is chewed (Rosenthal & Philippe, 2020). At the lower end of the hardness scale, we have semi-solid foods such as yoghurt (Zhao et al., 2020). Intermediate levels of hardness include carrot and cheese (Engelen et al., 2005).

Figure 2 shows that the limits of tactile perception are lower than those perceived in biting the softest foods, yet touch perception is important for other texture sensations such as stickiness or the viscosity of liquid foods.

2.2.2 Textural Spectrum of Foods

Figure 3 explores the consistency of foods which we consume, with solid foods at the top and thin liquids at the bottom. Consumption of foods at the extremes of the scale is not a problem for healthy, adult consumers; however, these extremes can pose challenges for individuals with swallowing difficulties. The mid-range bounded by the two broken parallel lines delineates the manageable range of foods for such special consumers.

While Fig. 2 deals with one physical phenomenon (hardness), Fig. 3 unites multiple stimuli, acting simultaneously and reinforcing the idea that perceived texture consists of multimodal stimuli often occurring concurrently with each other.

3 Scientometric Maps

As knowledge expands, identifying where and how 'food texture' relates to other disciplines is of great interest. This has been cleverly undertaken by Blazquez-Ruiz et al. (2016) who looked at keywords from the Scopus database. The frequency with which pairs of these keyword occurred provided a weighting which enabled topics to be linked together. Blazquez-Ruiz, Guerrero-Bote & Moya-Anegon's Scientometric map is shown in Fig. 4. The size of the nodes (and fonts) explains the frequency of the papers that use any particular keyword. The weight of the links identifies the level of association between pairs of keywords.

It is not surprising that texture has close links to sensory, sensory evaluation, sensory attributes on the one hand and rheology, microstructure, physical properties, physiochemical properties, functional properties on the other. Understandably, other sensory properties such as colour have a strong association, as does the less well-defined term 'quality'. When one looks at commodity groups, it is emulsions and hydrocolloids such as chitosan, pectin and starch, along with starch products such as bread, potato and extruded products that are most closely associated with the term texture. Presumably, this reflects the nature of the research that has historically been undertaken in this area.

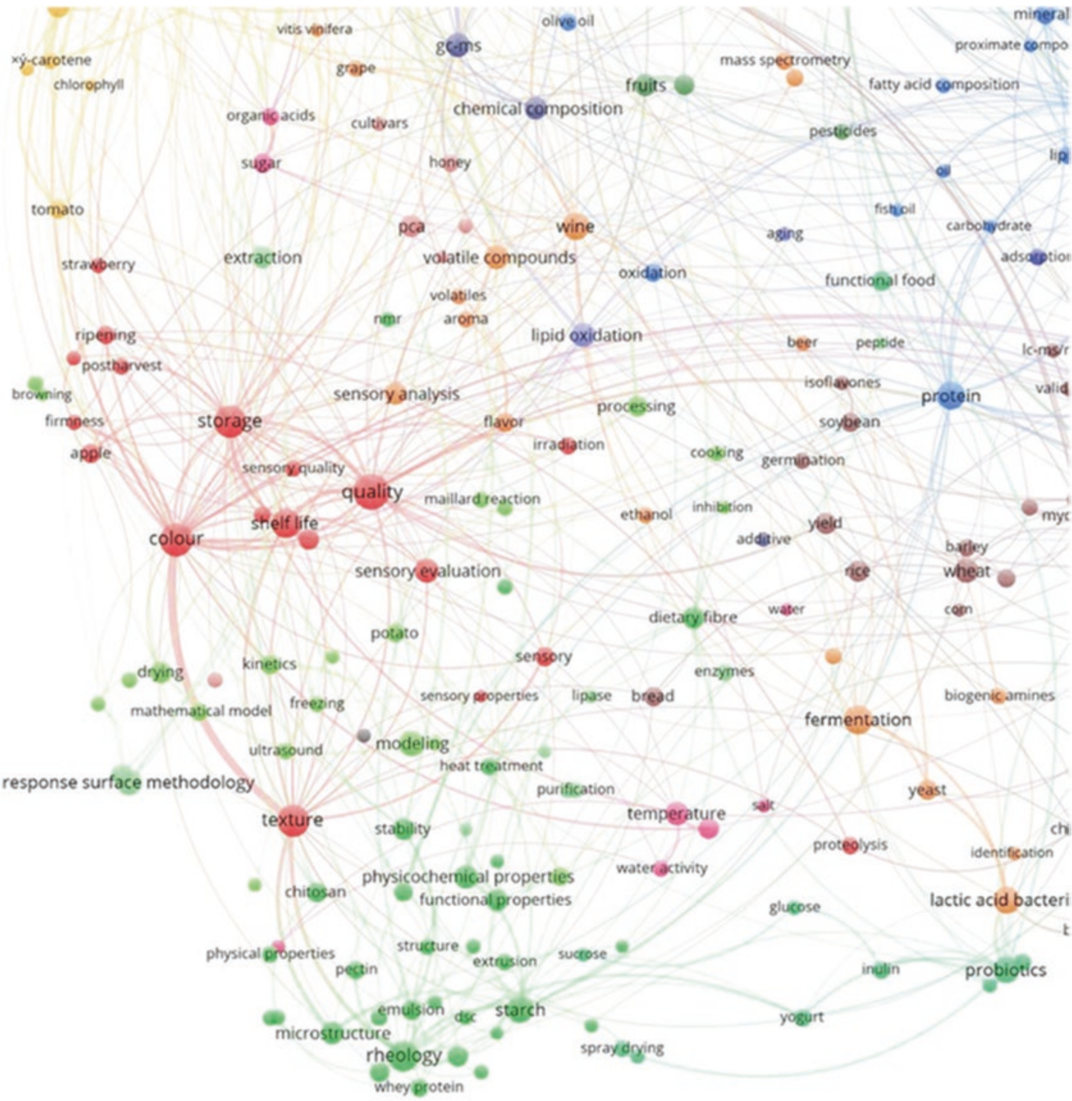

Fig. 4 A scientometric map. (From Blazquez-Ruiz et al., 2016)

4 Ingredient Maps

A number of diagrams exist that help show commonality and distinction between different foods. Such diagrams can be seen as maps inasmuch as they graphically show structure and texture of different products in relation to common axes.

4.1 Bakery Map

Many bakers represent recipes on a flour basis – that is, the ratio of each ingredient to the amount of flour present. This bakery map (Fig. 5) was conceived by colleagues at the Flour Milling and Baking Research Association (now Campden

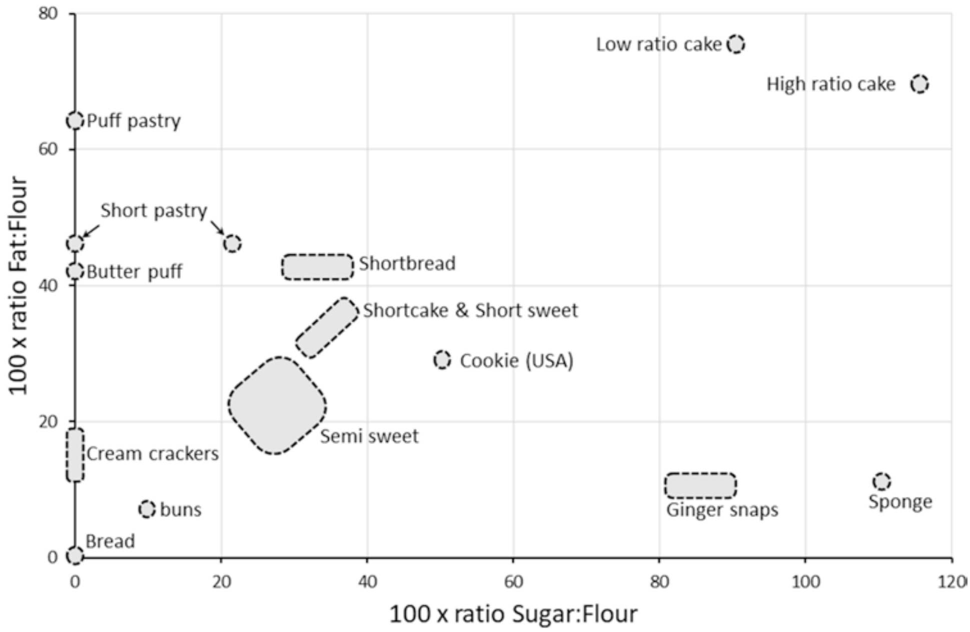

Fig. 5 The bakery map

BRI) in the 1980s. Though not previously published, it cleverly separates bakery products based on their structure and texture by plotting them on fat and sugar (flour basis) axes.

The space within the bakery map is not entirely linear, as we are working with proportions as opposed to absolute quantities. Consider mixtures of flour, sugar and fat. If we start at the origin, then we have 100% flour. Moving to the right the proportion of flour declines as the sugar concentration increases. Continuing to the point marked 100 on the horizontal axis, we have equal amounts of flour and sugar (but no fat). If we now move vertically up, the proportion of flour to sugar does not change, though the overall composition of the mixture does as the fat content increases.

In the bottom left-hand corner of the bakery map, with zero fat and zero sugar, we have bread. Moving up the vertical axis without the addition of any sugar we encounter crackers, savoury biscuits and pastries – with progressively lighter, flakier textures. Added fat in these products is in the form of shortening ingredients and emulsifiers. In contrast, if we start at the origin and increase the sugar content, we arrive at sponge cakes. The modest increase in fat content here comes from egg as opposed to added shortening. Cookies and biscuits arise through progressively greater additions of sugar and fat. It is notable that the high-ratio cakes actually have more sugar than flour in their recipe. Of course, such high levels of sugar help to maintain the sensation of moistness as it binds to the water present in the cake. This binding in turn reduces the water activity creating a long shelf life and spoilage occurs due to stalling of the crumb as opposed to microbial growth.

The bakery map forms a good basis to discriminate between the different bakery products, clearly showing their differences and similarities in composition as well as showing trends in texture.

4.2 Moisture Map

The moisture map (Fig. 6) was conceived by Andrew Rosenthal and first published in *Modifying Food Texture* (Chen & Rosenthal, 2015). Many foods are considered and represented on axes of fat and water, both on a fat-free,

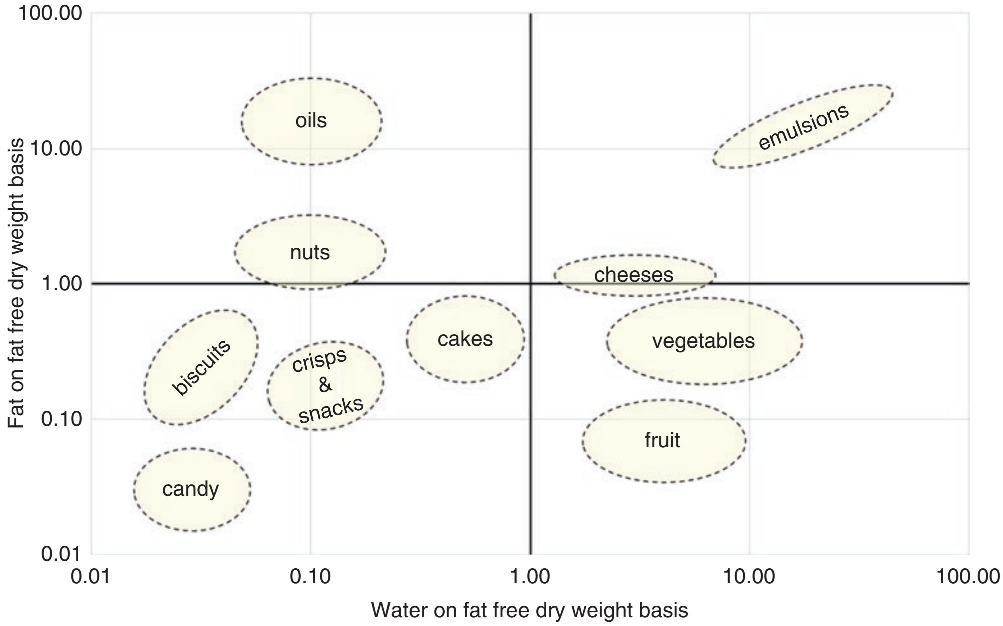

Fig. 6 The moisture map

dry-weight basis. The map separates foods into key commodity groups, and one can recognise different textural areas within its confines.

The moisture map uses a logarithmic plot set out on Cartesian coordinates. As with all logarithmic plots, it does disproportionately emphasise the low-water, low-fat items. In reality, the majority of foods lie in the bottom two quadrants of the map. Most fresh foods fall in the lower right quadrant, with moderately high levels of water. When both water and fat are scarce in the food (as is seen in the lower left quadrant), the predominant materials are the fat-free, dry materials such as carbohydrates and proteins. Here we find biscuits (cookies), crackers, breakfast cereals, cakes, bread, some sugar confectionery, etc.

The moisture map fails in its ability to separate light airy textures from denser materials; thus cotton candy appears at a similar locus to hard candy. When first described, Chen and Rosenthal suggested a third dimension lying orthogonally to the other two, which separated foods on the basis of density. While two-dimensional images are ideal to depict associations on the flat page, depicting three dimensions on a plane surface is less easy.

Figure 6 shows general locations of commodity groups on the map, yet we can populate with specific products to examine diversity within particular commodity groups; thus, Fig. 7 illustrates a variety of dairy products, with whole milk as a reference point blocked in grey (for emphasis). Acidification through lactic fermentation gives rise to yogurts and cheeses. The diversity of cheese is illustrated in a shift to the left as the water content is progressively reduced. Thus, we see moist cheeses like ricotta and cottage cheese close to whole milk, yet cheeses from which the whey is drained are beyond, towards Cheddar, and subsequent maturation and storage takes us further to left to dry cheeses like Parmesan. The different cheese examples included in Fig. 7 are not directly related, each being prepared by its own particular methodology. There are, however, processes which separate milk into different components and the broken lines illustrate the example of centrifugation. The two primary derivative products from centrifugation are skimmed milk (moving down) and cream (moving up). While skimmed milk appears directly below whole milk, the locus for single cream appears shifted to the right, for while there is less

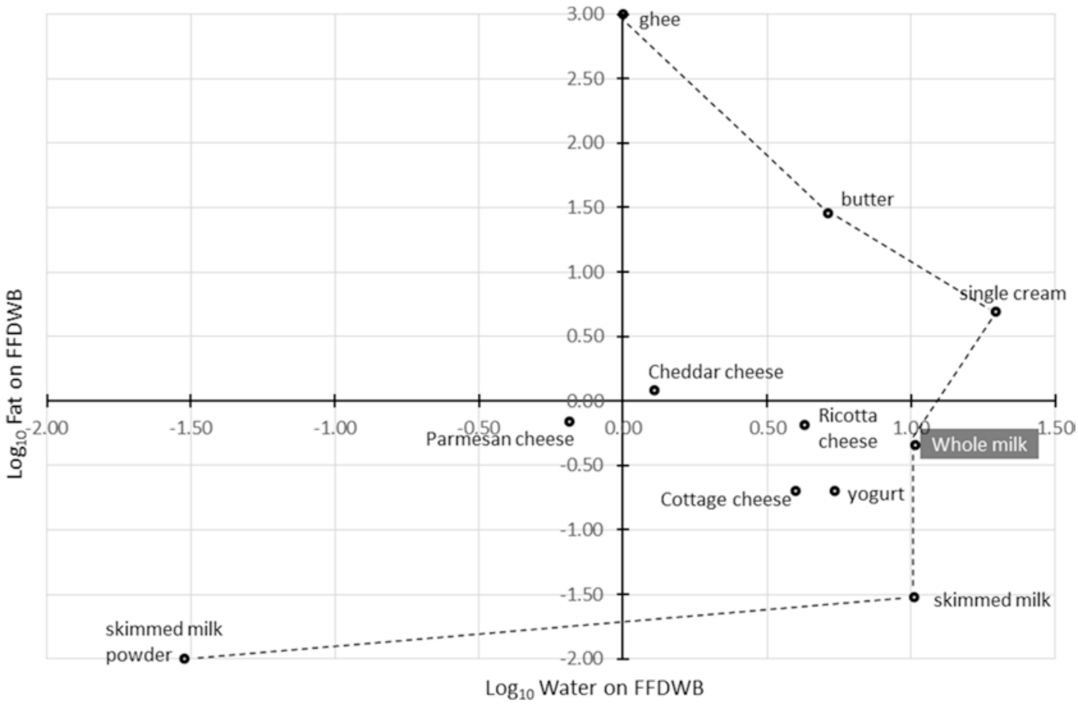

Fig. 7 Expanded moisture map with details of selected dairy products

water in absolute terms, the fat-free dry matter has been reduced from 8.8% (whole milk) to 3.9% (single cream) because the dissolved lactose is contained in the skimmed milk fraction. Both skimmed milk and cream can be further processed into derivative products. Thus, we can follow the manufacturing processes, which converts cream into butter and on to ghee, progressively reducing the water content while simultaneously raising the levels of fat. Similarly, the skimmed milk can be further processed by spray drying, which dramatically reduces the water content.

5 State Diagrams as Texture Maps

State diagrams are essentially maps of material behaviour in response to phenomena such as temperature and concentration.

While the temperature:pressure phase diagram for water is arguably the most important of such diagrams in food science, helping us to understand processes such as freezing, drying, freeze drying, it does not directly relate to texture. Of course, though there are textural changes associated with these state changes and we could consider textural changes resulting from the rate of freezing with resulting ice crystal formation and its impact on the texture of thawed foods, yet these are secondary effects and will not be considered here.

5.1 Sucrose:Water State Diagram

The sucrose:water state (phase) diagram in Fig. 8 is one of the simplest binary state diagrams, but acts well as an introduction to phase transitions. Of course, in foods it has great importance and it acts as a map to explain the structure and texture of the different products contained within.

The horizontal axis in the sucrose:water state diagram shows the percentage sucrose; at zero per cent sucrose (i.e. 100% water), the boiling point (broken grey line) is 100 °C and the freezing point (solid grey line) is 0 °C. Increasing the

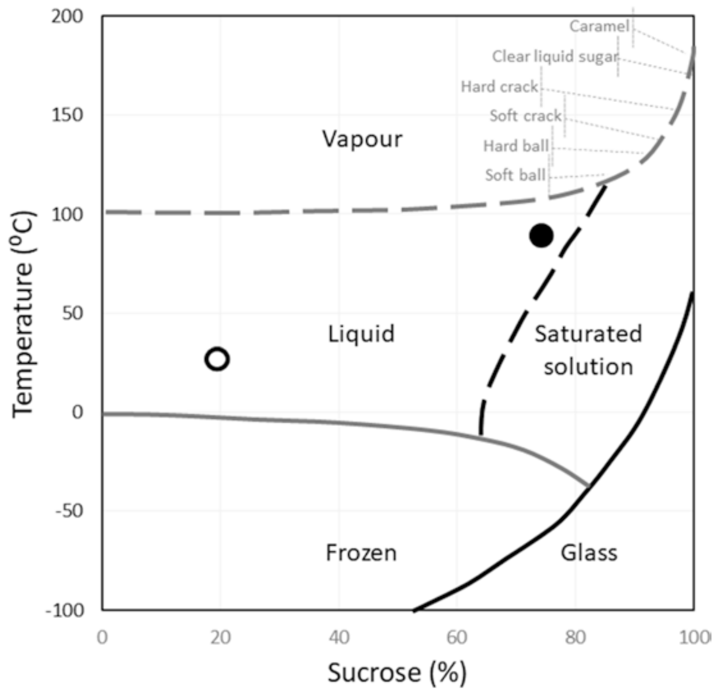

Fig. 8 Phase diagram for sucrose. Grey line for solution, broken is boiling and solid is freezing. Black line is for sucrose, broken is saturation and solid is glass transition. Open and filled circles are reference points referred to in the text. (Redrawn from van der Sman, 2017)

concentration of sucrose results in an increase in the boiling point as well as a depression in the freezing point.

There are three ways in which we can increase the sucrose concentration in the solution; we can use the open circle in Fig. 8 as a starting place to consider each in turn.

1. Solute addition: Working at constant temperature, we can add a small portion of sucrose crystals; these will dissolve resulting in a higher concentration. From the open circle in Fig. 8, we are moving horizontally to the right. Further small additions result in continued increase in concentration until we reach the broken black saturation line; beyond this point, the solution concentration is fixed at the saturation concentration, and further additions result in undissolved sucrose crystals existing in the solution.
2. Freeze concentration: Starting at the open circle on Fig. 8, consider what happens if we chill the mixture. The temperature falls till it reaches the solid grey freezing temperature line. At this point, the water starts to freeze, yielding a more concentrated solution. The concentration of the remaining solution is predicted from the locus of solution temperature on that line. On the diagram, we are following the freezing temperature line to the right. The limit of freeze concentration occurs where the saturation line meets the freezing line; beyond this point, both sucrose and water become solid.
3. Boiling and evaporation: By heating the solution at the open circle in Fig. 8, we move vertically up the chart until the broken grey boiling line is reached. Further heating results in evaporation. Continued boiling shifts us to the right along the boiling temperature line. On reaching the broken black saturation line, amorphous (non-crystalline) rubbery sucrose develops within the solution. Included on the boiling point line are the sugar boiling stages referred to by confectioners. These hot saturated solutions containing amorphous rubbery solids behave as a viscous liquid. The viscosity of these liquids increases when such a solution is cooled, and if cooled through the solid black glass transition line, they become amorphous glassy solids. Addition of bicarbonate to concentrated hot sugar solutions

results in a frothy foamy cinder toffee on cooling, thus modifying the texture of the glass.

Another way to solidify sucrose is cool concentrated solutions. For example, if we cool the mixture at the filled circle on Fig. 8, then the temperature will pass through the saturation line. At this point, solid sucrose will come out of solution. However, the form that those solids take depends on the rate of cooling, with rapid cooling resulting in a viscous amorphous rubbery material. Slow cooling, especially if a crystal seed is added, results in sucrose crystals growing in the solution.

For more information on the sugar:water phase diagram, see Chap. 'Candy Texture: Sugar Confectionery' and Hartel et al. (2011).

5.2 Starch

Starch is composed of two polymers, and in nature, it exists as a mixture of crystalline granules embedded in an amorphous matrix. The two maps which follow relate to the heating of starch with varying amounts of water, the general results being the creation of a liquid and the loss of crystallinity. For more details on starch, go to Chap. 'Starch, Modified Starch and Extruded Foods'.

5.2.1 Relatively Dilute Starch Systems

Working with relatively dilute, gelatinised starch solutions, Joyner and co-workers (2021) produced a texture map showing different textural properties as a function of starch concentration and swelling volume. Figure 9 shows the boundary conditions between Newtonian, shear thinning, elastic and cohesive behaviours. They point out that cohesive behaviours (solid, gluey, stringy, slimy sensation in the mouth) are generally less desirable when creating sauces and desserts than the more fluid non-cohesive textures.

The experimental design in Fig. 9 allowed independent control of both starch concentration and swelling power, allowing both axes to be set up as independent variables and effectively making the map a set of contours with limits of different textural behaviours. Numerically, the 'start of cohesiveness' contour is the product of the starch concentration and swelling volume.

Included in Fig. 9 are four sets of data points which correspond to constant viscosity curves. These curves increase in multiples of 10 giving a

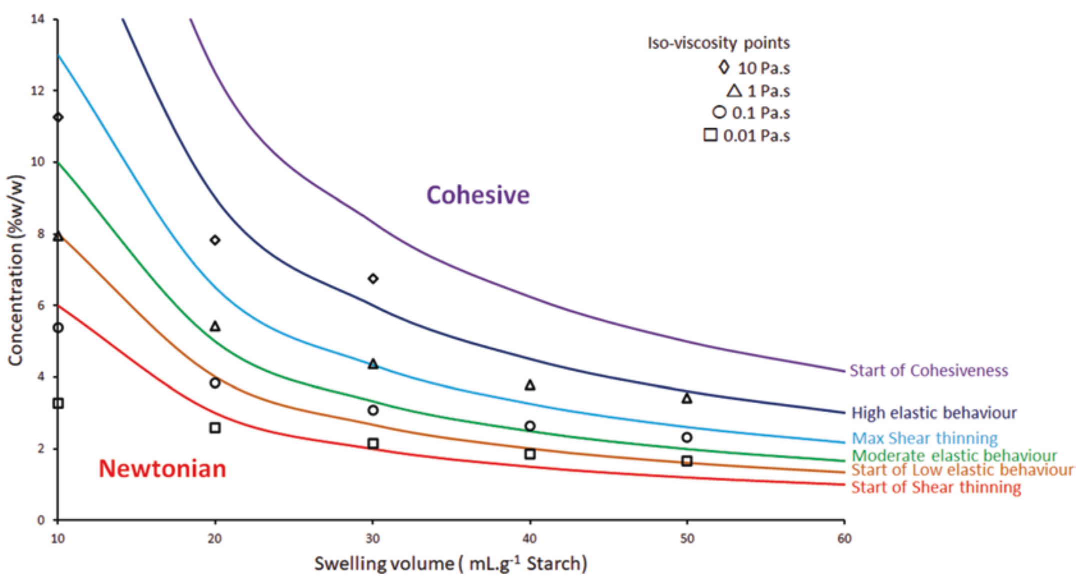

Fig. 9 Starch texture map showing various textural behaviours as a function of starch concentration and swelling volume. (Redrawn from Joyner et al., 2021)

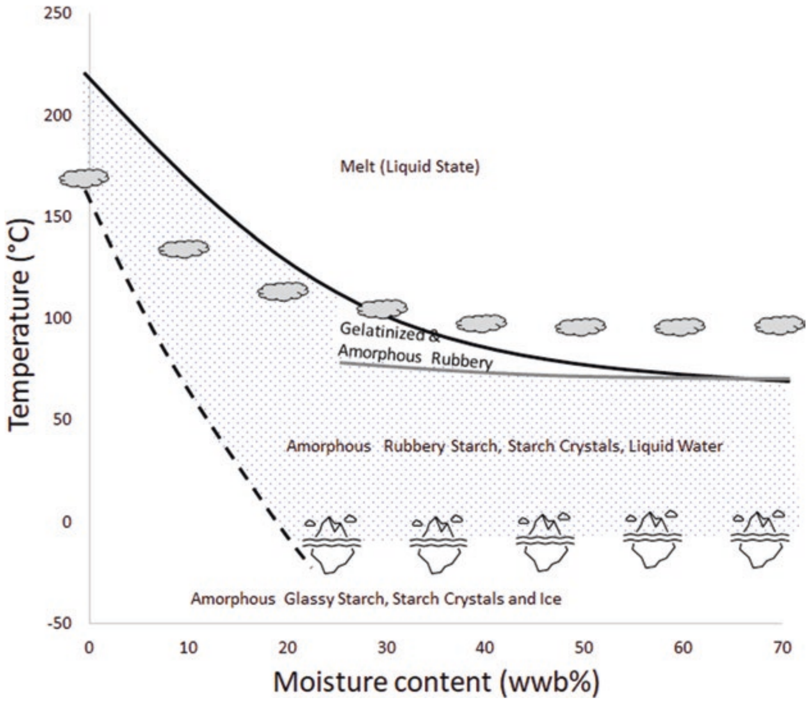

Fig. 10 Two-dimensional state diagram for starch. See text for explanation of lines and symbols. (Based on Kaletunç and Breslauer, 1996)

sense of how the consistency changes as swelling volume and concentration are adjusted. All these viscosity curves do level out with increased swelling volume (the 10 Pa.s curve has not been extended as it cuts into the cohesive region). The map was designed as an aid to product developers in formulating starch-based sauces and desserts.

5.2.2 Relatively Concentrated Starch Systems

As stated above, at room temperature native starches exist as crystalline granules embedded in an amorphous glassy matrix (the shaded central zone in Fig. 10). At high levels of water (>66%), heating results in gelatinisation, whereby the granules lose their crystallinity and form a viscous solution/gel. In such situations heating the starch:water mixture takes us through the solid grey gelatinisation line (Fig. 10).

Using differential scanning calorimetry, Donovan (1979) showed that heating starch:water mixtures with progressively less water present, resulted in a reduction in the amount of gelatinisation with a simultaneous increase in melting. The solid black line in Fig. 10 shows the melting transition and the wedge-shaped region between the grey and black lines contains gelatinised and amorphous rubbery starch. The grey line in bounding this wedge-shaped region marks the gelatinisation temperature, but the extent of gelatinisation diminishes as we move to the left, such that it is almost non-existent when the water content is 36% – thus, melting is progressively dominant as water content is reduced. Whether at high, moderate or low water contents, the overall effect of heating native starch is to lose crystallinity and produce a molten/liquid state.

The black dashed line in Fig. 10 is the glass transition temperature for starch. Cooling mixtures through this phase transitions gives rise to amorphous glassy starch, and if the mixture has not been melted or gelatinised then starch crystals will also be present. Figure 10 is primarily a map of starch behaviour, however that behaviour is inextricably linked to water, and the two remaining curves (drawn as icons) are for boiling water (clouds) and freezing water (icebergs).

Below we will consider two food processing operations for which the diagram helps us understand what is going on in manufacturing processes.

As a first example, let us consider deep fat frying of French fries in oil at 180 °C. Our potato starts with about 70% water, and we can pinpoint the starting state on the diagram at room temperature. When immersed in the hot oil, the surface temperature rapidly rises and we can follow a vertical line through the gelatinisation curve where the starch crystals lose their crystallinity, and on to the 'cloud-line'. As water is lost, the potato surface becomes drier, and we move along the cloud-line to the left. Of course, some water from the bulk will diffuse to the surface, but while any water remains at the surface, its temperature is predicted from the 'cloud-line' and the surface composition. If the potato surface dries to less than about 25% water, then the gelatinised, molten starch at the surface will transform into an amorphous rubbery state as it passes through the melt line. When the product reaches a golden-brown colour, it is considered to be 'done', and it is then removed from the oil and cooled back to room temperature, probably passing through the glass transition line as it cools (depending on final composition and temperature).

A second example is High Temperature, Short Time (HTST) extrusion cooking of a starchy feed with about 20% water, fed into the extruder barrel where it undergoes heating and shear. Since the barrel is sealed, a pressure develops, which prevents water from evaporating. The temperature of the starchy material in the barrel is able to exceed the 'cloud' and melt lines, forming a liquid melt with no change in water content. But when the melt is released at the die, the extrudate undergoes an abrupt pressure drop as steam boils off, expanding the extrudate structure. This sudden vaporisation of steam results in rapid water loss, and while it is difficult to predict from Fig. 10, we move diagonally downwards and to the left as the extrudate cools through the melt and glass transition lines.

The two examples above enable us to follow manufacturing processes and even if we did not know the products, we could predict that the French fries would have a hard, dry, crisp surface, while the highly expanded extruded snack would likely have a thin-walled glassy cellular structure, offering a delicate, brittle, friable, texture when eaten.

6 Rheology Texture Maps

6.1 Plastic–Elastic Map

The earliest rheological texture map that the author of this article could find was that of Davis (1937), Fig. 11. When one considers the instrumentation available during the 1930s, it is obvious that Davis employed tremendous creative ingenuity to measure the elasticity and deformation of various solid dairy products (cheese and butter). It is worth perusing the paper if only to see the instruments used!

Davis' experiments stressed and unstressed solid foods, while noting the change in dimensions. Effectively he was undertaking creep tests, and from the results, he was able to measure elastic and viscous behaviour. In the context of a creep test, viscous behaviour is the ability to flow irrecoverably. As we are dealing with a solid, there is clearly a yield stress which must be overcome before it begins to flow, and such materials are referred to as plastic. The axes in Fig. 11 are expressed in units of force. The vertical axis is a measure of elastic behaviour – that is, the extent to which a stressed body recovers when the stress is removed. In contrast, the horizontal axis is a measure of plastic behaviour – being the extent to which a stressed body deforms irrecoverably when the stress is removed. The term 'springiness' is derived from the extent that the material recovers after the stress is removed (the difference of the irrecoverable and the recoverable stresses). Davis labelled the extremes of behaviour in each of the corners; in redrawing his diagram, only three of these extremes have been included (the upper right label would be 'hard and inelastic').

Davis showed how different materials (i.e. butter and Cheddar cheese) with contrasting textural properties, occupy disparate regions on the map. Davis goes on to say that the same methodology can be applied to other solid food products.

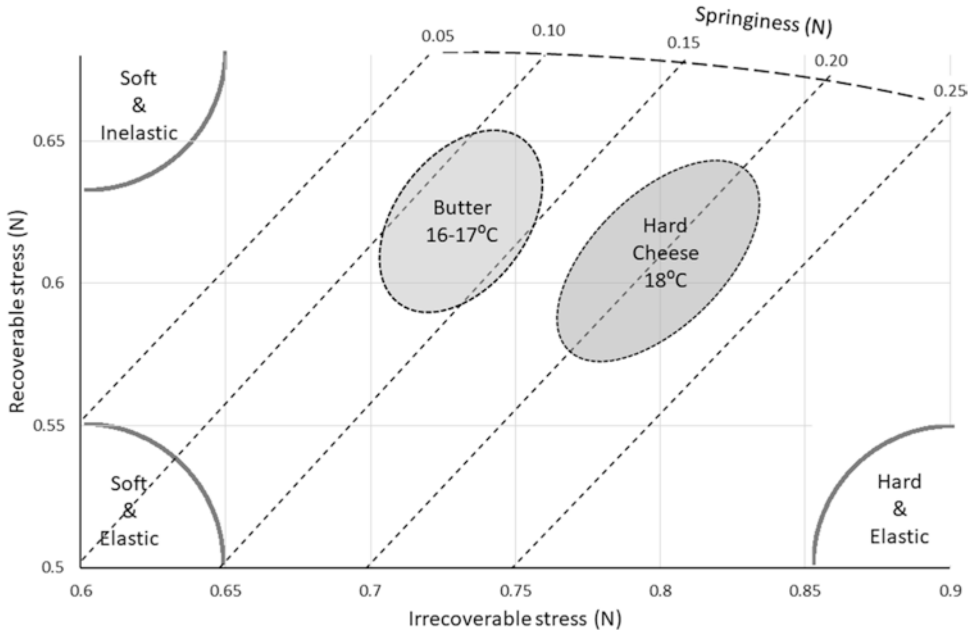

Fig. 11 Map of elastic (recoverable stress) vs. plastic (irrecoverable stress) for butter and cheese. Springiness is shown as broken diagonal lines. (Redrawn from Davis, 1937)

6.2 Stress–Strain Diagrams as Maps

A widely used map which depicts rheological behaviour plots stress and strain at the point of fracture. This plot has been mainly used to consider homogeneous gel-like foods, such as surimi or cheese.

Hamann and MacDonald (1992) applied rubber elasticity theory to the stress–strain yield point of various surimi formulations. They drew a possible qualitative relationship between stress and strain, coining the labels 'mushy', 'brittle', 'tough' and 'rubbery' to denote the sensory attributes of the four corners. Park (2000) used this stress–strain diagram (Fig. 12) and provided a narrative for the rheological behaviour of Hamann and MacDonald's sensory terms in each of the four quadrants. A 'brittle' behaviour is exhibited by a material which does not deform at low levels of stress, but fractures when more severe force is applied. In contrast 'tough' materials do not break under low stresses but progressively deform as the stress is increased, finally rupturing at high stresses and strains. A 'rubbery' material is one which deforms easily when only slight stresses are applied, and failure occurring when the sample is extensively deformed under only moderate stresses. If the sample cannot withstand even low levels of stress, breaking apart rather than deforming, it is described as 'mushy'.

Figure 12 includes the influence of processing and additives as to how the texture of the product changes. Surimi is a fish protein gel, and its locus is found on the right-hand side of the diagram, being relatively tough; if we were to add proteins such as egg white or beef plasma protein, then the sample becomes even tougher and diverges from the more yielding behaviour of surimi. Similarly, adding starch enables the product to accommodate more stress but reduces its ability to withstand strain. In contrast to adding protein, reducing the protein by diluting it with water makes the product less able to withstand stress, becoming more rubbery. The best quality product is created with fresh ingredients, but if the raw materials are stored possibly in the frozen state, then the ability to withstand strain is reduced, leading to a brittle or a mushy product.

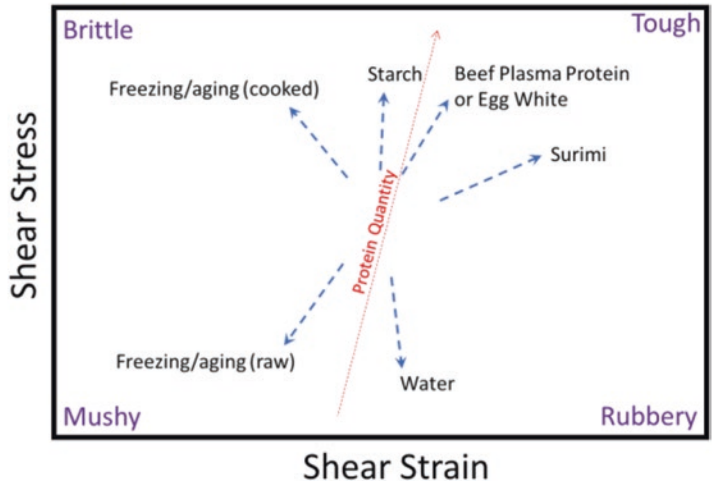

Fig. 12 Stress–strain diagram for surimi. Rheological axes with corresponding colloquial 'sensory' terms in corners blue arrows and labels indicate the influence of processing changes on the textural outcome; see text for details. (Redrawn from Park, 2000)

Several other researchers have used this same diagram; for example, Errington and Foegeding (1988) used this plot to examine a variety of whey protein gels, while Breidinger and Steffe (2001) used it to consider soft cheeses. Genovese and Rao (2003) used such an image to examine the behaviour of various starch dispersions, while Altay and Gunasekaran (2013) used this map to show how the consistency of xanthan–gelatin mixtures changed their properties as their proportions and moisture content changed.

While the food systems discussed above consider impact of process variables on one food product each, the map can be used to compare different food materials, such as done by Schreuders et al. (2021), who considered plant protein isolate (PPI) as a meat analogue with meats and other gel-like materials (Fig. 13). Not only does Fig. 13 compare different materials but it also includes actual values of stress and corresponding percentage strain at rupture.

7 Sensory Texture Maps

The sensory science literature is full of two-dimensional representations of how different products relate to each other. In the case of principal component analysis (PCA), the axes are unmeasured (latent) variables that explain the variation in the measured attributes. The first principal component (PC) explains the majority of the variation and subsequent PCs represent progressively less variation in the data set. The attributes or products that correlate well with each PC can be included on the PC plot. Attributes or products that lie at the extremes (+1 or –1) of the axes correlate well with that PC; conversely variables at the centre (i.e. around 0) correlate poorly. Attributes and products which do not correlate with either PC being displayed will definitely correlate with another one, not considered in that particular map. While there may be numerous PCs, in two dimensions only two can be plotted at any one time, thus authors sometimes provide several plots showing different PCs in relation to each other.

The following examples are by no means exhaustive but provide an illustration of how sensory assessors use perceived attributes to describe the extent to which products relate to each other.

7.1 A Sensory Exploration of the Stress–Strain Diagram

An interesting variant of the stress–strain rheology map, which forms a link to the previous section, is that which was presented by Devezeaux de Lavergne et al. (2017), who considered sensations during oral processing from the first bite (FB), through chew down (CD) to residual afterfeel (AF) when the bolus has been swallowed (Fig. 14). The map originates from two studies

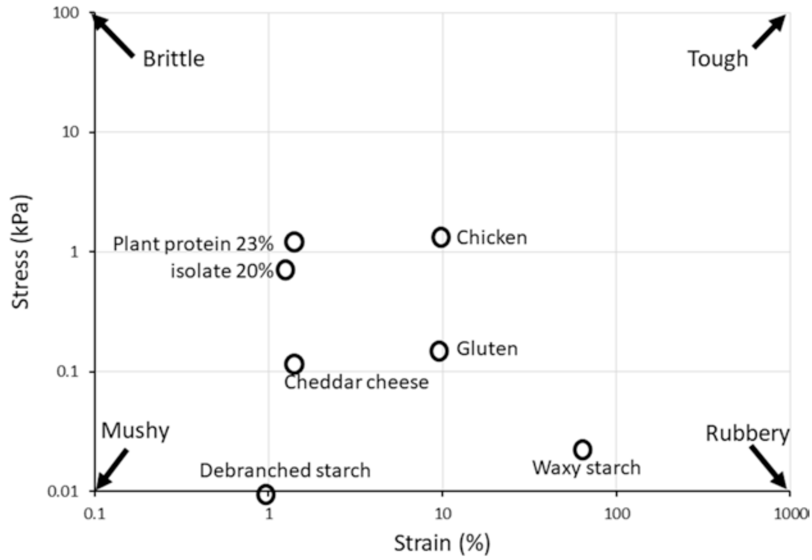

Fig. 13 Stress–strain diagram of pea protein isolate and other gel-like materials. (Redrawn from Schreuders et al., 2021)

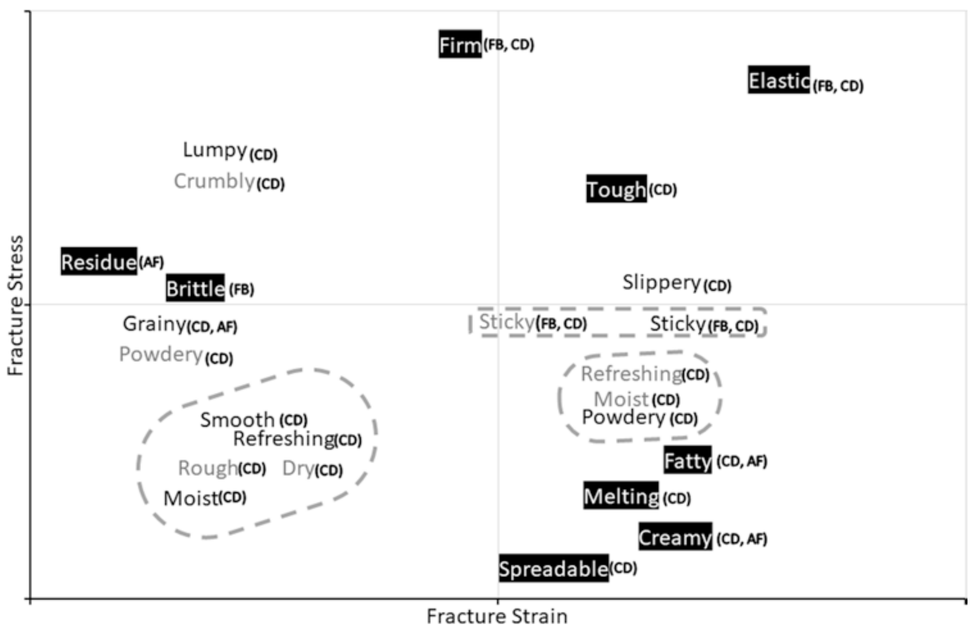

Fig. 14 Relation between fracture properties and texture attributes perceived at first bites (FB), chew down (CD) and after-feel (AF). See text for explanation of labels and clusters. (Redrawn from Devezeaux de Lavergne et al., 2017)

which examined semi-solid food gels (black text) and emulsion-filled gels (grey text). The two axes are based on mechanical testing and the positions of sensory descriptors derived by PCA of the sensory attributes assessed in the studies. Attributes common to the two studies are shown as white text on a black background and the common ones which differ in map location are grouped by broken lines.

The corner markers ‘mushy’, ‘brittle’, ‘tough’ and ‘rubbery’ used by Hamann and MacDonald (Fig. 12) do not all coincide with Fig. 14. Certainly ‘tough’ falls in the same quadrants, but brittle, while corresponding to low strain, occurs at a lower stress level than in the rheology maps. It may be that the naming of the quadrants by Hamann and MacDonald is the source of this discrepancy, for as rheologists, they coined the descriptions through anecdotal intuition. While the terms are not exact matches and the terms ‘spreadable’ and ‘creamy’ (Fig. 14) seem the closest in meaning to ‘mushy’ (Fig. 12), yet they occupy Hamann and MacDonald ‘rubbery’ quadrant.

What is interesting about this sensory map is the positioning of sensory characteristics that one would not associate with stress–strain diagrams such as stickiness as well as geometric, surface and body characteristics such as lumpy, slippery and grainy.

7.2 Vegetable Texture

Poelman et al. (2017) examined the flavour and texture of vegetables least liked by Australian children. Focusing on the texture, Fig. 15 shows the first two principal components (accounting for 58% and 24% of the variation, respectively). PC1 correlates with hardness on the right-hand side with products like raw carrot occupying this region. By implication, the negative end of the axis should associate with soft textures and predictably boiled carrots can be found there. The vertical axis relates to moist and fatty sensations, which is exemplified by the method of cooking, with boiled zucchini (courgettes) lying at the top of the axis as opposed to stir-fried zucchini at the fatty mouthfeel at the other end along with avocado.

Figure 15 has been redrawn with selected products and only three cooking methods compared to the published article. However, it contains multiple preparation methods for some products such as carrots, zucchini, capsicum and beans. It also includes raw salad products which tend not to be cooked such as cucumber, lettuce and avocado.

With the exception of avocado, which among raw vegetables has a uniquely fatty mouthfeel, most of the fresh vegetables cluster to the top right. Boiling generally shifts those vegetables to the top left quadrant while stir frying predictably moves down the vertical axis (except beans) towards a fatty mouthfeel.

Of course, items lying towards the centre of the plot such as boiled beans do not correlate well with either of the axes plotted and likely fit better

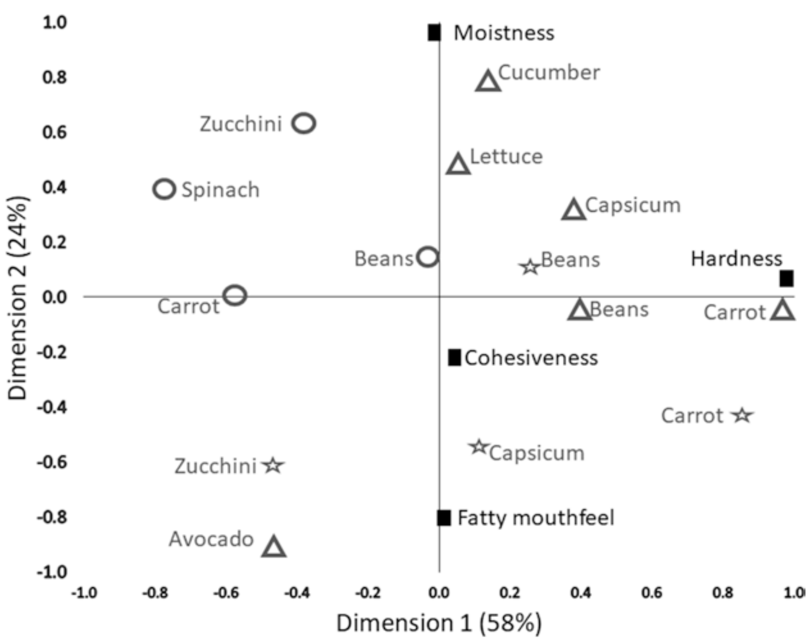

Fig. 15 Vegetable map. Solid black squares are texture terms. Grey symbols and text for preparation methods of vegetable: triangles are raw, circles are boiled and stars are stir-fried. (Redrawn from Poelman et al., 2017, with selected vegetables)

with a further PC lying orthogonally to the two shown here. With only 82% of the variation explained, we can expect at least one further PC to characterise such vegetable products. Moreover, the sensory attribute ‘cohesiveness’ only weakly associates with the two axes displayed and is perhaps the basis of an orthogonal dimension.

7.3 Apple Texture

Endrizzi and co-workers (2015) examined the consumer response to 21 apple varieties by quantitative descriptive analysis. On analysing the data, two principal components were found to describe 93% of the variation (Fig. 16). The first principal component (82% of the variation) was associated with texture terms, the extremes being ‘crisp’, ‘crunchy’, ‘hard’ and ‘fibrous’, which were opposed by ‘floury’ and ‘grainy’. The second and less important PC (=11% of the variation) was associated with taste attributes. In the case of this study, it is clear that texture is the key differentiating factor when it comes to apple varieties and their selection.

7.4 Fish Texture

Cardello et al. (1982) investigated the texture of 17 species of North Atlantic fish. Using the General Foods *[sensory]* Texture Profile method they created a vocabulary made up of six attributes for use on cooked fish: ‘hardness’, ‘oral flakiness’, ‘chewiness’, ‘fibrousness’, ‘moistness’ and ‘oily mouthcoating’. They additionally included the appearance attribute ‘darkness’ (related to lightness or whiteness, but intended not to suggest a colour hue). The authors created a two-dimensional representation of these attributes superimposed on the loci of the species. Figure 17 shows the first two dimensions which accounted for 91% of the total variation.

The horizontal axis seems to relate to oiliness of the flesh with Mackerel close to the oily mouthcoating attribute and non-oily species of Cod and Haddock on the opposite side of the axis. In contrast, the vertical axis seems to relate to flesh openness with flakiness towards positive end and chewiness, hardness and fibrousness at the other.

Towards the centre of the plot are tilefish, monkfish, flounder and halibut, not correlating

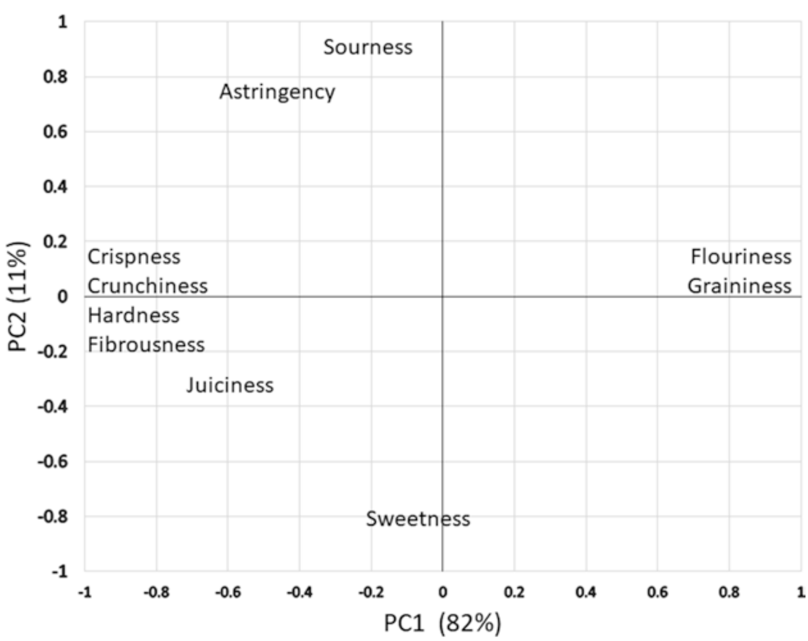

Fig. 16 Map of 21 apple varieties. (Redrawn from Endrizzi et al., 2015)

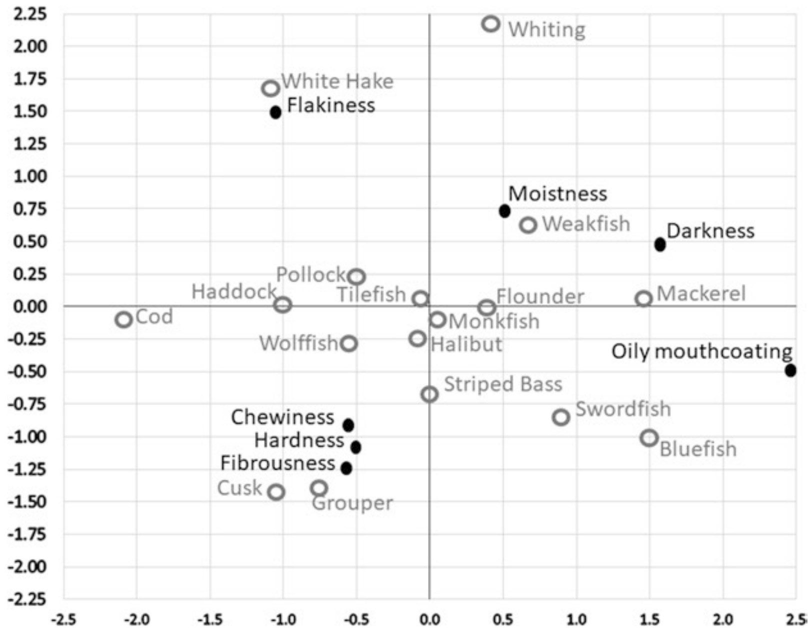

Fig. 17 North Atlantic fish texture solid black circles are sensory attributes; open grey circles are fish species. (Redrawn from Cardello et al., 1982)

well with either of the two axes and perhaps implying that the remaining 9% of the variation might be explained with at least one further axis.

8 Dimensions of Food Texture

Developing on the ideas of Rosenthal and Chen (2023) as well as those presented in Sects. 6.2 and 7.1 of this chapter, a conceptual map can be postulated to explain the key dimensions involved in food texture measurement (Fig. 18).

Focusing initially on the solid lined box, we consider the behaviour of solid foods when stressed or strained. Strong materials do not yield when stressed while weak ones exhibit deformation. Materials in which applied stresses build up are described as hard and conversely soft materials dissipate applied stresses.

Differences in how foods break down (blue, dash–dot line) depend on the material's ability to dissipate applied stress. Strong foods, which take a long time to relax, store stress energy which can build up until they fracture, exhibiting brittle behaviour. Conversely, weak solid foods (elastoviscous) which can dissipate applied stresses exhibit plastic/squashing behaviour. If we apply high stresses to weak solid foods, they will squash and we can force them through a narrow opening – squeeze flow. The shorter a material's relaxation time, the easier it is to make it flow, with liquids (broken line box) flowing under the force of gravity.

9 Oral Processing

9.1 Viscosity and Oral Perception

In the chapter Introduction to the Measurement of Sensory and Instrumental Food Texture', we discussed Shama and Sherman's (1973) classic paper, which compared instrumental measurements of 15 foods and compared them to the sensory panel scores. They showed that human perception occurred in a narrow band (Fig. 1 of Chap. 'Introduction to the Measurement of Sensory and Instrumental Food Texture') whereby when we eat highly viscous materials, we tend to exert low shear rates in the mouth to assess their viscosity, whereas low-viscosity foods are assessed at relatively high shear rates in the mouth. Thus, when attempting to relate viscosity measured instrumentally to human oral processing, we are obliged to undertake our instrumental measurements under conditions which correspond to human oral conditions for each particular food.

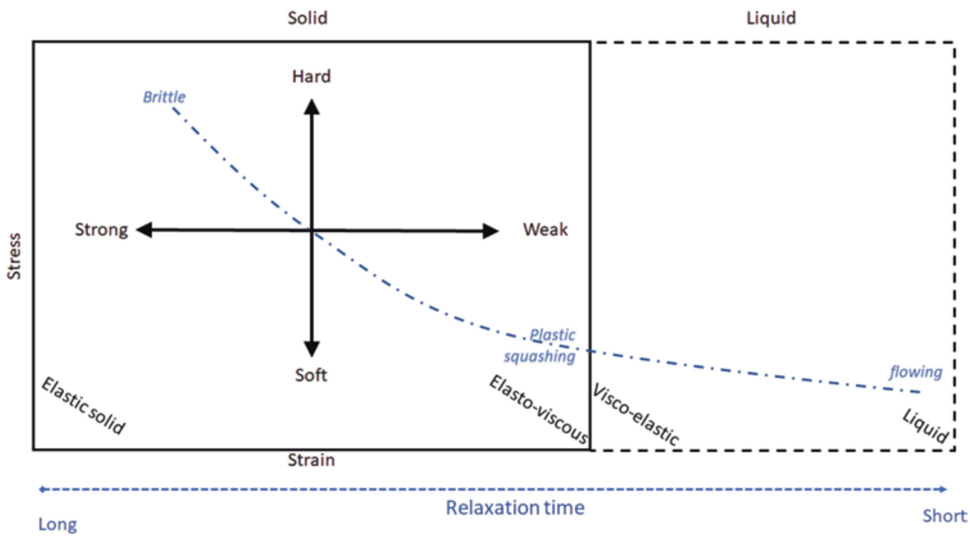

Fig. 18 Dimensions of food. Stress (hard–soft) and strain (strong–weak) axes along with breakdown behaviour curve

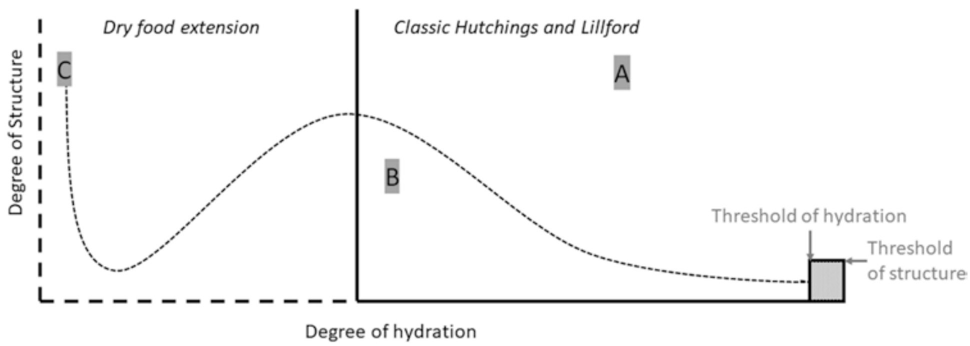

Fig. 19 Schematic oral breakdown path. See text for explanation of letters and curve. (Redrawn from Hawthornthwaite et al., 2015)

9.2 The Breakdown Path

Hutchings and Lillford (1988) proposed a three-dimensional model in which food structure is broken down by chewing and lubricated by the secretion of saliva, with time. A point is reached when the oral contents become adequately lubricated and of a reduced structure suitable for swallowing. While this model holds well for many fresh foods, those that lie in the third quadrant of the moisture map (Fig. 6) actually develop structure through hydration during the early stages of oral processing. It is only with extended oral processing that such foods become further hydrated to achieve a point suitable to swallow (Rosenthal, 2022).

Hawthornthwaite et al. (2015) refined the Hutchings and Lillford model to account for dry foods; in so doing they transformed the model into a two-dimensional map with independent axes for the 'degree of structure' and the 'degree of hydration' (Fig. 19). The only fixed point on the map is the swallowing box at the right-hand end. The duration of oral processing is reflected in how far along the axis the food enters the diagram. For example, food A, which might be an

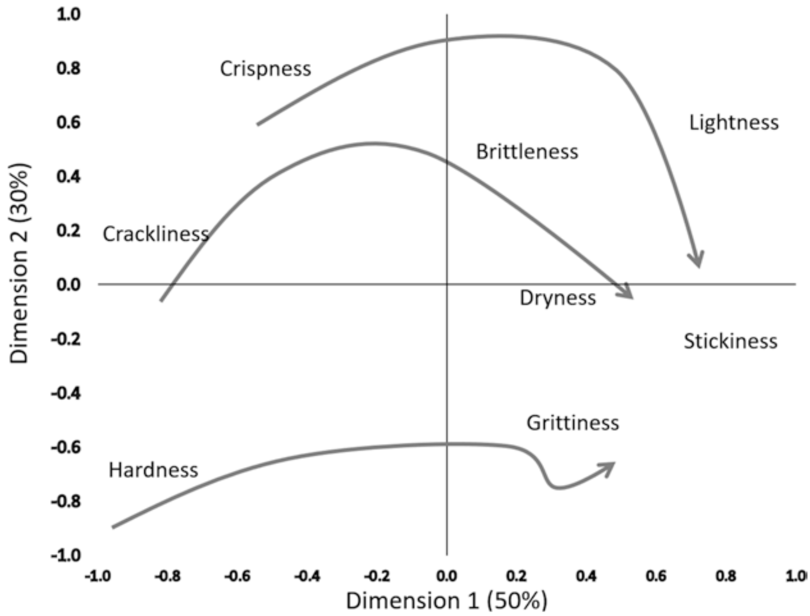

Fig. 20 The oral texture trajectories of three generalised wheat flakes. (Redrawn [and simplified] from Lenfant et al., 2009)

apple, has considerable structure, yet is quite moist and has a short oral residence time. In contrast, food B, which could be sliced meat, is drier than food A, though it has less structure and takes longer to process in the mouth. Food C could be Melba toast, being dry and structured. The oral trajectory for food C is shown by a broken line on Fig. 19, showing a rapid loss of structure, to less than the 'threshold for structure', yet it is still too dry to be swallowed and requires further hydration. Salivation results in de novo structure creation, as saliva is adsorbed to form a dough and only after further oral processing does it approach the swallowing box.

9.3 The Oral Trajectory

Of course the oral trajectory does depend on the nature of the food being eaten, yet the map of oral trajectory created by Lenfant et al. (2009) is a good example of how the textural characteristics experienced in the mouth change over the course of oral processing. Moreover, it comes from a highly influential paper that introduced the concept of the oral trajectory to our vocabulary. Figure 20, which is redrawn from their paper, emphasises the different sensory textural characteristics as well as simplifies sketching three of typical oral trajectories for wheat flake type breakfast cereals.

Lenfant et al. (2009) worked on wheat flake breakfast cereals, and Fig. 20 picks out three general trajectories. These lines have arrow heads showing they are progressive in relation to time (which has been standardised to compensate for differences in oral residence time of the assessors).

The three general types of wheat flake all start on the left-hand side of the map, some being crisp, others crackly or hard. During oral processing there is a general trend towards the right-hand side where they suck moisture from the mouth giving rise to a drying sensation and end up with a sticky bolus. Interestingly, while stickiness is the dominant sensation at the end of the oral trajectory, swallowing is independent of the degree of stickiness (Kazemeini et al., 2021).

While it is difficult to assign a name to the continuum of the first dimension, PC1 (accounting for 50% of the variation), it does have the first bite characteristics at one end and predominantly secondary textural attributes at the other. Thus, at the left-hand side, the descriptors are about

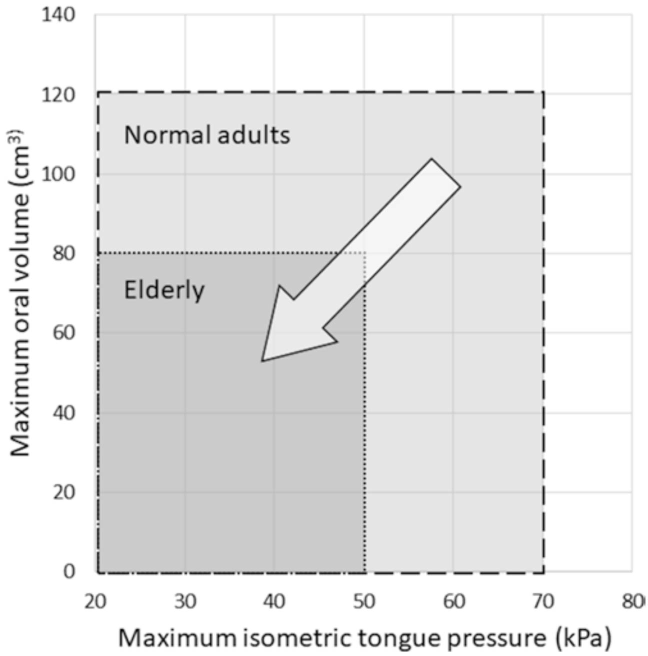

Fig. 21 Swallowing capability of young and elderly adults. (Redrawn from Alsanei & Chen, 2014)

hardness and crispness; as one moves to the right of the diagram (which is also the general trend of the three example trajectories), dryness and stickiness exist as do geometrical characteristics like grittiness. This ties in with the oral trajectories, which all move from left to right across the chart.

9.4 Eating and Swallowing Capability

Alsanei and Chen (2014) studied the eating capabilities of healthy, young and elderly adults. Figure 21 maps the independent variables of 'maximum isometric tongue pressure' and 'maximum oral volume' of the participants. The two rectangles capture the oral capabilities: the outer rectangle encompasses the entire population while the inner rectangle delineates the limit of eating capability for the older subset (over 65–92 years old). The general trend (the white arrow) is for a reduction in eating capability with age as the tongue and orofacial muscles decline in strength and functionality.

10 Conclusions

We have seen how the texture of food can be represented as two-dimensional maps. The basis of these maps is very varied, some based on sensory attributes, others on rheology, phase changes or even composition. Whatever the basis of the map, they do help us to appreciate the textural differences (and similarities) between foods. Some of the maps act as predictive tools, enabling us to understand food preparation operations.

Perhaps in time, additional maps might be collected and compiled into an atlas.

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Oral Physiology and Mastication

Marie-Agnès Peyron

1 Physiology of Elements in the Oral Cavity

The human masticatory system consists primarily of soft and hard tissues being the teeth, tongue, masticatory muscles and jaws. Other important organs or functions play prominent role in mastication, namely saliva, palate, cheeks, lips, for example in controlling food position inside the mouth and managing morsel positioning between teeth. Saliva, for its part, acts as a liquid glue, lubricating the mouth and reassembling all particles to form an aggregate that is safe for swallowing, as well as initiating chemical reactions associated with oral digestion.

1.1 Teeth

Teeth and their action during mastication are extensively documented as having adequate hardness and shape, being firmly rooted in the jaw bone to break, crunch and grind the food. Teeth are obviously essential elements for mastication and to a lesser extent, for swallowing. Teeth consist of crowns, which protrude in the oral cavity, and roots, which are firmly inserted in the jaw bones. The crowns are coated with a layer of enamel, which is a high-mineralised tissue, able to concentrate stress and to resist to wear and fracture. A full dentition includes 32 permanent teeth evenly distributed on mandibular and maxillary arches. The tooth shape determines its function. There are three classes of teeth: incisors, canines and post-canines. Incisors are eight front teeth and involved in biting act. Four canines have a cusp to tear up and pierce hard foods before crushing when food morsel is positioned in the region of the premolars and molars, which are the sites of mastication of all solid foods. Among the 12 molar teeth, the 4 most posterior ones (wisdom teeth) are often absent or with delayed eruption and not involved in mastication. Premolar and molar crowns shaped with cusps act for crushing and mashing actions. Thus, the main mechanical actions applied on food by these post-canine teeth during mastication are compression and shear stresses. Achievement of correct mastication is dependent on the number of posterior teeth, active tools during comminution, and more precisely the number of pairs of antagonist teeth, namely functional posterior units (FPU). FPU appear to be a more pertinent indicator to evaluate oral health or masticatory potential in comminuting food than the total number of teeth (El Osta et al., 2014).

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1.2 Jaws and Temporomandibular Joints

The human masticatory system is constituted of two jaws supporting teeth. The upper jaw, the maxillae, is part of the skull. The inferior jaw, namely the mandible, is attached to the skull through two temporomandibular joints (TMJ) which serve as jaw displacement's guide. Each jaw supports the same distribution of teeth described above. The two TMJ are anatomically distinct yet functionally bound as they share the same jaw movements. The mandible can move as a result of forces from contraction of the masticatory muscles. Following alternance of muscle contraction and relaxation, the mandibular jaw is lowered then raised to open or close the mouth. Its movements are guided by the two TMJ. A large variety of translational and rotational movements is possible thanks to the characteristics of the attachment of the mandible to the TMJ, permitting extensive movements of the mandible in several trajectories (Koolstra, 2002). These joints are characterised by a great complexity and importance in permitting rotatory movements (Ahamed & Dhanraj, 2017). Mandibular movements can be recorded by various methods and are described according to amplitude of displacement, angle, velocity, acceleration and duration of each position and phase, describing the jaw trajectory during each cycle constituting the masticatory sequence (Madhavan et al., 2018). Jaw movements are caused by forces generated by muscular contraction associated to reactive forces in joints, ligaments and teeth. Shape of posterior teeth and angle of cusp facets also play a role in the direction of mandibular movements especially in guiding the jaw during the closing phase, the occlusion of each masticatory cycle (Wang & Mehta, 2013).

1.3 Tongue

The tongue is a sensory and motor organ engaged in many oral functions (Doyle et al., 2022). It is a hardworking oral element continuously active during food oral processing, from food bolus formation to swallowing. It is a group of 17 skeletal muscles originating inside the tongue without a bone attachment (intrinsic) or originating outside the tongue (extrinsic). The contractile activity of these muscles during mastication participates in food management in the mouth providing an infinite variety of movements (Hiiemae & Palmer, 2003). Tongue movements are complex and result from activities of some of these muscles, which may act either jointly or in an antagonistic way. The tongue is positioned on the floor of the oral cavity and attached to the mandible, the styloid process and hyoid bone via its extrinsic muscles. The tongue occupies almost all the space inside dental arches. As the muscles of the tongue rapidly and precisely move in the mouth, they require a high level of control in response to stimulation or perception (Sawczuk & Mosier, 2001). This high flexibility, as well as its size and shape adjustments, enables well-coordinated oral functions related to food, including mastication of solid foods, positioning the food between teeth and assembling the fragments, management and squeezing of semi-solid foods, and swallowing. Knowledge on the coordination of movements, oral activities and muscular contraction of the tongue is limited because of high complexity of measurements inside the mouth during functional activity (Sawczuk & Mosier, 2001). Regarding the importance of the tongue coordination for smooth movements engaged in many functions among which the most important ones are mastication, swallowing, respiration and speaking, this organ is richly equipped in proprioceptors. Apart from this motor activity in conjunction with food management, the tongue is also the organ involved in taste perception, thanks to the numerous papillae covering the tongue surface to fulfil the role of gustation (Doyle et al., 2022).

1.4 Salivary Glands and Saliva

Saliva is the whole buccal fluid lubricating the mouth and participating to bolus formation. It is predominantly produced by the three pairs of major salivary glands, namely the parotid, submandibular and sublingual glands, and by the various minor salivary glands dispersed in the oral mucosae (labial, palatal, lingual and buccal mucosae). The saliva fluid is composed of at least 98% of water and also contains numerous electrolytes, glycoproteins, enzymes, immunoglobulins, plus many other products in various quantities (Humphrey & Williamson, 2001; Pedersen et al., 2002). Saliva is very critical for preserving the health of the oral tissues by continuously forming a lubricating coating layer aiding oral elements during mastication, speech and deglutition. Flow rate of saliva production varies in response to gustatory and mechanical stimulation. Saliva presents a normal range of pH between 6 and 7.5 and is characterised by buffer properties protecting the mouth against an aggressive environment. The normal daily production of saliva is about 0.5–1.5 L (Pedersen et al., 2002). The habitual flow is approximately of 0.3 mL/min in absence of or at low-level stimulation in most adults and can reach 7 mL/min under high-level stimulation, being highly dependent on the type of stimulation (Gavião et al., 2004). The large variations in flow and composition depend on oral activity and on the kind of stimulation. At rest, submandibular glands are the more active ones producing a viscous and mucin-rich unstimulated saliva. Sublingual glands contribute also, by producing a viscous saliva at rest. Salivary secretion, as well as its composition, is entirely controlled by the autonomic nervous system, modulated by a reflex arc involving the salivation centre, and mostly stimulated by taste and mastication (Pedersen et al., 2002; Carpenter, 2013; Proctor, 2016). The salivary reflex is elicited by gustatory signals coming from chemoreceptors majorly located on the tongue. It is also triggered during mastication by activation of mechanoreceptors located in the periodontal ligament (Carpenter, 2013), 5% of the normal masticatory forces being assumed to elicit mechanical saliva secretion (Gavião & der Bilt, 2004).

1.5 Masticatory Muscles

Mastication is operated by numerous skeletal muscles located around the skull whose contraction results in mandibular movements and the generation of forces needed to crush and manage the food in the mouth. Among them, the most powerful muscles are the masseter, the temporalis and the medial pterygoid, the first two being the most accessible covering their contraction, morphology, blood irrigation, for example (electromyography [EMG], tomography, echography, Doppler, etc.). In a simplified classification, they are referred as elevator muscles. In addition, the lateral pterygoid and the digastric muscles (anterior and posterior heads) are also important for jaw functioning and referred as depressor muscles. Opener muscles are described as depressor muscles, while closers are identified as elevator muscles (Miller, 2017).

The temporalis muscle is thin and fan-shaped attached to the skull (frontal, temporal and parietal bones) while the masseter presents a more complex organisation in separate bodies which are attached between the zygomatic arch and the mandibular bone (Fig. 1). The masseter and temporalis muscles are superficial, while the medial pterygoid is located more deeply. Jaw-closing muscles, such as the masseter, present a great complexity due to a multipennate and layered structure, segmented by aponeurosis. This

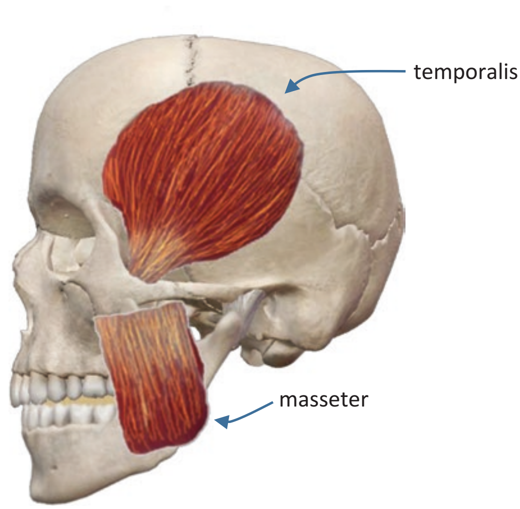

Fig. 1 The main elevator muscles convenient for electromyographic recordings (EMG) during mastication. The masseter is inserted between the zygomatic arch and the body of the mandible. The temporal muscle is inserted between the parietal bone of the skull and the coronoid process of the mandible

structuration allows a greater number of fibres in a smaller cross-sectional area than other skeletal muscles in the body, thus providing a high potential for power and force in short displacements as well as many ways to contract differentially in response to the oral demand (Koolstra, 2002; Miller, 2017).

Regarding their structural organisation, the masseter and the pterygoid muscles serve the primary role of producing force while the temporal muscles are better suited to control jaw stability. A complex and harmonious alternation between contractions and relaxations of masticatory muscles generates mandibular movements that realise masticatory cycles. Contraction of muscles is finely controlled and highly coordinated to ensure the complex masticatory pattern displayed by mandible. A masticatory cycle is the result of successive recruitment of several groups of fibres inside a muscle or from different agonist muscles on which contractile activities are superimposed. The high level of complexity in coordination of masticatory muscles determines the direction of mandibular movement as well as a fine control of force applied, especially at the occlusal point.

Besides these active masticatory muscles, other head and neck muscles also participate to the masticatory activity, either actively or in postural stability of jaw position (Giannakopoulos et al., 2018). Tongue, lip or cheek muscles also play a determining role during mastication because they participate in food fragments positioning, assembly of food fragments, mixing with saliva and even bolus swallowing as described in other sections.

1.6 Other Oral Elements

The front and lateral walls of the mouth are controlled by the *orbicularis oris* (lips) and the buccinator (cheek) muscles. These muscles are active during mastication (Schieppati et al., 1989), helping in keeping food between teeth; they participate in gathering food particles and mixing with saliva during bolus formation. The buccinator muscle forms a part of the cheek and acts in coordination with tongue to force food morsels between teeth. Their contractile activity is synchronised with that of masseter muscle (Casas et al., 2003) and is active just at the beginning of the mouth closing (Dutra et al., 2010). Lip action prevents the food particles or the food bolus from slipping out of the mouth in case of mouth opening, and is also active during swallowing (Tamura et al., 2009). Pressure is the main characteristic of these muscles useful for comprehensive description of their role during mastication. Indeed, the strength of these muscles is important during mastication. A positive association between high perioral pressure and masticatory performance has been identified, as well as its role on bolus wetting and the time required for bolus formation (Mazari et al., 2007; Takahashi et al., 2013). Buccinator contraction has also been suggested to help saliva secretion (Kang et al., 2006). Central coordination is clearly required for the perfect monitoring of the complex activities of these oral elements during mastication without incidents such as biting tongue or cheeks (Takada et al., 1996). Moreover, the contractile activities of orbicularis and buccinator have been shown to change according to physical properties of food, thus confirming the specific role of these muscles during mastication (Hanawa et al., 2008).

2 Control and Adaptation of Mastication

All oral motor activities (including muscle contraction along with functional jaw and tongue movements) require a fine control permitting biting, mastication, food oral management and swallowing. To accomplish this control and to adjust mastication parameters, the brain needs sensory information about what happens in the mouth. This information derives from various sensory organs distributed in oral structures. Sensory information is relayed to the central nervous system (CNS), which uses it in combination (superimposition, overlapping?) with the basic control of rhythm together with jaw reflexes.

2.1 Mechanoreceptors and Proprioceptors

The mouth is a very sensitive organ, densely innervated with nerve fibres and receptors involved in tactile perception and proprioception. During mastication, these receptors provide sensory feedback on events arising in the mouth during food transformation; feedback is also used for food texture perception (Lund, 1991; Türker et al., 2007). A combination of inputs from all these receptors gives a complete image of what is perceived in the mouth in terms of food, food bolus properties and its position. Mechanoreceptors, as their name suggests, are sensitive to tactile and kinaesthetic (i.e. during movement) stimulation such as constraints, stresses, strains, vibrations, pressures, slipping or flow. Many types of mechanoreceptors have been described in the oral regions, e.g. Meissner corpuscles, Ruffini and Krause endbulbs, Golgi organs, etc. (Avivi-Arber & Sessle, 2018). Such receptors are arranged in the mouth to cover all types of stimulation, and their regionalised location depends on the specific assignment or the oral element in perception. Mechanoreception is attributable to receptors located in the tooth supporting tissue, namely the periodontal ligament, in the hard palate, the cheeks and lips, the TMJ and throughout the mucosae. Periodontal receptors are involved in the control of direction and intensity of forces (Trulsson, 2006, 2007; Piancino et al., 2017). As a complementary sensitivity, proprioception encodes signals providing information on static position and movements. This sense is served by muscle spindles, arranged in the elevator and tongue muscles and signalling their stretching, Golgi tendon organs stimulated by muscle contraction, and also mechanoreceptors in the TMJ encoding for flexion and extension in the joint during movements. De facto, mechanoreception includes perception of food characteristics, while proprioception is more related to position, velocity and direction of movements, both types of perception playing an important role in the control of food oral processing since their combined inputs provide an overall and precise image of what is in the mouth, where it is positioned, and in what state, together with a fine knowledge of level of contraction and position of oral structures (Foegeding et al., 2015). Proprioception has also been suggested to participate in swallowing initiation (Takeda & Saitoh, 2016).

2.2 Neural Mechanisms

The fundamental pattern of mastication issues from a network of neurons, located in the brainstem, called the central pattern generator (CPG). The CPG is able to elicit the basic rhythmic activity of the jaw muscles independent of any descendent input (cortical) or sensory afferents coming from oral receptors (Lund, 1991; Avivi-Arber & Sessle, 2018). The CPG is composed of neurons mainly associated with the trigeminal system. Apart from this autonomous rhythmic activity, it is controlled in a goal-oriented behaviour by inputs descending from higher centres in the brain (cortical areas), and the motor activity of mastication is also governed by mechanisms receiving peripheral feedback (Lund et al., 1998). Many orofacial muscles are represented in different cortical areas which can modulate the CPG activity. Additionally, the masticatory process displays large variation in the afferent inputs which provide feedback on the transformation of food in the mouth. This oral processing functionality relies heavily on peripheral feedback, which provides fine modulation to the basic pattern, generating an accurate physiological masticatory activity perfectly adjusted to oral events and the characteristics of the food/food bolus being processed (Lund & Kolta, 2006). Thus, high variability in muscle contractions and the consequent jaw movements are the result of central commands by the CPG producing rhythmic activity modulated by inputs from the oral cavity. The range of muscle activation patterns and jaw movements offers many possibilities for optimisation of masticatory strategies to food properties and individual characteristics (e.g. age or dental state), which are the main extrinsic sources of variability of masticatory pattern (Lund & Kolta, 2006; Woda et al., 2006). During mastication, the

CPG motor command is continuously and finely adapted to sensations arriving from the oral area and related to changes in food characteristics along bolus formation (Lund & Kolta, 2006). Thus, among all these sensations, texture is the primary food property providing guidance to the motor commands defining the oral process thanks to the links between food structure and its perception.

2.3 Innervation of Muscles Involved in Mastication and Associated Oral Functions

The sensory information captured at the level of orofacial structures is transmitted to the CPG via the trigeminal nerve, which is the fifth cranial nerve (CN V; Fig. 2). This is a large and complex cranial nerve containing sensory and motor fibres. The CN V has ophthalmic, maxillary and mandibular branches, the former two containing sensory fibres only. The maxillary division of the CN V relays sensation from the face. The three branches converge on the trigeminal ganglion, which contains the cell bodies of fibres. The maxillary branch carries sensory information from the upper region including the cheeks, the upper lip and the upper teeth, while the mandibular branch conveys sensory information from the lower area containing the lower lip, the lower teeth and the jaw (Fig. 2). The motor part of the trigeminal nerve innervates the jaw opening and closing muscles, namely masseter, temporalis, pterygoid, mylohyoid and digastric muscles, and also conveys proprioceptive inputs from the TMJ (Yamada et al., 2005; Westberg & Kolta, 2011).

Muscles responsible for tongue motility are innervated by motoneurons connected with the hypoglossal cranial nerve (CN XII) that only contains motor fibres and controls all tongue movements. Activity of CN XII motoneurons is controlled by higher centres in the brain, which also receive, on the one hand, inputs from respiratory and swallowing centres, and, on the other hand, sensory information from the trigeminal (CN V) and the glossopharyngeal (CN IX) cranial nerves. Considering that tongue is a major partner to the teeth during mastication, having even been identified as a masticator per se, other general sensations of the tongue, including taste perception, are transmitted through the facial, glossopharyngeal and vagus nerves, which participate in sensory feedback and play an important role in coordination of tongue movements and other oral activities (Yamada et al., 2005; Hori et al., 2006). This coordination probably follows different ways depending on the role of the tongue either participating in particle gathering and bolus formation, to soft food squeezing

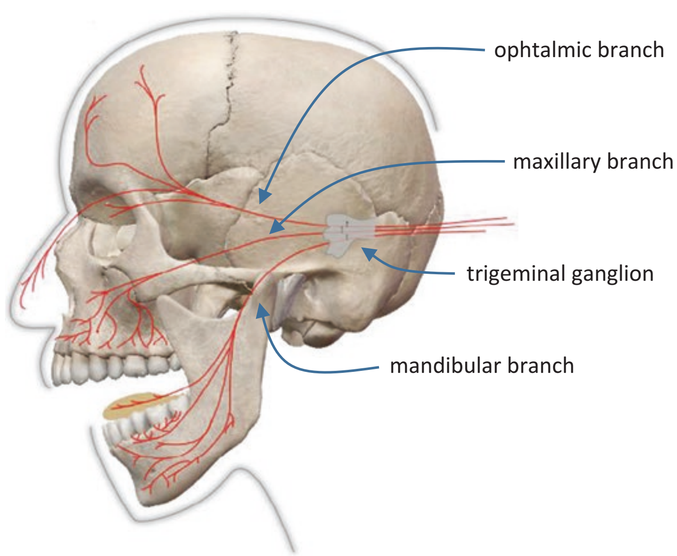

Fig. 2 The trigeminal nerve is the fifth cranial nerve (CN V) containing sensory and motor fibres. It includes three divisions: ophthalmic, maxillary and mandibular branches converging on the trigeminal ganglion

against hard palate, or during swallowing (Lowe, 1980; Taniguchi et al., 2013).

Facial muscles including those in cheeks and lips are innervated by the CN VII for facial motor control. This nerve also presents a sensory function responsible for taste perception. There are many connections with other cranial nerves innervating the oral and facial area, and among them with all branches of the trigeminal one.

Activation of all these different groups of cranial motoneurons occurs during mastication and their precise coordination in performing this step is essential to ensure smooth operation of all the oral functions involved in food oral processing (Yamada et al., 2005).

2.4 Jaw Reflexes

Several reflexes can be described for the jaw motor activity and are responsible for the cyclic and stereotypical movement engaged in oral functions (Türker, 2002). These jaw reflexes are generally considered as the base for governing the motor activity caused by muscle contraction and responsible for jaw movements. The main reflexes contributing to oral functioning are jaw-closing and jaw-opening reflexes (Lund & Olsson, 1983). The jaw-closing, or jaw-jerk, reflex is a typical myotatic reflex beginning with the stretch of the muscles, which activates the spindles located in the main elevator muscles (e.g. masseter or temporalis). The jaw-opening reflex is elicited in the jaw-opening muscles, such as the anterior digastric. It can be caused by a pressure applied on the teeth, a tap on the lips or pain in these tissues. Perception of a force applied to the periodontal mechanoreceptors signals a contact between antagonist teeth or contact with a food morsel. This elicits an increase in the jaw elevator muscle activity during biting or during the occlusion phase of the masticatory cycle.

The well-coordinated activation and inhibition of all jaw reflexes permits their efficient contribution to masticatory pattern, which is required for smooth oral functioning (Yang & Türker, 1999). Simple reflexes such as jaw-closing and -opening may be activated per se quite infrequently during normal oral functioning and only some of their components provide help to the oral complex functions (Dubner et al., 1978). Such reflexes contribute to oral motor activity in providing a stereotyped pattern which can be modulated and finely adjusted to oral perceptions. Sensory feedback from the oral receptors associated with inputs from the cortex level co-activate the CPG which can modulate the basic jaw motor pattern. Since masticatory muscles are able to generate very high levels of force, and teeth and tongue have to work together in a harmonised way, the jaw reflexes contribute to a fine control of forces and movements, especially in protecting the oral structures from pain and damages during mastication.

2.5 Bite Forces and Masticatory Forces

In contrast to masticatory forces (exerted during mastication), bite forces relate to biting. In mastication the forces are exerted in a dynamic mode, alternating isometric (no change in muscle length) and isotonic (constant force with change in muscle length), while biting is generally applied as an isometric contraction during static exercises. In normal use, forces developed by the masticatory apparatus are caused by contraction of masticatory muscles and produce crushed food placed in the mouth. Variability of maximal bite force values depends on the recording device, the teeth considered and some other physiological factors, such as dental state, muscle strength, anatomy and neuromotor mechanisms; forces are generally higher in men than in women or with natural teeth compared to artificial ones (Koc et al., 2010). Nevertheless, independent to this variability, these measurements give an overall picture of what forces can be developed by the masticatory apparatus. The maximal force developed by the whole jaw possessing natural teeth is about 60–75 kg (i.e. 590–740 N) (Gibbs et al., 1981). When measured for a pair of antagonist teeth, values relate to the location on the arch and also probably to the teeth shape (Carlsson, 1974). The greater values ranging from 300 to

600–700 N have been measured in the first molar section, which corresponds to the region of masseter attachment (Fløystrand et al., 1982; Hagberg, 1987; Bakke et al., 1990). Lower values of maximal bite force have been recorded in the more anterior teeth, around 300–400 N for the premolars and canines, and about 100–200 N for the incisors (Ingervall & Helkimo, 1978; Haraldson et al., 1979; Hagberg, 1987). Masticating with the posterior teeth requires less energy when compared to the anterior teeth. Indeed, to reach a given functional force with anterior teeth, a greater muscular activity would be required due to the mechanics of the TMJ working like a lever (Devlin & Wastell, 1986).

Bite forces are estimated to represent only a small percentage of the maximal forces that can produce the masticatory apparatus (Gibbs et al., 1981) but these latter are not easy to record during movement and dynamic events elicited during mastication and only approximation can be extrapolated from muscle contraction recordings during functional mastication (Ferrario et al., 2004).

3 Oral Processing of Food

Food oral processing encompasses many various oral elements and functions including breaking and masticating the solid food thanks to jaw movements activated by contraction of masticatory muscles, mixing of food fragments with saliva, tongue movements placing the food between the active teeth, or to compress soft food against the hard palate etc. All these activities share the common objective of preparing a food bolus with characteristics favourable to a safe and secure swallow without pain or increased risk of dysphagia. Since food oral processing is a recent and fast-emerging research area, some famous reviews have organised an abundant literature in this area combining physiological and food perspectives (Wang & Chen, 2017; van Eck et al., 2019; Guo, 2021; He et al., 2022). Taste, tactile and kinaesthetic perception, as well as oral digestion, are also important functions associated with food oral processing. All these activities can be considered as part of the food oral processing and can be evaluated through various methods, which are implemented either to study physiology or health of oral function or to study adaptations to food changes.

3.1 Principal Methods for Studying Food Oral Processing

Different methods used to study the oral functions and food oral processing mostly relate to movements and forces/pressures generated by or on oral elements during mastication, tongue movements or swallowing, which can be combined with the study of the characteristics of the resulting food bolus and the characteristics of saliva production (Liu et al., 2022).

3.1.1 Forces and Muscular Contraction Recordings

Bite Force

The recording of bite and masticatory forces has received considerable attention for a long time, and many reports can be found in literature. Generally, measurements can be made with electrical devices (of varying complexity) placed between a pair of antagonist teeth or section of teeth. Today, electronic devices provide accuracy and precision (Fernandes et al., 2003; Koc et al., 2010; Liu et al., 2022). Masticatory forces are more difficult to measure accurately since they are developed during dynamic conditions, and inserting a transducer inside the working mouth can disrupt mastication. Despite these technical difficulties, masticatory forces have been shown to depend on food hardness. Values around 19 N have been reported for mastication of cheese, between 20 N and 50 N for bread and approximately 50 N for carrots or peanuts (Michael et al., 1990). When measured on the whole dental arches, values were greater than measured on a dental section, around 220 N for cheese and 350 N for peanuts (Gibbs et al., 1981). Significant correlations have been obtained between the bite force and the masticatory performance (Okiyama et al., 2003). This difficulty in force measurement has favoured the emergence of electromyography as a method to address masticatory force through recording muscular contraction under the dynamic conditions of mastication. Muscular contractions are the result of electrical activity in the muscle fibres and on the oral level, responsible for multiple masticatory movements of the jaw and tongue.

Electromyography

Difficulties in force measurement have favoured the emergence of surface electromyography (EMG), which addresses masticatory force through muscular contraction recorded under dynamic conditions. Surface EMG is a non-invasive technique and has been largely applied in food oral processing studies thanks to its ease of use (González et al., 2001; Gonzalez Espinosa & Chen, 2012). During muscle contraction, EMG electrodes record global electrical activity, namely the motor unit action potentials generated in muscle fibres which have been filtered by tissue (Gonzalez Espinosa & Chen, 2012). The relationship between EMG and forces is linear in isometric muscular contraction, thus relationship between EMG signal and force generated is neither direct nor simple. The relationship between EMG and bite forces can be linear in isometric contraction under well-controlled recording conditions, but neither direct nor simple during mastication mixing different muscular contraction modalities (isometric and isotonic) and jaw displacements. Nevertheless, it provides access to physiological mechanisms causing muscle contraction and movement, along with the resulting force generated during physiological function (Lindauer et al., 1991). EMG signals can be impacted by physiological parameters (motor unit recruitment, temperature, skin surface properties, etc.) and by technical parameters such as electrodes type or placement, filters, signal amplification, etc. (Gonzalez Espinosa & Chen, 2012).

As force is generated to break the food morsel, the masticatory muscle contraction reflects several useful indications on how the food is perceived in mouth and how the masticatory system is programmed to break down and form the bolus. The main masticatory muscles accessible for EMG recordings during mastication are the masseter, temporalis and digastric muscles (Fig. 3). Some publications also report EMG measurements of buccal and lingual contractile activities (Casas et al., 2003; Hanawa et al., 2008). Thus, despite some limitations in the technique and a real risk of mistakes or misinterpretations, EMG presents great interest in the assessment of oral function for integrative access providing rich information on how the food is managed during mastication, and how the masticatory apparatus adapts to oral processing of specific foods (Lassauzay et al., 2000; González et al., 2001). After several steps in the raw data processing, some useful variables may be extracted from the recordings, namely the total duration of the masticatory sequence, the number of masticatory cycles, the total muscle activity for the whole masticatory sequence (sum of the areas of rectified EMG signals of each masticatory cycle), the average of the activity of contraction per cycle, amplitude of the contraction etc., which can be analysed linked with food characteristics and their perception (Lassauzay et al., 2000; Peyron et al., 2002; Woda et al., 2006; Gonzalez Espinosa & Chen, 2012; Kazemeini et al., 2021).

3.1.2 Methods for Mandibular Movement Recordings

Any movement of the mandible is a consequence of contraction of masticatory muscles within the constraints of the temporomandibular joints (TMJ), which facilitate a large variety of movements. During the masticatory sequence, contraction of elevator muscles (e.g. masseter muscles) occurs during mouth closing to crush the food. Thus, for a more complete and dynamic analysis of food oral processing, EMG and mandibular movements are often recorded simultaneously. Several methods, from simple to advanced ones, can be employed to record these jaw movements. Most such recordings operate with a sensor attached to the mandible. Such sensors work on a physical principle, for example accelerometers, electromagnetic inductance, or optoelectronic elements related to mechanics, graphics, telemetry, magnetics, optoelectronics, videography,

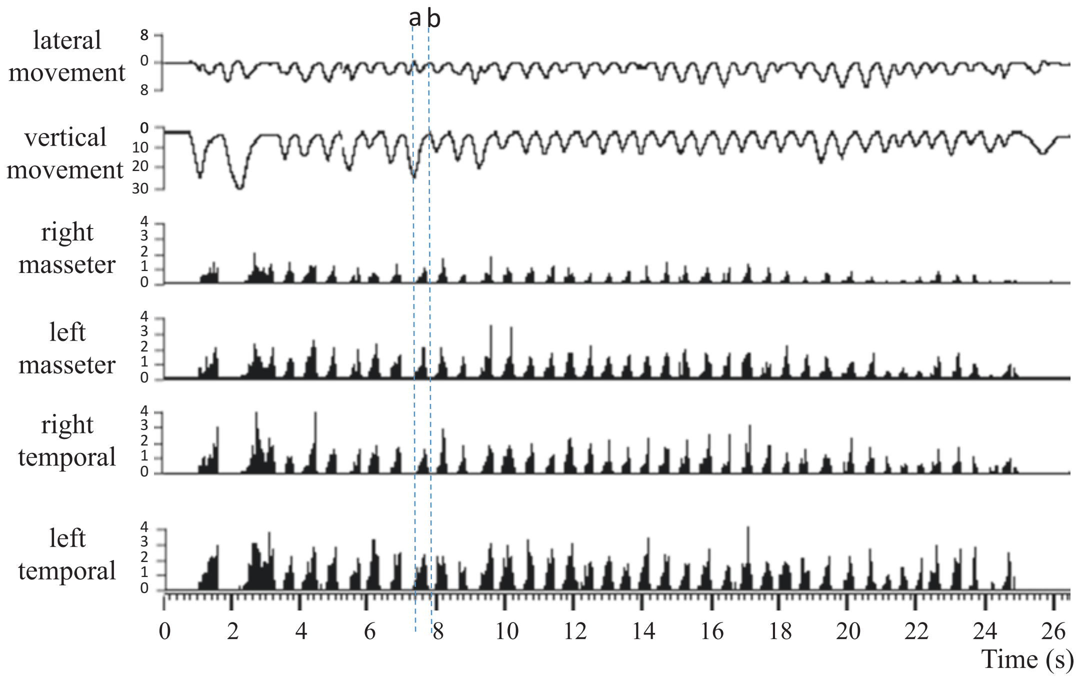

Fig. 3 Example of electromyographic recordings (EMG) from right and left masseter and temporalis muscles and vertical and lateral mandibular movements during a complete masticatory sequence. Dotted lines, noted **a** and **b**, delineate a single masticatory cycle, with the beginning (**a**) and the end (**b**) of jaw closing, corresponding to a burst of action potentials in each elevator muscles contracting to face the food. Jaw movement is expressed in mm and muscle contraction in mV

ultrasonography, etc. (Lepley et al., 2011; Madhavan et al., 2018). Numerous parameters can be extracted to characterise the jaw movements in terms of amplitudes, velocities, duration of each period of the masticatory cycles, or of the complete masticatory sequence, and provide a wide range of information on the dynamics of what happens in the mouth while forming the food bolus (Chew et al., 1988; Horio & Kawamura, 1989; Peyron et al., 1997). In some clinical conditions, these advanced techniques cannot be used, directing researchers to less invasive methods, such as videography, whose use has been validated against EMG (Hennequin et al., 2005). The major limitation in recording human jaw displacements is embodied when physical elements are placed inside the mouth and interfere with normal movements, perception and mastication control. EMG and movements recording combination provide data on the muscular activity in each mandibular position and for each phase of the masticatory cycle.

3.1.3 Tongue Movements and Tongue–Palate Pressure Recordings

Tongue movements can be followed through videofluorography (an X-ray technique requiring mixing food with a radio-opaque contrast medium), ultrasounds or functional magnetic resonance imaging (fMRI) (de Wijk et al., 2006; Okada et al., 2007; Taniguchi et al., 2013; Genna et al., 2021). These recordings provide data on the functional contribution of the tongue, and other oral structures, to the different events occurring during food management, food bolus formation and the early phase of swallowing initiation, as well as location of the food at any time during the masticatory sequence (Mioche et al., 2002). Horizontal and vertical dimensions of the tongue present different amplitudes during the different phase of mastication and are also dependent on food consistency (Taniguchi et al., 2013). Functional magnetic resonance imaging has been useful to provide a visual description of specific tongue muscle contribution during swallowing (Gassert & Pearson, 2016). Oral movements of the tongue have been explored via an ultrasound method that linked perceived sensory attributes (de Wijk et al., 2006).

In addition, many methods have been developed to assess intraoral tongue pressure, such as small pressure sensors embedded in a palatal appliance or in a denture, air pressure measured in a balloon compressed by tongue, the Iowa Oral Performance Instrument (IOPI, Oakdale, Breakthrough) or other hand-held pressure sensors (Youmans & Stierwalt, 2006; Engelke et al., 2011). All these methods have been used with the same general objective, which is the analysis of the tongue behavioural contact with palate, including analysis of its position, what areas are in contact and what is the pressure exerted by tongue against the palate, during food oral processing as well as with a focus of its role in swallowing (Ono et al., 2004; Hori et al., 2006; Kieser et al., 2011; Funami, 2016). Another item of information often recorded is the maximum isometric tongue pressure (MITP), which is generally reported with values between 10 kPa and 70 kPa (Youmans & Stierwalt, 2006; Utanohara et al., 2008; Alsanei & Chen, 2014). As observed for masticatory muscles, the MITP values are higher for men than for women, and decrease with advance in age (Youmans & Stierwalt, 2006; Utanohara et al., 2008). The biomechanical coordination of tongue and jaw movements is described according to the phase of the masticatory cycle, with tongue pressure occurring during the occlusal phase (opposite teeth in contact) with a quick peak just before jaw opening (Hori et al., 2006). It has also been used to describe food oral processing and its specificities according to the food characteristics or when the tongue is involved in food oral processing of soft foods that are squeezed against the palate (Nakazawa & Togashi, 2000; Koç et al., 2013; Yokoyama et al., 2014; Funami, 2016; Nishinari et al., 2020).

3.1.4 Saliva Sampling

Given the importance of saliva in the many aspects of oral function, besides maintaining oral health, its characteristics are interesting across several dimensions. Measuring saliva flow or composition or viscoelastic behaviour, for example, is needed to obtain normal reference values. Assessment of variations in saliva properties depending on individual characteristics or environmental conditions such as food features or type and moment of collection, for example, is important in food oral processing studies. Whatever the context or the objective of the sampling, saliva collection is a non-invasive technique. Several methods for saliva collection are described in literature (Navazesh & Kumar, 2008). Resting saliva flow, which is saliva produced in absence of any source of stimulation, is allowed to drain in a receptacle and the flow estimated by volume or weight and reported over a sampling period. This unstimulated saliva can also be recovered by spitting by the participant. Suction tubes, cotton rolls, strips or technical papers can also be placed on the floor of the mouth to absorb saliva. This latter method can also be used to estimate saliva coming from minor salivary glands (Shern et al., 1990). Saliva collection during gum chewing or citric stimulation that produces a larger quantity of saliva is referred to as stimulated flow. In order to collect saliva from individual major glands, a cotton roll can be placed at the orifice of a selected gland but, in addition, specific devices with an instrument directly connected to that gland duct are useful (Navazesh & Kumar, 2008). Several studies have reported results on the reliability and reproducibility of these methods, irrespective of the high degree of variability due to individuals, time of the day at which it is collected, stimulation mode or the circadian rhythm (Navazesh & Christensen, 1982; Fontana et al., 2005). Nevertheless, maintaining or verifying the stability of saliva during its collection and its use is a crucial challenge to face in food oral processing studies. Indeed great vigilance is required to ensure reliable results, regarding salivary amylase activity, viscosity, biochemical composition, pH etc., that is either for biochemical assessment of saliva or to study its role in food bolus formation or perception (Ngamchuea et al., 2018).

3.1.5 Food Bolus Characterisation

Apart from the fact that the food bolus produced by mastication is a heterogeneous material, the choice of method used for its characterisation is driven both by the objective of the study and specificity of the characteristics being measured. This choice is pertinent since outputs can be used to assess both texture perception and mastication adjustment along the physiological process.

Food bolus characteristics depend on the initial nature of the food matrix and, whereas it undergoes continuous deformation during mastication, it also depends on the masticatory stage for which the bolus is considered (between first bite and swallowing). A plethora of methods have been developed to cover the different physical and biochemical dimensions of food bolus features (Panouillé et al., 2014). The main ones concern the physical aspects of the bolus playing a key role in swallowing, namely particle size, rheological behaviour and level of saliva incorporation.

Bolus particle size is the most frequent measurement reported in the literature. Through sieving or image analysis, bolus has been described with the number of particles, their size distribution and the median, or particle shape (Jalabert-Malbos et al., 2007; Rodrigues et al., 2014). As bolus formation involves simultaneous fragmentation and lubrication of fragments, methods giving access to rheological description and level of hydration are undoubtedly useful. When these measures are performed on the food bolus collected just before swallowing, they provide knowledge of the quality that the bolus must meet for a safe swallowing (Peyron et al., 2011). Many varied methods, such as the texture profile analysis (TPA test), compression test or oscillatory rheometry, to name a few, have been chosen for food bolus characterisation depending on the nature of the food matrix and on the objective of the measure (Panouillé et al., 2016). Tribology is another phenomenon considered for food bolus characterisation giving access to the degree of friction in the mouth in relation to oral lubrication (Shewan et al., 2020; Sethupathy et al., 2021). Bolus hydration is an interesting variable, linking food structure and mechanisms of bolus formation, which impact on rheological behaviour and swallowing. With a purpose of studying the role of the oral phase in digestion and nutrition, several biochemical analyses can be conducted on the bolus, such as alpha-amylase activity, or presence of nutrients or of molecules signing the initiation of oral digestion (Freitas et al., 2018; Blanquet-Diot et al., 2021).

Obviously, a combination of different methods characterising several dimensions of the food bolus could be interesting to gain complementary information about this complex material. Whatever the method used, it should be used and interpreted with caution due to the complex nature of the food bolus and the dynamic mode of its formation.

3.1.6 In Vitro Simulation of Mastication

Several devices have been developed for in vitro food oral processing studies. Most of these have been conceived on the basis of the food breakdown into similar sizes to what is observed in natural mastication (Salles et al., 2007; Woda et al., 2010). These devices make it possible to control some of the masticatory variables, such as the number of masticatory cycles, the force applied, a dynamic saliva addition and some movements simulating particles gathered by the tongue. They are mainly operated with the final objective of providing bolus with particle size characteristics comparable to the in vivo bolus. These devices also provide access to oral mechanisms, sometimes complex, which address in vivo studies such as the effect of oral processing on flavour release (Salles et al., 2007) or the role in nutrition (Peyron et al., 2019). Furthermore, simulation models provide interesting access to analyse specific oral deficiencies on food structure disruption, bolus formation, and as bolus at swallowing, avoiding in vivo clinical trials potentially dangerous for frail individuals. Other interesting systems have been proposed to analyse oral behaviour of soft or semi-solid foods (Prinz et al., 2007; Raja et al., 2022).

3.2 Influence of Oral Physiology on Food Oral Processing and Food Bolus Formation

3.2.1 Food Oral Processing

Food oral processing is a dynamic process covering management and process of a food placed in the mouth and requiring several physical transformations to be suitable for swallowing, the resulting material being called the food bolus (Fig. 4; Chen, 2009). The physical transformation operated during food oral processing refers to a combination of physical fragmentation, lubrication with saliva and management of oral transport of food material at all times of the oral stage from biting to swallowing (Mosca & Chen, 2016; Wang & Chen, 2017; Guo, 2021). The major oral functions accountable for these operations are mastication, salivation and tongue activity; the degree of involvement of each factor varies according to the nature of the food, for example the degree of solid or semi-solid consistency (de Wijk et al., 2011; Nishinari & Fang, 2018). The initiation of digestion for some foods also occurs during food oral processing (Bornhorst & Singh, 2012; Blanquet-Diot et al., 2021). Food oral processing involves the activity of all oral muscles, including the tongue, jaw movements and saliva provision, all contributing to the preparation of a food bolus for safe swallowing. This process reflects interactions between oral structures and food characteristics, their dynamic interdependence being the main factor governing the food oral processing. When a food is placed in the mouth, every component constitutes a set of stimuli which are perceived by all receptors dispersed in the oral tissues. Sensory information is conveyed towards the central nervous system, which respond by a motor command to the masticatory muscles strictly adjusted to the initial set of stimuli (Lund & Kolta, 2006). The global motor response is expressed through the masticatory act which relates to the food perceived and analysed in the mouth. Characteristics

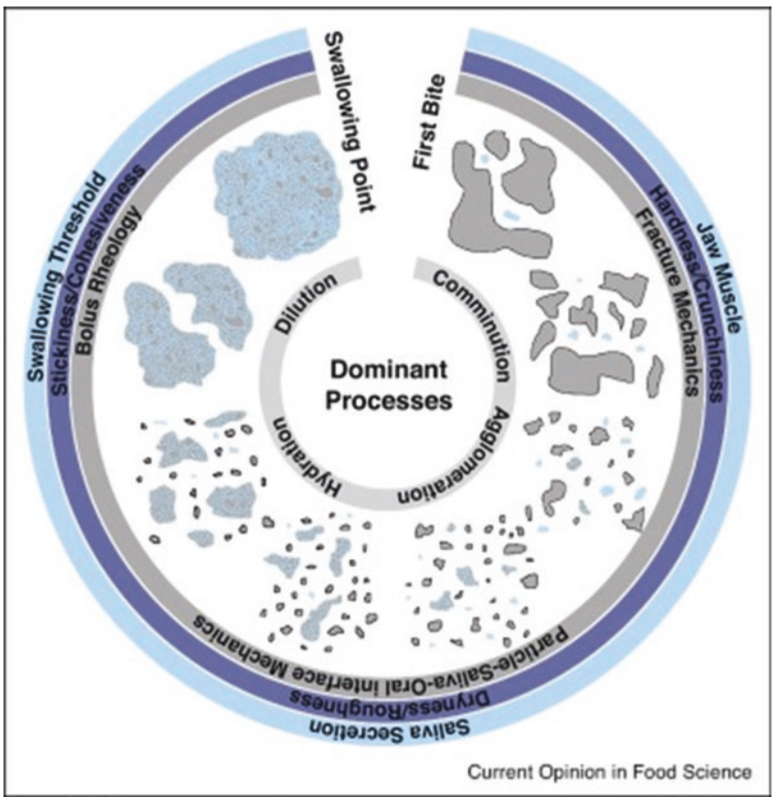

Fig. 4 Schematic illustration of mechanisms involved in food oral processing, from first bite to bolus swallowing. Rings represent major processes regarding particle size reduction and food–saliva interaction, together with physiological elements involved and main physical dimensions which can describe the food bolus along the process. A full description can be read in the related publication. (From Witt & Stokes, 2015, with permission)

of the oral structures, such as dental state, saliva flow, tongue motility, muscular potential, are factors influencing the food oral processing in terms of particle fragmentation, saliva provision and gathering food fragments in a food bolus safe for swallowing (Chen, 2009). Plenty of physiological inputs occurring during food oral processing are converted into sensory signals at any moment of food transformation and serve both as indicators to continue adjustment of motor activity and to offer sensory perception of food characteristics (Wilkinson et al., 2000; Salles et al., 2010; Koç et al., 2013; Pascua et al., 2013; Foegeding et al., 2015; Nishinari & Fang, 2018).

3.2.2 Food Bolus Characteristics

Apart from an influence of oral physiology, the food bolus characteristics relate to mechanisms of solid food fragmentation under the action of the teeth, namely breakage function and food–saliva interactions (Fig. 4). The food bolus is unsurprisingly a heterogenous and complex material with various physical properties continuously varying during the entire oral transformation whether the food is solid or semi-solid. Fracturing, which is a major mechanism during mastication, is dependent on initial physical properties of food as well as its geometry, fracture propagation, composition and interactions with saliva (Lucas et al., 2002; Swackhamer & Bornhorst, 2019). Thus, many different physicochemical dimensions can be described for a food bolus, the most important ones relating to rheological behaviour, saliva impregnation and fragmentation level (Panouillé et al., 2016). Softening, reduction in size, hydration and cohesion or plasticity are common physical characteristics for bolus of most swallowable boluses, even if different kinetics or patterns are described depending on food structure (Jalabert-Malbos et al., 2007; Peyron et al., 2011; Loret et al., 2011; Stokes et al., 2013; Larsen et al., 2016; Gao et al., 2018). The particle size generally decreases as the number and area of particles increase along the progress of the masticatory sequence (Le Bleis et al., 2013). As particle size is one of the main requirements that the bolus must meet to be safely swallowed, it is not surprising to observe similar size distribution in boluses of a given food (Peyron et al., 2004b; Jalabert-Malbos et al., 2007). Bolus lubrication generally increases with addition of saliva, which is mixed with fluids coming from food matrix such as juice or oil, oily or moisture foods needing less saliva incorporation than dry foods for example (Drago et al., 2011). In addition, bolus can be characterised in many other dimensions covering lubrication relating to the rheology and surface properties, as well as recoverability or plasticity to facilitate slipping during swallowing (Stokes et al., 2013). Indeed, saliva is a complex biological fluid presenting unique rheological characteristics. Its incorporation in the food bolus changes rheological and tribological properties of food through hydration and also hydrolysis of some food components. For example, this decreases viscosity of food bolus and increases bolus consistency, leading to a stretchable and deformable material as required for safe swallowing. At the same time, and since food particles interact with surfaces of all oral elements, saliva is clearly useful in reducing the frictional forces resisting movements during mastication and swallowing, avoiding particles to escape from the bolus (Le Bleis et al., 2013; Mosca & Chen, 2017; Khramova & Popov, 2022).

3.2.3 Role of Saliva

In addition to the diverse aspects of its function in preservation of oral health, saliva strongly participates in food oral processing, food bolus formation and digestion. Despite great variations between individuals' flow rate and composition (Heintze et al., 1983; Humphrey & Williamson, 2001; Dodds et al., 2005; Zussman et al., 2007; de Almeida et al., 2008), the rheological properties of saliva are key during food management and bolus formation (Pedersen et al., 2002; Bongaerts et al., 2007; Mosca & Chen, 2017; Boehm et al., 2020). The specific rheological properties, especially viscosity, allow a rapid spreading of saliva both on the oral surfaces and on the food fragments (Schwarz, 1987; Drago et al., 2011; Carpenter, 2013; Boehm et al., 2020). In this way and in association with its composition, saliva also contributes to food breakdown through mechanical and biochemical actions. During mastication, a film of saliva protects oral tissues and helps in reducing friction. Food fragments produced by action of teeth are mixed with saliva as soon as they are formed. Addition of saliva serves in coating food fragments, moistening them and aiding their agglomeration. Additionally, and in combination with dissolution of some constituents as well as mixing with food liquids, these actions provide a specific rheological environment to the bolus. Lubrication favours food softening and acts in particle gathering; it also exposes food constituents to salivary components such as alpha-amylase, which acts in degrading food and modifying rheological properties (Mosca & Chen, 2016; Boehm et al., 2020; Pu et al., 2021). Participating to bolus formation, saliva also importantly contributes to food textural perception through mechanical disruption and enzymatic reactions causing food breakdown (Janssen et al., 2007; Mosca & Chen, 2017; Laguna et al., 2021) besides taste perception for which the liquid phase is essential. Apart from the level of food breakdown, initiation of swallowing is also strongly linked to the degree of lubrication of the food bolus (Coster & Schwarz, 1987; Pedersen et al., 2002; Chen & Lolivret, 2011; Tobin et al., 2020). At the end of mastication, the level of lubrication ensured by saliva addition initiates swallowing of a food bolus characterised by strong cohesive forces between the food particles (Fig. 4; Prinz & Lucas, 1995; Chen & Lolivret, 2011; Mosca & Chen, 2016; Boehm et al., 2020; Liu et al., 2020).

Saliva deficiency has been shown to increase the duration of mastication, insufficiently soften food bolus, disturb swallowing or reduce perception of taste (Hamlet et al., 1997; Peyron et al., 2018).

3.2.4 Role of the Tongue

Besides the role of the tongue in taste perception, food oral processing depends on actions of the tongue first in moving the pieces of food towards the posterior teeth with a pullback movement. During mastication the tongue remains very active to place food between the teeth, to sort out the food fragments before each occlusion for further crushing, to gather particles into a rounded mass called the bolus, to favour mixing with saliva and to prevent food parts from escaping.

All these tongue movements are coordinated with jaw displacements. Mastication comes to an end when the food bolus structure has been sufficiently disrupted, and the tongue serves as an actor for transition towards swallowing by making a major contribution in oral and pharyngeal phases of swallowing. The tongue acts to position the food in posterior area of the mouth so it can be safely swallowed and progressively squeezed against the hard palate. It imparts peristaltic movements and pressure to place the bolus in the direction of the pharynx and then retracts to move the bolus down in the pharynx and oesophagus (Hiiemae & Palmer, 2003; Youmans & Stierwalt, 2006; Kieser et al., 2011; Nishinari et al., 2020). During swallowing, the tongue is in contact with both the hard and soft palate, and its shape, area and contour are adjusted to bolus volume (Kahrilas et al., 1993).

The role of the tongue in mastication and swallowing is well documented with substantial amount of literature on tongue strength and consequences of deficiencies on its performance (Ono et al., 2004; Clark & Solomon, 2012). Apart from its role in bolus formation, mastication has significant influence on taste perception since it is responsible in release of taste compounds by breaking the food matrix and increasing access to taste receptors (Salles et al., 2010; Liu et al., 2017).

3.2.5 Interindividual Variability in Food Oral Processing and Food Bolus Characteristics

Individuals develop different strategies for oral processing, according to their oral physiology and specifically the main features of the physiology of mastication (Gibbs et al., 1982; Brown et al., 1994). This large variability between and among individuals is observed independently of the food characteristics and expressed for example in the number of masticatory cycles, the duration of the masticatory sequence, the masticatory frequency, the amplitude of muscular contraction and force generated for a given food (Brown et al., 1994; Lassauzay et al., 2000; Peyron et al., 2004a; Woda et al., 2006). Important differences have been observed in several masticatory parameters between males and females masticating the same food, males developing for example greater muscular contraction, with larger vertical amplitude and velocities during mandibular movements related to a larger oral cavity, finally using different food oral processing strategies (Ketel et al., 2020; Rosenthal & Philippe, 2020). Maximal tongue pressure has also been reported to greatly vary between individuals (Loret et al., 2011; Alsanei et al., 2015; Pematilleke et al., 2021). In contrast, individuals clearly display reproducible patterns of masticatory process for a given food chewed on different repetitions or occasions (Lassauzay et al., 2000). Wide variations in masticatory strategies between normodentate individuals for a given food have their rationale in the common need of producing a safe swallowable food bolus, in terms of granulometry as well as rheological behaviour, which has been verified for several foods (Woda et al., 2006; Loret et al., 2011; Pematilleke et al., 2021).

3.2.6 Impact of Ageing on Food Oral Processing

The consequences of ageing on food oral processing have been largely investigated and despite the heterogenicity of elderly population, some common characteristics have been highlighted. In brief, ageing alone has little impact on masticatory performance or on the ability of old people to fragment food in smaller particles and to make a smooth and cohesive bolus (Feldman et al., 1980; Ikebe et al., 2011, 2012). Several physiological changes progressively adapt the oral sensorimotor functions to ageing so that the purpose of mastication in providing a safe bolus for swallowing is achieved. For example, without any gender difference but great interindividual variability, tongue strength appears to be lowered in elderly even if no clear decrease has been observed for swallowing pressure (Taniguchi et al., 2008; Fei et al., 2013; Alsanei & Chen, 2014; Kim et al., 2021). Maximal bite force and masticatory muscle mass have been found to decrease with age (Bakke et al., 1990; Newton et al., 1993; Hatch et al., 2001; Yoshida & Tsuga, 2020). The total number of masticatory cycles performed for a given food increases with age probably to reach the same amount of saliva impregnation in the bolus, but masticatory frequency is preserved (Fig. 5; Peyron et al., 2017; Aguayo-Mendoza et al., 2020). This has an impact on the total EMG activity, which increases de facto (Peyron et al., 2004a; Park et al., 2017). In contrast, the same level in masticatory muscle contraction (EMG activity) is produced during individual masticatory cycles when correct oral conditions are maintained, and this despite an association between sarcopenia and masticatory function (Fig. 5; Kohyama et al., 2002; Peyron et al., 2004a; Yoshida & Tsuga, 2020). Amplitude and velocities in mandibular displacements significantly decrease with age even with good oral state (Karlsson & Carlsson, 1990). In contrast, the masticatory frequency does not undergo significant changes during ageing, but neither does particle size distribution, at least for some foods (Peyron et al., 2004a; Mishellany-Dutour et al., 2008).

3.2.7 Impact of Tooth Loss and Oral Deficiencies on Food Oral Processing and Food Bolus Characteristics

Ageing is frequently associated with dental loss, and masticatory function is largely impeded when teeth are missing (Ikebe et al., 2012; Fan et al., 2022). The number of teeth, the number of posterior antagonist teeth (or posterior functional units) and the quality of opposite teeth contacts during mastication are determining factors for mastication functioning as well for food comminution (Kohyama et al., 2003; Hennequin et al., 2015; Huang et al., 2021). When teeth are missing, most of the sensory feedback normally coming from dental mechanoreceptors is reduced and the necessary modulation of oral motor activity is partial and improper (Veyrune & Mioche, 2000). In denture wearers, masticatory strategies associated with lower and imprecise masticatory forces are generally characterised by a decrease in masticatory frequency, and a lack of adjustment of muscular activity to food hardness. Facing their bad oral conditions, they try to compensate miss-

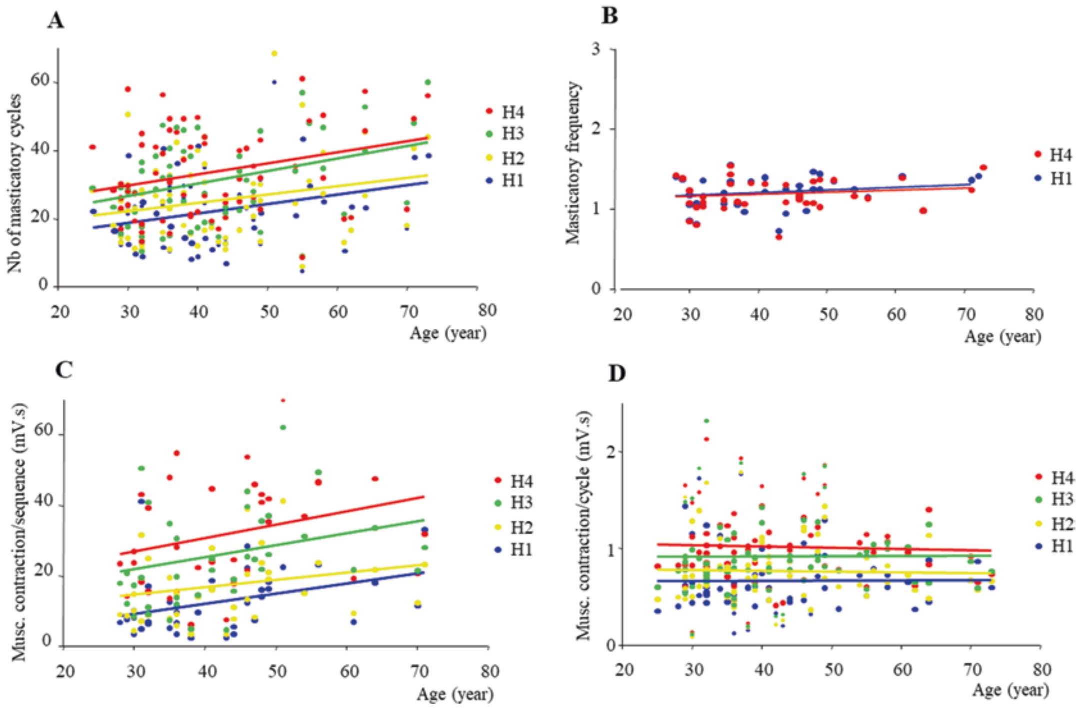

Fig. 5 Effects of healthy ageing (25–72 years) and hardness of an elastic food model (softest H1 to hardest H4) on number of masticatory cycles (**a**), masticatory frequency (**b**) and muscular contraction recorded by electromyography (EMG) for the complete masticatory sequence (**c**) and for a single masticatory cycle (**d**). Data for all individuals and four hardness are presented except for masticatory frequency (**b**) where only data for H1 and H4 are presented for better readability. (Modified from Peyron et al., 2004a, with permission)

ing teeth or inaccurate occlusion by increasing the number of masticatory cycles often without success in reaching the optimal particle size level for a safe swallowing (Fig. 6; Woda et al., 2006, 2011; Veyrune et al., 2007; Mishellany-Dutour et al., 2008). Oral deficiencies such as tooth loss constitute a steady impairment at various levels of food oral processing, resulting in an incomplete fragmentation and disorganised food bolus (Fig. 6), or inadequate softening, before swallowing, and this is particularly important in case of cumulated oral deficiencies (Yven et al., 2006; Mishellany-Dutour et al., 2008; Peyron et al., 2018).

3.3 Influence of Food Characteristics on Food Oral Processing and on Food Bolus

Although food oral processing varies according to individual oral capabilities, food structure also plays a prominent role in driving oral functions, especially muscles activity, and jaw and tongue movements, which are adjusted to food features as early as the first bite and modulated through the complete masticatory sequence as textural changes occur in the bolus (Lassauzay et al., 2000; Peyron et al., 2002, 2011). Some unclear or insignificant relationships between specific physical dimensions and physiological measurements can be related to a certain complexity in mechanical measurements, which cannot be unique for the large variety of foods and applied at different single measurement scale. Nevertheless, the common observation of a dominant link between food and its oral processing remains verified. There is an abundance of literature on how different food characteristics have clearly influenced oral functions (Woda et al., 2006; Rosenthal & Share, 2014; Hawthornthwaite et al., 2015; Tonni et al., 2020; Guo, 2021). Food oral processing is firstly driven by mechanical fragmentation of food, which in turn is largely dependent on food

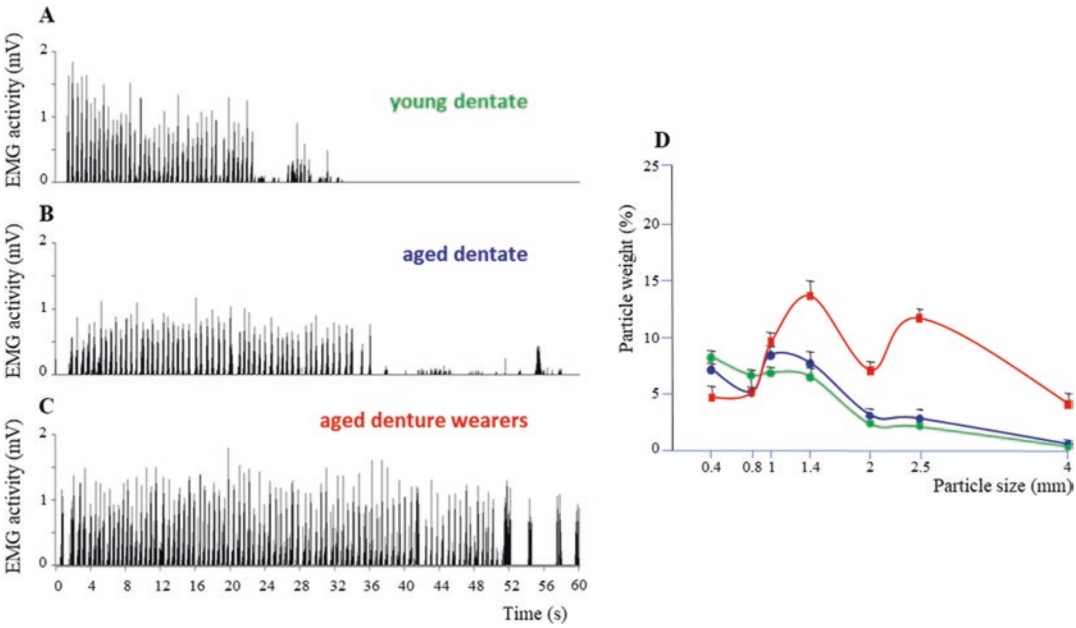

Fig. 6 Examples of electromyographic (EMG) activity recorded for the right masseter muscle during mastication of peanuts in a young dentate (**a**), an aged dentate (**b**) and an aged denture wearer (**c**) subject. Using a sieving method to study bolus granulometry, percentage of weight of particles retained in different sieves (**d**) is expressed in terms of size aperture giving particle size distribution curves for bolus from young dentates (green), aged dentates (blue) and aged dentated (red) subjects (n = 10). These examples show that aged individuals masticate longer and provide a correct bolus, with similar bolus particle size distribution as obtained for young dentate subjects. On the contrary, despite a longer masticatory sequence, aged denture wearer subjects are not able to form a correct bolus, which contains many larger particles (red curve). (Modified from Mishellany-Dutour et al., 2008, with permission)

nature and formulation, conferring specific physico-chemical characteristics including geometry (size, water content, volume, shape, weight or initial form), structure, heterogeneity and composition (Aguayo-Mendoza et al., 2019; Guo, 2021). These links have been demonstrated for various food families, such as bread, meat, dairy products, rice, gels, gums or confectionery (Yven et al., 2005; Jalabert-Malbos et al., 2007; Drago et al., 2011; Le Bleis et al., 2013; Pentikäinen et al., 2014; Gao et al., 2015; Larsen et al., 2016; Wagoner et al., 2016; Kohyama et al., 2016).

Despite some vagueness in mechanically defining various foods, hardness is probably the dominant characteristic used by the central nervous system to control masticatory force. For example, some studies showed that a mechanical index based on toughness and elastic modulus of complex foods can reflect the complex stimulation serving as inputs for the CPG (Agrawal et al., 1997; Lucas et al., 2002).

Indeed, amplitude and duration of muscular contraction during each masticatory cycle (EMG recordings) are related to an increase in food hardness (Horio & Kawamura, 1989; Peyron et al., 2002; Kohyama et al., 2003; Foster et al., 2006; Woda et al., 2006). Longer masticatory sequences consequently to higher number of masticatory cycles needed to masticate harder foods have been observed for a wide variety of food families such as rice, meat products, breads, gels or cheeses for example (Fig. 7; Aguayo-Mendoza et al., 2019; Pematilleke et al., 2020, 2021; Tonni et al., 2020; Guo, 2021). Food recoverability, adhesiveness, springiness or other dimensions measured to characterise food have influence on food oral processing (Kazemeini et al., 2021). Mastication of hard foods also signs for higher and larger jaw displacements, with

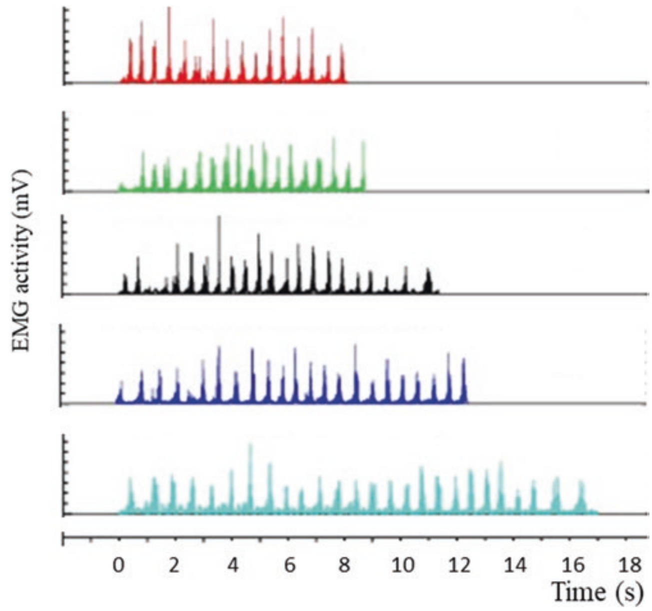

Fig. 7 Examples of electromyographic recordings (EMG) obtained for the left temporalis muscle during mastication of five different breakfast cereals by the same subject. (Adapted from Hedjazi et al., 2013; with permission)

generally smaller closure angles and higher velocities (Peyron et al., 2002, 2004a; Foster et al., 2006; Piancino et al., 2008). As demonstrated with elastic model foods, amplitude of mandibular movement clearly increases with hardness (Fig. 8). These jaw displacements also vary with other physical properties of foods to adapt the right combination of compression and shear constraints to accomplish the optimal mechanical food disruption (Lucas et al., 1986; Agrawal et al., 1997; Foster et al., 2006; Wintergerst et al., 2008). Mastication of fibrous products such as meat, or more adhesive ones, generally requires more shear stresses, which is illustrated with more lateral jaw excursion certainly permitting more lateral teeth opposition (Peyron et al., 2002; Foster et al., 2006). As for EMG activities or number of masticatory cycles, amplitude of jaw movement logically increases with food sample size (Peyron et al., 1997; Wintergerst et al., 2008; Goto et al., 2015; Kohyama et al., 2016). An increasing structural heterogeneity of food also results in an increase in food oral processing activity, reflected in a higher number of masticatory cycles, longer mastication duration or greater muscular activity, for example (Gao et al., 2015; Laguna & Sarkar, 2016; van Eck et al., 2019). Dryness is another food characteristic which has been addressed. Saliva impregnation is more important for dry foods, powder products being an extreme in terms of quantity of saliva incorporated in the bolus, and harder foods also provoking more saliva production (Mosca & Chen, 2017).

Overall and for a wide range of food types, the bolus particle size decreases with the increase in food hardness (Peyron et al., 2004b; Jalabert-Malbos et al., 2007; Chen et al., 2013). As mastication and food bolus formation are dynamic mechanisms, EMG activity and amplitude of vertical jaw displacement are gradually reduced with the progress of masticatory sequence, which is attributed both to a regular food softening and decrease in particle size (Lassauzay et al., 2000; Peyron et al., 2002; Grigoriadis et al., 2014). The strongest changes in muscular activity are in amplitude of jaw displacements observed during the first five masticatory cycles, which then decrease more regularly until the end of chewing (Peyron et al., 2002). These changes are proportional to the initial food hardness at the beginning of mastication while less significant at the end when the bolus properties have been reached whatever the initial hardness. Amplitude of tongue movements also increases during management of harder or at

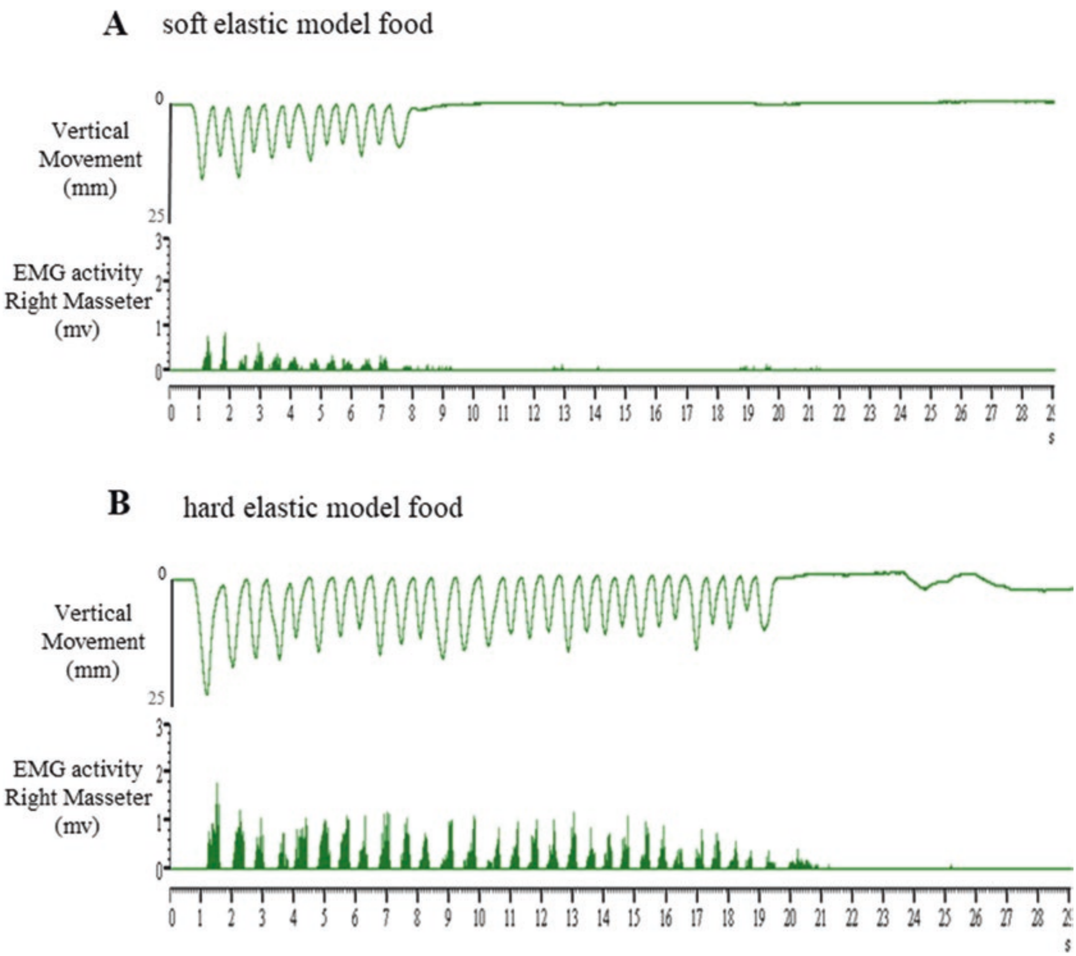

Fig. 8 Examples of electromyographic recordings (EMG) obtained from the right masseter in a normodentate individual masticating a soft (**a**) or a hard (**b**) elastic model food. Amplitude of vertical movement and muscular contraction, and number of masticatory cycles significantly increase with hardness

least more complex foods (Taniguchi et al., 2013).

In case of semi-solid foods requiring little mastication, the tongue acts as the main tool to break the soft food matrix by squeezing and compressing food against the hard palate. Increasing consistency or resistance to compression of these foods increases tongue activity with increased amplitude of lingual pressure (Kieser et al., 2011; de Wijk et al., 2011; Yokoyama et al., 2014; Nishinari et al., 2020).

3.3.1 Swallowing Threshold

Transition from mastication to swallowing defines the swallowing threshold. Swallowing is a complex and highly coordinated function which cannot be separated from mastication and which involves tongue, and tissues in the oropharynx. The masticatory sequence relates to a dynamic process, and a continuous perception of bolus physical properties by receptors in the mouth participates in the central decision of swallowing initiation. The first phase among the three constituting the process of swallowing is voluntary and proceeds in the oral cavity. It has been initially suggested that it can be triggered by critical particle size and accurate bolus lubrication, and completed by notion of flow and stretch levels perceived by oral receptors (Lucas & Luke, 1986; Hutchings & Lillford, 1988; Prinz & Lucas, 1995). The key and common point for swallowing is being as effortless as possible whatever the nature of the food. As bolus properties do not reach the correct particle size and lubrication levels to guarantee a safe swallowing, masticatory process continues in a loop model in order to mitigate the risks of swallowing large particles, not enough salivation incorporation or the risk of their aspiration (Foster et al., 2011; Gray-Stuart et al., 2017). Thus, mechanisms are based on perception of accurate particle size sufficiently lubricated, providing an entity presenting specific rheological features, such as plasticity and slipping properties (Prinz & Lucas, 1995; Peyron et al., 2011). Several other rheological bolus characteristics have been added in the swallowing threshold description such as flow- and stretch-ability, adhesiveness, plasticity, visco-elasticity and apparent shear viscosity, or cohesive forces allowing particles to cohere each other and form a definable entity, for example (Prinz & Lucas, 1997; Chen & Lolivret, 2011; Tobin et al., 2020; Pu et al., 2021). Food bolus consistency and its volume are also factors generating changes in timing of swallowing steps and in modalities of its propulsion towards pharynx (Chi-Fishman & Stone, 1996).

3.4 Challenges and Perspectives in Food Oral Processing Research Area

As an emerging research area in food science discipline, food oral processing study generally depicts mechanisms involved in food texture perception, masticatory effort to form a bolus, saliva action, aroma release and taste perception, bolus and saliva rheological characteristics, etc. Several perspectives have been identified in these research fields and cover comprehensive studies on structure disruption, bolus characteristics at different measurement scales, food–saliva interaction, food oral management, perception, role of tongue, oral digestion, etc., until projections in nutrition.

Plethora of literature has reported new research opportunities leading to new frontlines of science around interactions between food and mouth. In this dynamic, the most important challenge would be to increase and consolidate physiological considerations in studying oral mechanisms prevailing during mastication and swallowing. Apart from production of relevant knowledge, some issues addressed in food oral processing research area can be exploited in designing new foods for specific population such as children, aged and/or orally deficient people. This knowledge is obviously necessary to provide foods of improved textural quality, appropriated to age and individual oral capabilities, which are not only healthy and pleasurable but also matching nutritional requirements.

In this perspective, an important challenge to face is the construction of an efficient and active interaction to join knowledge and work on the interface of physiology, food science and clinical areas, for a relevant and beneficial result for all concerned. Indeed, an important gap still existing is probably an underestimation of physiological concepts in conducting food oral processing research, which may lead to undervaluation, and incomplete or misinterpretation of results. Simulation of oral processes (mastication, swallowing, tongue movements, saliva addition, etc.) would also benefit if driven with a good control of physiological concepts governing these functions.

This challenging strategy shall also include caution in choosing methods of measurement, not only for food and food bolus characterisation but also for physiological variables to consider. Saliva–food, saliva–mouth and mouth–food interactions clearly governing mechanisms during food oral processing could certainly be addressed with success if studied at the interface between different disciplines.

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Part II

Food Texture, Sensory and Human Interactions

Psychophysics of Texture Perception

James Makame and Alissa A. Nolden

1 Introduction

Food engineers and sensory scientists seek to uncover the techno-functional properties and composition of foods and beverages that can predict their palatability and acceptance (Huang et al., 2021). With respect to food texture, it is important to understand the psychophysical relationship between the variables responsible for texture quality, and the tactile perceptual responses they induce during food consumption to achieve consumer satisfaction. Tactile experiences are a pivotal part of consumer behaviour and choice (Post et al., 2023), enabling critical decision-making such as judging food's freshness and its fitness for consumption based, for example, on its perceived softness (Cavdan et al., 2021). Such information can assist in the systematic design and building of tactile sensations into products to satisfy consumers' needs (Arakawa et al., 2022). Psychophysics, a scientific field that investigates the relationships between physical stimuli and the sensations and perceptions they produce, plays a critical role in examining expectations and actual perceptions of consumers regarding food products (Moskowitz, 2020).

Sensory perception, per se, is a neurophysiological process through which human beings interact with and interpret (perceive) information (sensory stimuli) from the external environment. This process is mediated through very complicated internal psychological mechanisms that cannot be easily duplicated by instruments (Chen et al., 2021). Sensory panellists have reliably been used in judging the psychophysical texture quality and intensity of foods (Lv et al., 2017; Hadde et al., 2019; Blok et al., 2021; Deblais et al., 2021). However, sensory evaluation can be expensive, necessitating oftentimes a need for use of less expensive instrumental measurements in routine analysis. Hence, to inform reliable instrumental predictions of food texture quality, understanding the psychophysical relationships between food texture perceptions and their instrumentally assessed material property correlates (e.g. rheological properties) is imperative. The *two-alternative forced-choice (2-AFC) method* – a subvariant of the *methods of constant stimuli* – has been a common choice procedure in many food texture psychophysical studies (Camacho et al., 2015; Breen et al., 2019). Like any constant stimuli method, the 2-AFC method provides assessors with a binary of qualitative options, where they must select only one choice (e.g. *select which of the two samples is thicker/has higher intensity of some sensory attribute*).

Humans often judge food texture perceptions qualitatively, categorically and discretely (e.g.

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thick, too thick, thin, slimy, soft and hard), although psychophysical evidence suggests that intensity is continuous (i.e. progresses from weak to strong, low to high variants of a stimulus) (Snyder et al., 2006). It is therefore logical to conclude that panellists subconsciously appeal to the 'sensory difference threshold' when rating sensory perceptions based for instance on 2-AFC, to determine whether two stimuli belong to the same 'intensity category' or not. Other sensory methods have also been used in food texture psychophysical evaluations, including the *modified Spectrum method* with a 16-point categorical scale (Deblais et al., 2021), and *the ranking method* in predicting psychophysical functions for tactility in oral stickiness, firmness and creaminess in mayonnaise (Schädle et al., 2022).

Tactile cues play a significant role in food quality perception and purchase decisions (Upadhyay et al., 2020), greatly influencing food preference and enjoyment (Lv et al., 2020; Miles et al., 2022). The variables like physical swallowing safety, eating comfort, sensory palatability and nutrient intake moderation are all related to texture quality in many foods. Safe food textures are a prime consideration for all consumers, especially in individuals with limited oral processing abilities, including dysphagic patients (Ibañez et al., 2019) and young children (Makame et al., 2020). Clinical cases of elderly men who died after choking on *mochi* (a traditional Japanese sticky rice cake eaten in many countries) have been described in literature (Nagata et al., 2018). Stickiness perception can be related to both extensional and shear viscosity (He et al., 2016), and to tribological events during food oral processing (Bikos et al., 2022). Schädle et al. (2022) reported a strong correlation (r = 0.97) between the coefficient of friction at the sliding speed of 180 mm·s^{-1} and sensory stickiness of mayonnaise, suggesting stronger psychophysical links between the deformation properties of the mayonnaise samples and their stickiness eating quality. It is therefore critical to know a priori by what magnitude of intensity a food material property must be varied to achieve target formulation objectives without compromising physical safety and palatability from a sensory perception viewpoint.

Humans are exquisitely sensitive to the microstructure and material properties of objects, with a remarkable ability to discriminate surfaces that differ even by a single layer of molecules through touch exploration (Carpenter et al., 2018; Long et al., 2022). Despite this degree of tactile acuity, the psychophysics of food texture is complicated by multiple factors, including sophisticated food matrix effects and the concept of derived sensory properties (Chen, 2020). Texture is perceived holistically through the stresses and/or strains exerted on the oral mechanoreceptors during food oral processing (Strassburg et al., 2009; Lv et al., 2020). Food in the mouth is deformed and flows under the shearing of the teeth and tongue, and textural attributes such as elasticity, stickiness and viscosity are perceived (Sherman, 1969; Rosenthal, 1999). It is of interest to fully understand the psychophysical functions that model/describe the translation of sensory stimuli (food mechanical properties) into sensory perceptions via neural processes in the brain. Fig. 1 graphically visualizes this psychophysical representation.

2 Background and Milestones in Psychophysics

Psychophysical laws quantitatively relate perceptual magnitude to stimulus intensity (Zeng, 2020). There have been three main theories driving the scientific principles of basic psychophysics, chronologically represented by Weber's fraction, Fechner's logarithmic law and Stevens' power law (Johnson et al., 2002). Recently, the modified Stevens' power law has been proposed (Chen et al., 2021), while a consolidation of Fechner's log law has also been defended (Deblais et al., 2021). In this chapter, we will refer to the consistency index K and the flow behaviour index n from rheological models. Therefore, for convenience purposes, we use K_W and n_p to represent Weber's fraction and the power index respectively. A smaller k will represent a proportionality constant as described in the chapter.

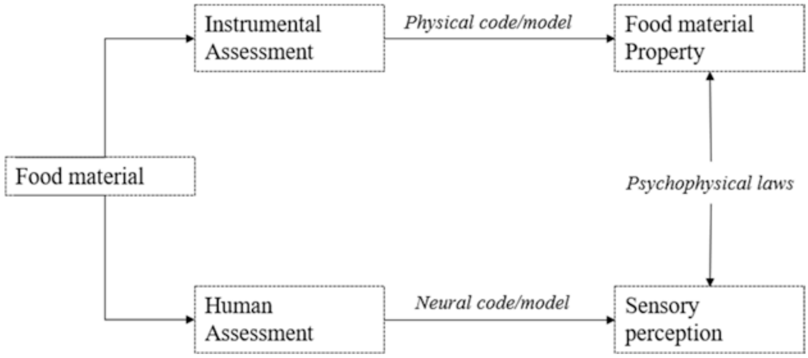

Fig. 1 Relating sensory perception to a material property. (Adapted from Chen, 2020)

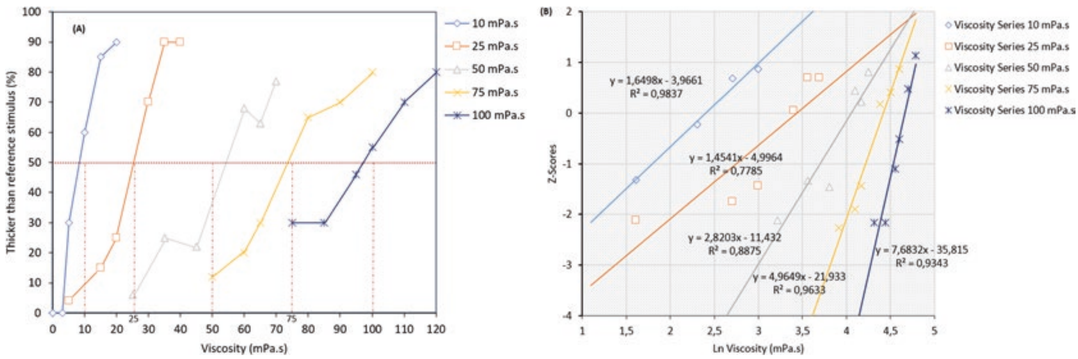

Fig. 2 (**a**) Percentages of selections of 'thicker than reference stimulus' as a function of stimulus viscosity. (**b**) Linear regression between z-coordinates (y-axis values in **a** transformed) as a function of the natural logarithm of viscosity. Each line series shows results for a reference and its set of comparison stimuli. (Redrawn from Camacho et al., 2015)

2.1 Weber's Fraction (1830s)

Weber's fraction, K_W states that: '*the magnitude of a "just noticeable difference" (JND) is proportional to the intensity of the stimulus already present*'. German physiologist Ernst Heinrich Weber observed that the amount that a physical stimulus needed to be increased to be just perceivably different from the comparative starting level was a constant ratio (Lawless & Heymann, 2010). To find this ratio (K_W), the percentages of stimuli assessed by the sensory panel as '*higher intensity than reference (Ref) stimuli*' in a psychophysical task (e.g. 2-AFC test) are established for a series of stimuli pairs (Fig. 2a) and transformed into z-coordinates to linearize the sigmoid psychometric function (Lawless & Heymann, 2010). Linear regression is then applied on z-coordinates as a function of the natural logarithm of the stimulus (e.g. viscosity) (McBride, 1983; Le Berre et al., 2008) (Fig. 2b).

The equations from linear regressions are then used to calculate the *just noticeable difference* (JND) (Camacho et al., 2015):

$$\text{JND} = \frac{\text{Stimulus at 75\% Correct response} - \text{Stimulus at 25\% Correct response}}{2} \tag{1}$$

The JND refers to the smallest change that can be detected between two stimuli (the sensory difference threshold) in human sensation (Breen et al., 2019; Niu & Lo, 2022). JND values can also be determined from the detection threshold test (same-difference test) by plotting a log-normal fit (probit analysis) of the cumulative population detection (%) versus the log concen-

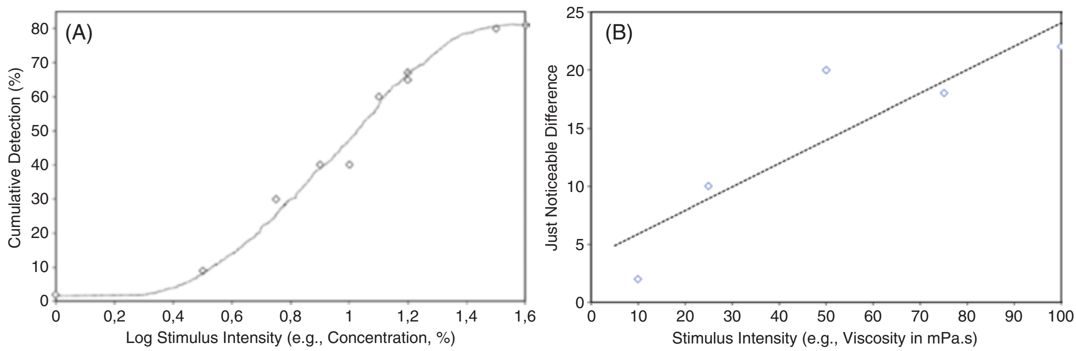

Fig. 3 (**a**) Log-normal fitting (probit analysis) of the cumulative population detection percentage versus the log concentration (w/w) for shear viscosity. (Redrawn from Lv et al. 2017). (**b**) Linear relationship between JND of oral thickness perception with viscosity of the reference stimulus (I). (Redrawn from Camacho et al., 2015)

tration (w/w), taking 50% as the population cumulative detection average (Fig. 3a) (Lv et al., 2017). In Ketel et al. (2022), a cumulative frequency of correct answers of 75% (half way between chance level; 50% and perfect performance; 100%, no log transformations on both axes) was used as estimate of population sensitivity threshold by interpolation of the data assuming linearity. Proceeding from Fig. 2, Weber's fraction is then graphically derived from a plot of JNDs versus I (physical stimuli) (Fig. 3b) (Camacho et al., 2015).

The mathematical formula for determining K_W based on the collective reference stimuli series data is:

$$K_W = \frac{\Delta I}{I} \text{ or } K_W = \frac{\text{JND}}{I} \quad (2)$$

where ΔI or JND is the change in the physical stimulus that was required to notice the discriminable difference from some base level, I, which is the intensity of the reference stimulus. The fraction, $\Delta I/I$ (*Weber's fraction,* K_W) is an index of the sensitivity of the sensory system to detecting changes in a certain stimulus or changes in product attributes (Lawless & Heymann, 2010; Breen et al., 2019). It is a constant fractional increment that should be added to the stimulus magnitude, I, for the minimal change to be noticed (Algom, 2021).

2.2 Fechner's Logarithmic Law (Around 1860)

Based on Weber's fraction, Fechner founded his law, which states that *the perceived or subjective sensation of a stimulus is proportional to the logarithm of stimulus changes (the intensity of physical stimulus)* (Mertens et al., 2021; Gao et al., 2023). Fechner named his first law 'Weber's law', in honour of his mentor (Weber), who had conducted the experiments needed to formulate the law (Weber et al., 2018).

Fechner's logarithmic law is specified as:

$$S = k.\log(I) \quad (3)$$

where I and S represent the stimulus and perceptual intensities, respectively (Deblais et al., 2021), and k is a proportionality constant linking the two variables.

2.3 Stevens' Power Law (Around 1961)

Fechner's logarithmic law was to be challenged by Stevens nearly 100 years later in his seminal scientific piece '*To honour Fechner and repeal his law: A power function, not a log function,*

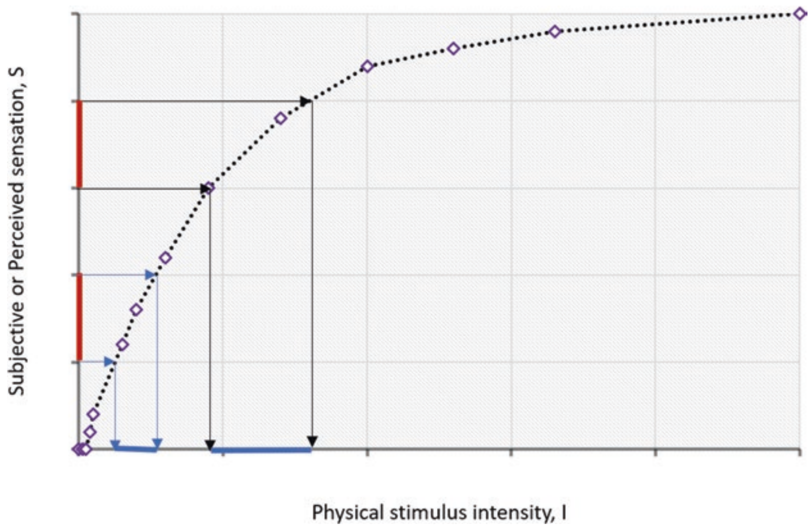

Fig. 4 A generalized logarithmic relationship between the subjective human sensation and the stimulus intensity, based on Weber's law. (Redrawn from Gao et al., 2023)

describes the operating characteristic of a sensory system' (Stevens, 1961). Stevens spotted a vital error made by Fechner in assuming that the just noticeable difference (JND) remained a constant regardless of the intensity and considered that the JND varies, and its value should increase in proportion to the intensity of the stimulus as was indicated by Weber's law (Fig. 4).

Based on this consideration, Stevens demonstrated that the perceived psychological magnitude of a stimulus S should have a power law relationship with its physical magnitude I. Stevens' power law states: *the stimulus intensity sensed by human organs is represented by a power law of the instrumentally observed physical stimuli or quantity* (Johnson et al., 2002; Mertens et al., 2021):

$$S = k(I)^{n_p} \tag{4}$$

The parameter k (small letter) represents a proportionality constant, with units dependent on the instrumentally measured stimuli (I) (Schädle et al., 2022). The characteristic power law index, n_p represents the curvature of the power function, which defines the relationship between the two properties, and provides an estimate of the sensitivity of human perception to the change of the physical stimulus (Chen et al., 2021; Schädle et al., 2022). The higher the n_p value, the more sensitive human perception is for such a material property (Lv et al., 2017). When $n_p = 1$, the perceived sensory sensation varies in a linear form with the stimulus intensity of the instrumental measurement; when $n_p > 1$, the sensation magnitude increases more rapidly than the stimuli intensity; and when $n_p < 1$, the sensation magnitude increases less rapidly than the stimuli (Arancibia et al., 2013).

2.4 Proposed Modified Stevens' Law (2021)

Chen et al. (2021) found Stevens' law to be mathematically self-inconsistent in terms of the units, and inapplicable when multiple physical stimuli are involved in the perception of a sensory attribute. To resolve for its self-inconsistency, a modified Stevens' law has been proposed (Chen et al., 2021):

$$S = k\left(\frac{I}{I_0}\right)^{n_p} \tag{5}$$

where I_0 is the threshold value, a critical value at which stimulation begins to be perceived (that is, $S = 0$, when $I = I_0$). Currently, all psychophysical models can only describe the one-to-one relationship between a sensory attribute and its associated physical stimulus. Where multiple physical stimuli are involved in complex sensations and derived sensory properties like creaminess, more research is required to develop adequately adapted functional psychophysical relationships/laws (Chen et al., 2021).

2.5 A Consolidation of Fechner's Logarithmic Law (2021)

Although the power law is the most extensively adopted psychophysical law currently, Deblais et al. (2021) found that oral thickness was proportional to the logarithm of the shear stress on the tongue (Fechner's log law). The variations amongst findings may also arise from differences in protocols used in various studies, as well as panellists-related factors. For example, in a study by Lv et al. (2017), participants used the finger-palm system in sensory thickness tests, finding a power law fit to the data, while in Deblais et al. (2021), participants used the tongue-palate system, which confirmed Fechner's log-law fit (although they did not rule out the power law).

Table 1 shows different psychophysical functions that were found to describe the relationships between specific food material properties and their sensory texture perceptions in different studies.

The sensitivities of the human sense of touch across different food texture attributes seem to be fairly comparable to other sensory modalities (sight, audition and taste), as noted by Camacho et al. (2015) (haptic texture), being generally compressive ($n_p < 1$). However, Schädle et al. (2022) reported on the expansive tactile sensitivity indices ($n_p > 1$) for oral stickiness, firmness and creaminess based on Stevens' power law fit to experimental data (rheological, tribological and sensory) for reduced fat mayonnaise (Table 2), in agreement with Lv et al. (2017) for the extensional viscosity versus haptic thickness relationship ($n_p = 1.2$). Their data showed that the perceived viscosity intensity was proportional to the exponent (power function) of the ratio of the physical intensity and the absolute threshold of the respective stimulus (as represented in Equations 4 and 5). The expansive nature of n_p for extensional viscosity suggests that it could be a more relevant variable of interest for psychophysical thickness sensory prediction than shear viscosity ($n_p = 0.54$).

This more rapid increase of the tactile sensory perception than the instrumental measurement shown in Table 2 suggests that humans are more sensitive in touch than other sensory modalities, and more sensitive to food texture stimuli than the specific measuring instruments used.

The application of psychophysics to food texture studies has given rise to a specialized field of science called psycho-rheology.

3 Food Psycho-rheology

Psycho-rheology is a branch of psychophysics that investigates the relationships between the physical material parameters of foods, with the sensorial texture perception of humans (Rauh et al., 2012). Psycho-rheology has also been defined as the relationship between the consumer food preferences and rheological properties of those foods (Singham et al., 2015). The former epistemology explores the relationships between material texture properties and sensory perception through psychophysical laws and correlations. The latter is concerned with consumers' texture-driven product preferences, often modelled through methods such as partial least-squares regression (PLS). Psychophysical measures of product use experience play a fundamental role in our understanding of sensory perception and hedonic processes (Snyder et al., 2006). For instance, Tobin et al. (2020) used PLS regression to predict the perceptions of mouthfeel (smoothness, residues in mouth, mouth coating, particle size perception, effort required to swallow and difficulty in swallowing) and ease of swallowing in the elderly, from rheological parameters (shear viscosity, viscoelasticity, yield stress, extensional viscosity and cohesiveness) of broccoli purees. In that study, the perception of ease of swallowing was correlated with yield stress and extensional viscosity in boli prepared with xanthan gum, providing insights into the design of personalized foods for populations with swallowing disorders.

Psycho-rheology can inform the effective design of edible mechanical metamaterials with

Table 1 Human sensitivity to food-based texture stimuli and the psychophysical laws that were found suitable to describe the relationships between specific food material properties and sensory perception

Tactile perception	Tactile stimulus	K_W or n_p	Psychophysical law	Method	Haptic/oral	Panel	Reference
Creaminess perception	Apparent viscosity varied by fat content	K_W: 0.16	Weber's fraction	2-AFC	Oral	Trained panel ($n = 15$)	Zahn et al. (2013)
Creaminess perception	Apparent viscosity varied by locust bean gum content	K_W: 0.22	Weber's fractions	2-AFC	Oral	Trained panel ($n = 15$)	Zahn et al. (2013)
Creaminess perception	Apparent viscosity of dairy-based emulsions	K_W: 0.20	Weber's fractions	2-AFC	Oral	Trained panel ($n = 15$)	Zahn et al. (2013)
Thickness of Newtonian model stimuli (maltodextrin solutions).	Viscosity varied in model beverages	K_W: 0.26	Weber's fraction	2-AFC	Oral	Untrained panel ($n = 15$)	Camacho et al. (2015)
Grittiness perception of chocolate	Particle size in chocolate as a model food	K_W: 0.17	Weber's fractions	2-AFC and two-interval-forced-choice (2-IFC) method	Oral	Naïve consumers ($n = 51$)	Breen et al. (2019)
Firmness of edible fats	Sectility testing	K_W: 0.20	Log law	2-AFC	Haptic – cutting the spreads with knife	Untrained panel ($n = 12$)	Rohm and Raaber (1992)
Spreadability of edible fats	Cone penetration	K_W: 0.27	Log law	2-AFC	Haptic – spreading with knife	Untrained panel ($n = 12$)	Rohm and Raaber (1992)
Thickness of liquid food products from their non-Newtonian rheology	Calculated total viscous shear stress, σ, on the tongue due to the varied liquid food viscosity	K_W: not available. n_p: 0.77 (*unpublished data*)	Log law Power law	Modified Spectrum method with a 16-point category scale (0–15)	Oral	Highly trained panel ($n = 11$–14)	Deblais et al. (2021)
Perceived hardness using rubber samples	Elastic modulus using rubber samples	n_p: 0.7	Power law	Method of constant stimuli	Shaking/turning a bottle with liquid, stirring with a rod (blind-folded viz eyes open)	Untrained panel ($n = 10$)	Stevens and Guirao (1964)
Perceived thickness of silicone oil	Viscosity of silicone oil	n_p: 0.4	Power law	Method of constant stimuli	As above	Untrained panel ($n = 10$)	Stevens and Guirao (1964)
Haptic thickness of thickened model solutions	Shear viscosity (η_s) and extensional viscosity (η_e) in thickened model solutions	n_p η_s: 0.54 n_p η_e: 1.24	Power law	Magnitude estimation	Haptic	Untrained panel ($n = 19$; 21)	Lv et al. (2017)

Table 2 The relationship between sensory and instrumental data using Stevens' power law, with the constant k, the exponent n_p and the correlation coefficient R^2 (Schädle et al., 2022)

	Sensory stickiness			Sensory firmness			Sensory creaminess		
Instrumental measure/stimuli (I)	k	$^{\#}n_p$	R^2	k	$^{\#}n_p$	R^2	k	$^{\#}n_p$	R^2
Hysteresis area	0.041	1.30	0.91	0.015	1.48	0.93	0.045	1.28	0.93
Shear viscosity at 10 s^{-1}	1.20×10^{-5}	1.60	0.95	9.91×10^{-7}	1.85	0.92	2.35×10^{-5}	1.53	0.95
Shear viscosity at 100 s^{-1}	1.53×10^{-3}	1.33	0.93	1.55×10^{-4}	1.62	0.89	1.76×10^{-3}	1.31	0.95
Yield stress	0.28	1.26	0.88	0.19	1.36	0.83	0.27	1.27	0.91
Consistency index, K	0.19	1.61	0.95	0.017	2.38	0.94	0.57	1.30	0.91
Kokini oral shear stress	0.022	1.55	0.94	5.38×10^{-3}	1.83	0.91	0.029	1.50	0.95
Work of shear (area under the curve of the positive peak)	10.91	1.70	0.96	7.69	2.04	0.94	11.87	1.61	0.97
Work of adhesion (area under the curve of the negative peak)	61.26	1.52	0.96	61.34	1.80	0.92	61.01	1.48	0.97
Firmness (positive peak force in penetration test)	3.81×10^{-5}	2.85	0.97	9.97×10^{-7}	3.58	0.96	4.37×10^{-4}	2.36	0.91
Stickiness (negative peak force/resistance in penetration test)	9.21×10^{-4}	2.24	0.97	5.27×10^{-5}	2.82	0.95	3.4×10^{-3}	1.97	0.94

#The exponent n_p indicates the sensitivity and type (compressive or expansive) of the relationship between the sensory and the instrumental data, and k is a proportionality constant linking the perceived sensory (texture) intensity, S, to the instrumentally measured material/physical stimulus, I. The units of k are dependent on the instrumentally measured stimuli tailored fracture properties, to control mouthfeel sensory experience. Metamaterials are artificially created physical products with unusual and superior properties that come from their carefully designed structures rather than their composition (Souto et al., 2022). For instance, using psychorheology principles, it has been possible to create chocolate metamaterials with controllable fracture anisotropy (directionally dependent behaviour), biting force, number of cracks and specific, tunable anisotropic mouthfeel properties (e.g. brittleness, softness and stiffness) (Souto et al., 2022). A noticeable difference in ease of bite was reported between the anisotropic material strength of chocolate metamaterials and perceived anisotropy in ease of bite.

Schädle et al. (2022) used psycho-rheology to understand the mouthfeel (creaminess, firmness and stickiness) of reduced fat mayonnaise based on the Herschel–Bulkley model (Eq. 6), Kokini oral shear stresses (Eq. 7) and Stevens' power law:

$$\tau = \tau_0 + K \times \dot{\gamma}^n \qquad (6)$$

where τ is the shear stress (Pa), τ_0 is the yield stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), K (capital letter) is the consistency index ($Pa{\cdot}s^n$) and n is the rheological flow index.

Inspired by Cook et al. (2003)'s method for measures of in-mouth viscosity, Schädle et al. (2022) then applied the Herschel–Bulkley parameters to calculate the *Kokini oral shear stress* τ (Kokini OSS) (Eq. 7):

$$\tau = \tau_0 + Kv^n \left(\frac{1}{h_0^{\frac{n+1}{n}}} + \left(\frac{F}{R^{n+3}} \times \frac{n+3}{2\pi K} \right)^{\frac{1}{n}} \times \frac{(n+1)t}{2n+1} \right)^{\frac{n^2}{n+1}} \qquad (7)$$

with the velocity of tongue $v = 2\ cm{\cdot}s^{-1}$, normal force $F = 1$ N, radius of plug $R = 2.5$ cm, time $t = 1$ s, initial plug height $h_0 = 0.2$ cm and the Herschel–Bulkley parameters yield stress t_0, consistency index K and flow index n (*see Table 2 for the corresponding psychophysical results*).

Deblais et al. (2021) considered that the perceived thickness of the food product is proportional to the shear stress (σ) at the surface of the tongue (inspired by Thomazo et al., 2019), and that it is this stress that squeezes out the food product from the gap between the tongue and the palate. On that basis, the authors developed a mathematical model (Eq. 8) that is closely related to Schädle et al. (2022) (Kokini OSS), to calculate the viscous shear stresses on the tongue due to the food (some viscous bouillons), for predicting oral thickness from rheology:

$$\sigma = KV^n h_0^{-1} \left(1 + \frac{(n+1) F_N h_0^{n+1} V^{1-n}}{2\pi n K R^4} t \right)^{\frac{n}{n+1}} \qquad (8)$$

where σ is the total viscous stress exerted on the fluid by the tongue (similar to Kokini OSS), K and n represent the consistency and the flow index respectively, from rheological data, h_0 is the initial gap between the tongue and the upper part of the oral cavity, R is the radius covered by the viscous food product on the tongue, F_N is the lingual force and t is the characteristic time (s) needed for assessment (i.e. the residence time for the liquid product during the sensory test) (Deblais et al., 2021).

4 Importance of Texture Psychophysics in Food Science

An important issue in product design is to know the magnitude of a material property to be manipulated before a change in sensory perception can be detected (Zahn et al., 2013). Therefore, when developing new food products or optimizing existing ones, one needs a reliable indicator of sensory texture discrimination and preference, particularly when designing foods for individuals with special needs (Liu et al., 2022). The *raison d'etre* of psychophysics is to test the consumers' ability to recognize and differentiate stimuli. Its core element is the *sensory threshold*, which measures the acute sensitivity of humans to an external stimulus (Niu & Lo, 2022). This basic element positions psychophysics as a tool usable by product designers to understand how components (stimuli) drive responses (user perception) (Niu & Lo, 2022; Lie-Piang et al., 2022b). In the section below, the motivation for texture psychophysics in food research is presented.

4.1 Texture Psychophysics and Novel, Alternative, Healthy and Sustainable Foods

Companies have been challenged with redesigning products to offer more appealing textures in a healthy and more sustainable way, and this has brought researchers head-on to the question of how food structure translates into perceived texture (Koç et al., 2013; Bikos et al., 2022). To answer this question, one needs a deeper understanding of food biophysics and chemistry, as well as the sensory psychophysical principles that govern food oral processing and texture perception. Texture psychophysics plays a critical role in the development of new, sustainable food products from alternative biopolymers. Psychorheology acts as a tool to drive the optimization of sensory perception and hedonic ratings throughout the food texture design process. As an example, fat is important for energy provision, essential fatty acids, and for food pleasantness (Rolls, 2020). However, the intake of fat must be controlled for health reasons. In order to successfully develop new and healthy foods with the mouthfeel and creamy perception similar to fat based on alternative ingredients, an appreciation of the psychophysics of how fat is sensed in the mouth becomes critical (Rolls, 2020; Blok et al., 2020; Ma & Chen, 2023). In this case viscosity-inducing polysaccharides and other hydrocolloid variants come as prime candidates for use as fat replacers, viscosity modifiers and water binders (Theocharidou et al., 2021). Nonetheless, insights on how varying their proportions in a formulation would affect texture perceptions need psychorheological consideration.

Akhtar et al. (2006) reported that some food emulsion samples with the same apparent viscosity prepared from different fat replacers (maltodextrin and xanthan) gave significantly different levels of perceived creaminess (Table 1). In another study, Zahn et al. (2013) observed a psychophysical perceptual shift in oral tactility (viscosity and creaminess) of some dairy-based emulsions, due to ingredient substitution in the formulation. The viscosity JNDs when manipulating fat content were much lower (0.04–0.08) than for samples where locust bean gum content was manipulated (0.07–0.11). The authors showed that when fat-replaced formulations were not corrected for viscosity (by making the solutions iso-viscous), it was easy for the subjects to distinguish emulsions with different fat or locust bean gum content based on creaminess and viscosity.

Oral lubricity is another essential driver of food hedonics, which is governed via frictional mechanisms. However, the precise correlation between coefficient of friction and texture in many foods is still less clear due to a gap around the relationships between tribology and sensory perception (Vieira et al., 2020). Many non-fat substances can produce low coefficients of sliding friction, including some polysaccharides, providing potentially healthier alternative food ingredients with a desirable fat-like mouthfeel (Mills et al., 2013). As consumers transition to flexitarian and even more plant-based diets, psycho-rheological impact can be anticipated on product liking. Formulation science must respond appropriately with novel ingredients to achieve optimal suprasensory tactile thresholds, and adapt processing technology accordingly to promote similar or superior magnitudes of product texture perceptions in the market.

4.2 Texture Psychophysics, Quality Control and Marketing

Psychophysical laws quantitatively relate the sensory perceptual magnitude to stimulus intensity (Zeng, 2020), and may have a quality control function in food science through, for example, the application of different sensitivity measures such as the detection thresholds, JNDs, and the *d prime* (*d*′). The *d*′ is a sensitivity index based on signal detection theory, which is mainly used in sensory difference methods (e.g. duo-trio, triangle, 2-AFC and 3-AFC) to estimate the discriminability between two stimuli (Brockhoff et al., 2016; Pellegrino et al., 2021). A *d*′ = 0 (i.e. 0.5 correct responses) represents identical samples/no difference, while a significant positive or negative *d*′ value corresponds to the test product having the strongest or weakest intensity of the attribute in question (Linander et al., 2019). The detection threshold describes the minimal stimulus intensity that can be perceived, while the JND addresses stimulus intensity discrimination: the quantitative difference between two sequential stimuli that have distinct sensory intensities (Kim et al., 2020). Food texture quality is dependent on systematic design, formulation, structuration, and careful planning and monitoring of process conditions. Therefore, investigating how physical properties relate to psychophysical sensory responses supports stronger links between materials science and product design (Howes et al., 2014; Miodownik, 2007).

Understanding the psychophysical principles of sensory perception is required for establishing reliable correlations between instrumental food characterization and human sensory perception (Chen, 2014). Although there is substantial knowledge regarding the influence of specific material properties on affective consumer responses, the effect of tactile perception on pleasantness in more realistic scenarios is lacking, such as when interacting with products that have a combination of material properties (Post et al., 2023). This is especially so regarding food. In such instances, psychophysics would provide product designers with indications into any potential or existing product blind spots, significant defects or predictable consumer hedonic responses to allow targeted quality design and reduce market failure risk. Such knowledge would be important in the development of tactile branding, and production of quality food products for healthier human consumption (Howes et al., 2014; Spence & Gallace, 2011). Properties such as texture bring about aesthetically pleasing tactile experiences to consumers when interacting with products, and play a vital role in the persuasive efforts marketers engage in to drive new product adoption and increased sales (Gallace & Spence, 2014).

An interesting behavioural trend that is also attracting the attention of food product designers is consumers' demand for less processed ingredients and foods. Less refined ingredients inherently require less processing steps and, therefore, are generally more sustainable (Lie-Piang et al., 2021). However, mildly refined food ingredients are often prejudiced as inferior quality due to their complex multi-functional behaviour (Lie-Piang et al., 2022a). Food products can be formulated from mildly refined ingredients, by relating their techno-functional properties to the targeted textural responses (e.g. final viscosity and gel stiffness), concurrently optimizing for nutritional quality and sustainable resource utilization (Lie-Piang et al., 2022a, b). The driving force of food psycho-rheology is the acquisition of a better understanding of the sensory perception of all the physical properties of foods (Guinard & Mazzucchelli, 1996). To realize this goal, the texture perception and mouthfeel properties of newly developed products are predicted through psycho-sensory investigations before product market introduction (Rauh et al., 2012).

Psychophysical expertise is also a prerequisite for the achievement of ideal food product qualities in designing specific, premium products such as a well-tempered chocolate with a desirable smoothness, a slow melt in the mouth and a snap bite (Peyronel & Pink, 2021). For instance, Breen et al. (2019) found that naïve consumers could discriminate between different chocolate samples based on oral grittiness (particle size JND ~5 μm; K_W ~0.17). Gritty chocolate that falls out of the critical quality control limits can be creatively used to manufacture novelty chocolates and other food products with a different mouthfeel profile (Peyronel & Pink, 2021). Psycho-rheology can also be used for market segmentation, to better understand the market through clustering consumers based on tactile sensitivity phenotypes (see Withers et al. (2013) and Breen et al. (2019)). Using signal detection theory and the *d*′, Pellegrino et al. (2021) found that individuals with high touch sensitivity could confidently discriminate liquid food stimuli by its mouthfeel (oral viscosity), while those with low touch sensitivity required more than texture modality to discriminate the fluid food samples. Similarly, individuals with different levels of oral hardness sensitivity were found to differ in their judgments of oral hardness perception and liking of jellies (Puleo et al., 2021b).

The preceding discussion speaks to the potential role of psycho-rheology in quality control vis-à-vis critical limits because, as a matter of definition, variations below the JND will presumably not be noticed by consumers (Breen et al., 2019). The highly sensitive consumers (high K_W and n_p) may be significantly responsive to food texture deviations, affecting hedonic ratings and product market success. Nonetheless, it is important to acknowledge that these sensitivity parameters vary with food samples, subjective texture attributes and with individuals or different consumer populations. Guinard and Mazzucchelli (1996) submit that psychophysics can also help to improve current instrumental techniques and sensory methodology for measuring texture. In this regard, combining the material measures under mechanical, thermal and frictional action with sensory studies will give better insights about food oral processing and hedonic responses (Bikos et al., 2022). This is relevant given that in many instances, the results of empirical rheological measurements alone have failed to show whether instrumentally observed food textural differences can be perceived by the human subject (Rohm & Raaber, 1992).

4.3 Sensory Texture Claims Substantiation

Another area where psycho-rheology could find practical relevance is in making product sensory claims. A product claim is a statement about a product that highlights its advantages, sensory or perceptual attributes, or product changes or differences compared to other products to enhance its marketability (ASTM E1958-20, 2006). We may soon begin to see texture-related food sensory claims, such as '*creamier than x*' and '*texturally equivalent to x in stickiness or thickness*'. Any sensory texture claims made should be more defensible. A superiority claim is supported if a statistically significant proportion of the respondents prefer the advertiser's product (ASTM E1958-20, 2006). A hedonic claim is broadly concerned with measuring the degree of liking and preference (overall or limited to one or more specific attributes), while attribute/perception claims apply to intensity when measuring one or more specific product attributes (ASTM E1958-20, 2006). Psycho-rheology could potentially be used as basis for sound scientific evidence/substantiation in litigations involving sensory texture-related product claims, representing a potentially effective case resolution method for both the defendant and the challenger.

4.4 Texture Psychophysics Across the Life Cycle

Psycho-rheology could improve our understanding of the biophysiological processes of eating and swallowing to support special food product innovations across the life cycle. Oral tactile sensitivity may be related to physiological measures such as bite force, oral capacity, dental health, jaw muscle activity and saliva production (Liu et al., 2022), which varies amongst infants, young children, healthy adults and geriatrics. With this motivation, Shibata et al. (2017) applied psychophysical principles to develop a robotic sensing system, and used it to evaluate the oral dynamic texture (elasticity, smoothness, stickiness and granularity) of gel-like foods. The robotic system successfully predicted the human sensory evaluation values for 23 types of gel-like foods ($R^2 > 0.92$). Similarly, Lavoisier et al. (2022) developed a novel soft robot to investigate the swallowability of therapeutic agents (delivered through fluid food carriers such as yoghurt and apple puree) by children and the elderly. These efforts would benefit immensely from psychorheological insights. Despite the current advances

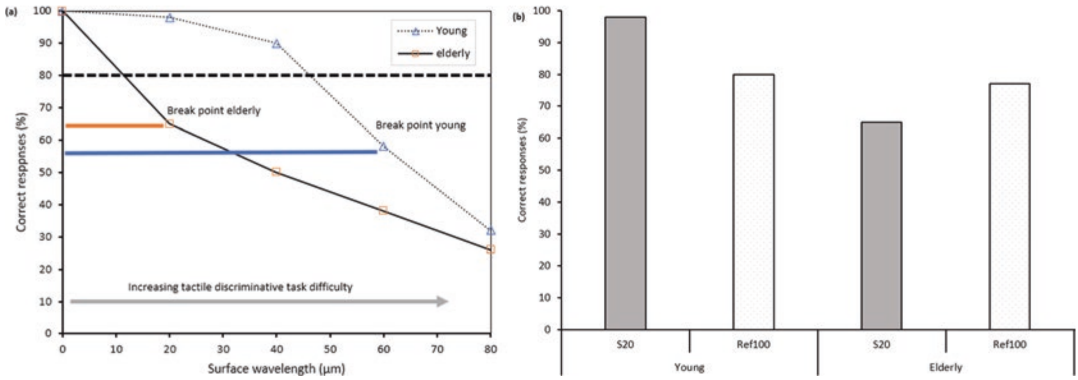

Fig. 5 Tactile discrimination ability for young and elderly participants in a finger-sensitivity task. (**a**) Proportion of correct answers in identifying a stimulus different from the reference, Ref100 (100 µm in wrinkle wavelength). The 'break point' (here defined as when the success rate falls below 80%) was S20 (20 µm) for the elderly group, and S60 (50 µm) for the young group (n = 30 for both groups). (**b**) A plot of the means from each participant in the two groups ($n = 2 \times 30$), showing the tactile discrimination ability of S20 versus Ref100 as well as the correct responses for Ref100 versus itself. (Redrawn from Skedung et al., 2018)

in psycho-rheology, a lot is still unknown about the driving mechanisms for tactile perceptions arisng from sliding friction between soft surfaces for instance, making it a challenge to recapitulate the full haptic (and oral) experience for both human applications and robots (Peng et al., 2021).

Tactile perception weakens with age, inducing physical and emotional dysfunction amongst elderly people (Kremer et al., 2007; Abdouni et al., 2018; Liu et al., 2022). Several reasons have been suggested to explain the loss of textural acuity in adults, including poor dentition (Roininen et al., 2003; Zhang et al., 2022), sensory decline with aging (Morley, 2001), social factors, polypharmacy/medications, physical and physiological issues (Donini et al., 2003). Touch sensitivity to food thickness might predict overall texture perception and preference (Liu et al., 2022). Age affects the mechanical properties of the skin as well as neurophysiological capabilities for the detection, transmission or interpretation of touch signals (Skedung et al., 2018). Conroy et al. (2017) showed that elderly consumers were not able to differentiate between the tenderness categories of beefsteak relative to younger consumers in a sensory evaluation task. Poor identification of tenderness classification was found in the 71–85 age cohort. If texture sensitivity in elderly people reduces significantly, they may not enjoy meals due to food anhedonia, which can affect their health status and quality of life. An indifference to consuming various food products will result in malnutrition and other life-limiting diseases (Conroy et al., 2017). A study by Skedung et al. (2018) on texture discrimination of surface roughness by fingers in young and elderly participants showed that elderly participants had significantly reduced finger tactile acuity (Fig. 5).

The elderly group also showed a reduction in the biomechanical properties of their skin (finger moisture, elasticity and friction coefficient). Skin morphology and hydration have been reported to contribute to the 'feel' of an object (Carpenter et al., 2018). Finger or skin features such as hydrolipid film, and environmental variables (e.g. temperature and humidity) can modify the finger characteristics and sliding conditions like normal load and velocity (Messaoud et al., 2016). Moderate moisture increases the friction of the skin, while in wet skin conditions, the film of water formed can act as a lubricant in mixed or hydrodynamic regimes (Tomlinson et al., 2011).

Skedung et al. (2018)'s findings were in agreement with the lower power law exponents (suggesting poorer viscosity discrimination with age) previously reported for older participants (<70 years), in oral and oropharyngeal perceptions of fluid viscosity (Smith et al., 2006; Steele et al., 2014). It would be important to consider conducting more psychophysical studies focusing on how bio-tribological properties change at the finger-palm or tongue-palate systems in elderly people, to identify the cause of tactile sensitivity deterioration with age for informing potential interventions. Such research could be used as guidelines for industrial uptake in designing tactile-friendly food products for the elderly (Conroy et al., 2017).

4.5 Texture Psychophysics in Health and Disease States

Despite the important role of oral texture perception in feeding and nutritional homeostasis, there is a view that its impairment has not been of particular clinical interest, and to date, clinical protocols to evaluate its acuity are either inadequate or not available at all (Furukawa et al., 2019). As with touch sensitivity in good health, the assessment of texture psychophysics during disease is important. Sensitivity to specific food texture attributes such as thickness might predict texture perception, swallowing comfort or ease, and preference, yet pathological changes may have negative influence on the somatosensory system and tactile sensitivity (Liu et al., 2022). Food texture psychophysics plays a critical role in determining what is fit for consumption by people suffering from mastication and swallowing disorders (Wagner et al., 2017). Changes in sensory sensitivity can lead to inadequate dietary behaviour and consequently increase risk of malnutrition (Schiffman, 1993). In some cancer patients, dysgeusia has been shown to reduce spatial tactile acuity, causing a negative impact on oral texture sensitivity and perception (Bogdanov et al., 2021). As confirmed by Schimmel et al. (2017), stroke, for example, may affect intraoral tissue tactile sensitivity contralesionally, potentially affecting food texture appreciation. Psychophysical studies among head and neck patients (n = 7) also showed reduced oral tactile function, but its correlation with food texture perception remains elusive (Riantiningtyas et al., 2022).

Cazzolla et al. (2022) observed alterations of oral tactile (food consistency) sensitivity (plus thermal and taste dysfunction) in a study involving 1155 patients with mild or moderate COVID-19 through a questionnaire and inflammation biomarker tracking. The alterations in food texture perception were hypothesized to be due to direct damage of filiform papillae by tissue inflammation, allowing virus binding to cell surface angiotensin-converting enzyme 2 (ACE2) receptors of the filiform papillae-containing cells (Cazzolla et al., 2022). The filiform papillae damage leads to immediate alteration of tactile and thermal sensitivity, arising from the action of the virus through spike proteins (Cazzolla et al., 2022). Oral tactile sensitivity alterations seem to be a function of the extent of neuronal and tissue impairment from the pathological condition, which would lead to tactile disturbance (Liu et al., 2022). Filiform papillae are bundles of thin protrusions (0.3- to 0.9-mm long) on the tongue, which play a large role in oral texture perception (Colijn et al., 2022). The SARS-CoV-2 virus binds via its spike protein to the cell surface ACE2 located on the filiform papillae to gain cell entry (Wang et al., 2020). The cell entry receptors of SARS-CoV-2 have been identified in salivary glands (Zhu et al., 2022) and the oral epithelium (Xu et al., 2020).

Few patients, however, were enrolled in the described study, which applied survey-type questions with yes/no answers for disorder identification/evaluating oral tactile acuity alterations. Larger studies using systematic psychophysical approaches are needed for confirming both the observed oral texture perceptual alterations in conditions such as COVID-19 and the mechanisms for texture sensitivity changes that have been advanced. In a separate investigation on the lingual tactile sensitivity of patients with subjective taste disturbance, taste dysfunction was also found to impact on oral mechanosensitivity and oral texture perception (Bogdanov et al., 2021).

Appreciating the psychophysics of oral texture could lead to more effective treatment options for potentially life-threatening conditions, such as dysphagia (Thomazo et al., 2019).

Studies on viscosity discrimination for non-Newtonian thickened liquids in the nectar- and honey-thick range (51–1750 mPa s at 50 s^{-1}) prescribed by the National Dysphagia Diet (NDD) revealed the possibility of several increments of detectably different viscosity magnitudes (JNDs) within the ranges proposed then, for nectar- and honey-thick liquids (Steele et al., 2014). Ong et al. (2018) also observed that within the same International Dysphagia Diet Standardization Initiative (IDDSI) level (which represents a range of viscosity behaviour or flowability) further differences in sensory properties were distinguishable based on the thickener used for thickened liquids, and the medium being thickened (Kongjaroen et al., 2022). The importance of understanding how large viscosity differences need to be, in order to be perceived or discriminated in the mouth during swallowing, is therefore recommended (Steele et al., 2014). Patients with sensory alterations show altered food behaviour including food aversion, modified food preference, reduced appetite and lower food enjoyment, leading to lower food intake and malnutrition (Riantiningtyas et al., 2022).

4.6 Psychophysics and Ingestive Behaviour

Although food texture is a key element of ingestive behaviour, a detailed understanding of its perception in humans currently remains elusive (Thomazo et al., 2019). Food and eating experience cannot simply be explained by ingredients' materiality without regard for how people perceive the food (Lee et al., 2019). Guinard and Mazzucchelli (1996) stated decades earlier that understanding how and what is perceived in response to different texture stimuli is developing slowly, compared with advances in other branches of sensory physiology. The knowledge of psychorheology is becoming indispensable in food texture innovations. Understanding variations in sensory sensitivity between different consumer groups might help to better appreciate differences in food choice behaviour and food preferences between groups (Ketel et al., 2022). The significance of texture psychophysics is also apparent in oral processing behaviour; for instance, an animal must make assessments of the food's hardness and viscosity to exert the appropriate force to chew or ingest (Foster et al., 2011; Koç et al., 2013). Insufficient chewing force would cause poor food processing, while excessive force can hurt the tongue or teeth (Zhang et al., 2016).

Food texture also moderates both food intake behaviour and metabolic response to ingested nutrients (Forde & Bolhuis, 2022). Pellegrino et al. (2019) observed that the psychophysical ability to detect viscosity changes in milk samples of varying viscosity was linked to the assessment of caloric density, satiety and satiation, with reported oral viscosity JNDs of approximately 0.3 mPa·s. Such findings have implications for the design of low-energy-density satiating foods. Future research is needed to determine whether texture-based acute differences in eating rate and energy intake can support longer-term reductions in eating speed and energy intake for positive health outcomes (Janani et al., 2022). Psychophysics has become a tool by which to understand how ingredients drive consumer responses regarding the perceived sensory intensity of some property in foods or beverages, or the degree of liking (Moskowitz, 2020). A better psychophysical understanding of how texture and mouthfeel are perceived should allow food scientists, nutritionists, dietitians and food manufacturers to inform food design, potentially predict metabolic responses to specific food consumption or infer food product acceptance in a more systematic way.

5 Texture Psychophysics of Food Systems

5.1 Texture Psychophysics of Liquid and Semi-Solid Foods

5.1.1 Thickness Perception and Viscosity

Fluid foods constitute a significant portion of food intake in human diet. Foods such as sauces, dressings, mayonnaise and pastes among others are characterized by a coherent but weak structure that allows oral processing with minimum or no mastication (Theocharidou et al., 2021). In these foods, viscosity is one of the several texture properties of importance to consumers, often described sensorially in terms of thickness. Cutler et al. (1983) studied the viscosity of various Newtonian fluid foods (golden syrup, maple syrup, rosehip syrup, fresh milk and various dilutions of honey) by both oral sensory evaluation and instrumental measurements, obtaining a power law index of only 0.22. Such a very low power index seemed to suggest that a human mouth is much less sensitive in detecting viscosity change. This, however, is very unlikely given the extensive innervation of the oral system and its dense somatosensory system. Lv et al. (2017) recently reported a power law index of only 0.54 based on the finger-palm system. Further research is still required to enable more robust and precise predictions of oral thickness perceptions from the food physical parameters.

Creaminess and spreadability are other extremely important viscosity-related quality attributes with a significant influence on product acceptance in fluid foods (Singham et al., 2015). Creaminess is particularly a complex sensory attribute that is affected by friction-dependent, fat-related and viscosity-related perceptions (Akhtar et al., 2006; Zahn et al., 2013; Blok et al., 2020). In efforts to decrease the fat content of a fluid food system while maintaining suitable viscosity, one method is to exploit the rheological principles of particulate suspensions. The degree of viscosity increase in fluid suspensions depends mainly on the particle volume fraction, φ (at $\varphi < 0.2$, (Metzner, 1985)). Optimizing or increasing the polydispersity/particle size distribution (PSD width) for a given φ, by adding coarse particles within specific limits for instance, would decrease suspension viscosity (Do et al., 2007). The mechanism is that, under flow, small particles act as a lubricant for the flow of larger particles; their presence reduces the overall viscosity (Servais et al., 2002). This procedure however may lead to a 'gritty/sandy' textured product. Also, as the particle volume fraction approaches maximum value (φ_m) with increasing suspension concentration, viscosity rises dramatically due to significant particle–particle interactions (Do et al., 2007).

Regarding fluid foods, Liu et al. (2022) submit that an individual's tactile sensitivity is linked to their psychophysical thickness perception, which essentially defines their capability to discriminate differences in the viscous nature of foods. More viscous foods are also often perceived to be more slippery than less viscous ones (Blok et al., 2020). According to Kokini and Cussler (1987)'s model, slipperiness is proportional to both the frictional and viscous forces on the tongue.

A key challenge to sensory psychophysical analysis of fluid food viscosity, however, is the uncertainty of the rate of actual deformation in-mouth and upon deglutition (Lv et al., 2017). The human swallowing process involves a range of shear rates, and in vivo food deformations are unlikely to be purely shear as in a rheometer (Hanson et al., 2019). Additionally, it is often difficult to establish consensus sensory terms to describe specific food material properties, yet such insights guide formulation procedures to generate targeted sensory texture percepts in food products. In terms of mouthfeel thickness and oiliness perceptions of fluid foods, Huang et al. (2021) showed a positive and negative relationship between human sensory ratings and the instrumentally measured viscosity and coefficient of sliding friction, respectively. The high-fat liquids were more viscous and slippery, and perceived as thick with oily mouthfeel by human panellists (Huang et al., 2021). Deblais et al. (2021) used an improved biophysical model which accounts for in vivo squeezing flow phenomena during liquid food consumption, instead of correlating thickness perception to viscosity at a single shear rate. Fig. 6 shows the relation between the 'subjective thickness' assessed by the sensory panel and the total shear stress on the tongue, as determined by Deblais et al. (2021).

5.1.2 Grittiness and Smoothness Perception: Particle Size, Friction and Matrix Effects

The presence of particles in food impacts mouthfeel sensorial perception via increased grittiness, chalkiness, graininess, dryness or reduced

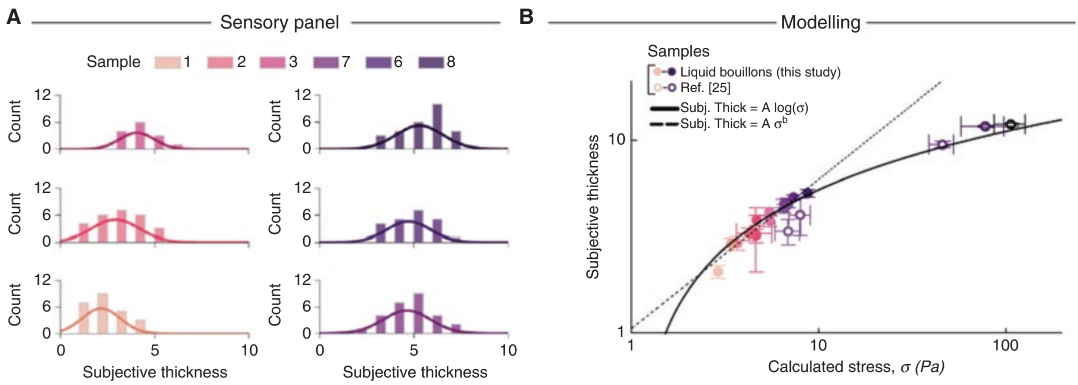

Fig. 6 Predicting the mouthfeel 'thickness' of a thin liquid sample. (**a**) Typical 'subjective thickness' distributions obtained from panellists (five typical samples are shown). (**b**) The black continuous line indicates a logarithmic dependence (Fechner's law), while the black dotted line shows Stevens' power law relationship. (Adapted from Deblais et al., 2021)

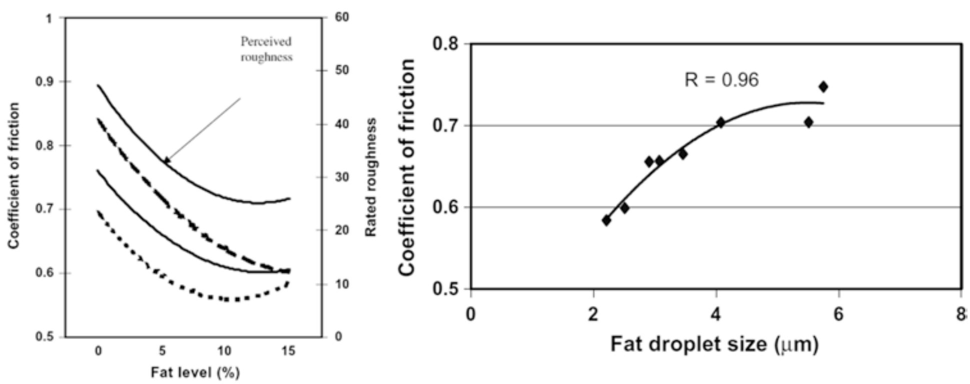

Fig. 7 Left: Fat level of vanilla custard desserts versus perceived roughness (solid grey line), friction of vanilla custard as is (solid black line), diluted by 15% ww of water (dashed black line), or broken down by 15% w/w of stimulated saliva (dotted black line). Right: Effect of fat droplet size on the coefficient of friction, measured by Confocal Laser Scanning Microscopy (CLSM) image analysis in mayonnaises. (De Wijk & Prinz, 2005)

creaminess, and is dependent on the food matrix phase and the particle size, modulus, shape and concentration (Mantilla et al., 2020, 2022). Receptors localized on the tongue, palate, jaws and teeth act in the perception of the granulometry and consistency of foods respectively (Morell et al., 2017; Liu et al., 2022). Hard or sharp particles in food are more easily detected than softer or more rounded particles (De Wijk & Prinz, 2005). It has been reported in some yogurt samples (Varela et al., 2021) that a more viscous and thicker food matrix lowers grittiness perception. At sufficiently high concentrations, particles of 5 µm in diameter can be detected as they give rise to sensations of roughness and dryness, while at low concentrations even large 2-mm-diameter particles may be completely missed (De Wijk & Prinz, 2005). Wang, Zhu, Ji and Chen et al. (2021) found that consumers could discriminate the O/W emulsions based on oil/fat droplet size, at least up to nano-sized droplets (d_{90} = 0.3 µm) (Wang et al., 2021). Particle size effect on roughness perception has also been observed in other foods (such as mayonnaises), where increasing fat content above a certain critical limit led to increased friction due to increasing fat droplet size (De Wijk & Prinz, 2005) (Fig. 7).

5.1.3 Fat Perception and Greasiness Detection Thresholds

Oil/fat is an essential source of food palatability, and its oral perception plays a key role in influencing consumers' sensory pleasure and preference for a food product. However, the mechanism for oral sensory perception of oil/fat remains elusive, and two very different theories have been advanced: the fatty taste theory and the tactile sensation theory (Ma & Chen, 2023). This apparent lack of clarity on whether the mechanism of oral fat perception is chemical or touch/mechanical in nature shows how complex and potentially multisensory it may be. Recently, the important role of saliva in fat perception has been highlighted (Feron & Poette, 2013; Ma & Chen, 2023). Feron and Poette (2013) proposed a model/mechanism for the involvement of salivary variables in mouthfeel detection, perceived fat-related sensory qualities and their intensity (creaminess, melting and smoothness) and preference patterns toward oil-containing foods (Fig. 8).

Feron and Poette (2013)'s model suggests that salivary components and the shear forces applied during mastication contribute to the breakdown and/or destabilization of fatty matrices in emulsified food systems. This creates mouthfeel perceptions such as creaminess and smoothness.

An alternative theory/mechanism of oral fat psycho-rheology leading to a greasy perception has been advanced by Ma and Chen et al. (2023). It states that oil/fat will be perceived very differently when in bulk phase compared to when it is in dispersed status. It is suggested that oil/fat ceases to exist in the bulk phase following food intake, but rather as dispersed droplets covered by a layer of salivary proteins (Ma & Chen, 2023). Therefore, the oil-holding capacity of saliva determines the sensation threshold of greasiness, which occurs when the amount of oil/fat in a food system exceeds one's capacity of oral emulsification. In their protocol (Fig. 9), the *threshold of greasiness sensation* is the oil content of the sample corresponding to the transition point from 'non-greasy' to 'greasy' in a sensory detection assessment task.

For fat-rich food, consumers' hedonic evaluation typically transits from a pleasant 'fat and/or creamy perception' to an unpleasant 'greasy and/or fatty perception' with increasing oil content (Ma & Chen, 2023). Considering the effect of oral emulsification, if the amount of oil/fat present in a food is relatively small, a stable saliva

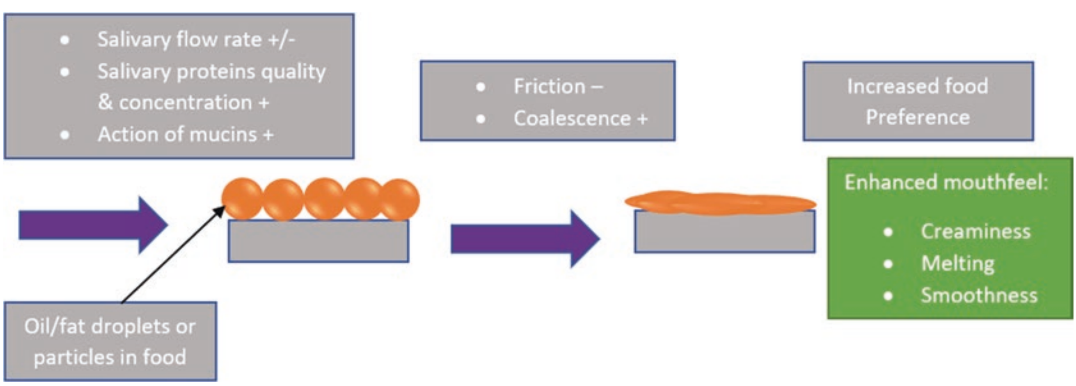

Fig. 8 Proposed mechanism for the role of saliva in fat texture perception and preferences. During oral processing, salivary flow, salivary protein concentration and mucins contribute the most to the destabilization of the food emulsion. Salivary flow participates in the clearance of the product from the surface of the tongue. High levels of proteins and mucins favour the flocculation and coalescence of the emulsion, principally by depletion phenomena and charge attraction. All these in-mouth processes favour the retention of the product on the tongue surface, enhancing the hedonic response to fat texture. In emulsions with low hedonic values, low salivary flow leads to longer oral clearance and thus to enhancing the perception of undesirable characteristics and rejection of the product. (Redrawn from Feron & Poette, 2013)

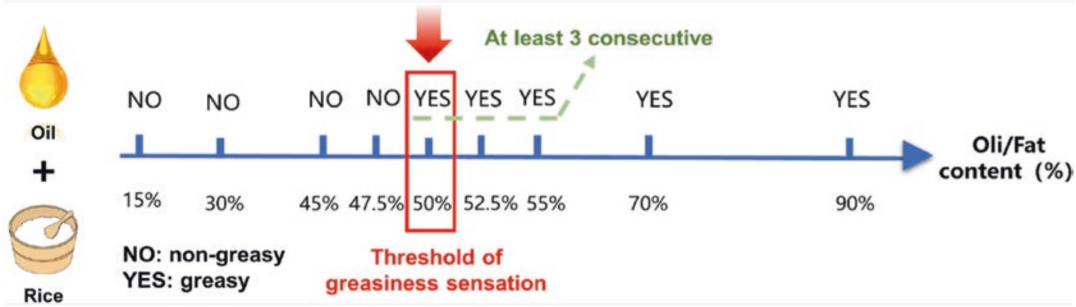

Fig. 9 Schematic protocol of the ascending method of the threshold of greasiness sensation. The threshold of greasiness sensation was designed to be the transition point from 'non-greasy' (answer: *no*) to 'greasy' (answer: *yes*) when tasting a series of samples with different oil contents. The oil content of the sample corresponding to the transition point was considered the threshold of greasiness sensation. (Adapted from Ma & Chen et al., 2023)

emulsion will be formed during oral processing and oil/fat will be converted into a dispersed phase. However, once the amount of oil/fat exceeds the upper limits of saliva emulsification, the saliva is no longer capable of holding oil/fat in stable emulsion droplets, and a continuous oil/fat film (or free oil/fat) may exist inside the oral cavity (Ma & Chen, 2023). It is very likely that once free oil/fat starts to emerge inside the oral cavity, greasiness sensation (unpleasant) starts to occur (Ma & Chen, 2023). However, large inter-individual variability is observed in saliva characteristics, which may lead to variability in fat sensory perception and the different modalities used to detect fat (Feron & Poette, 2013, Ma & Chen, 2023).

These observations give new evidence on the possible role of the oil-holding capacity of saliva in oil/fat sensation, which itself is affected by the physicochemical properties of saliva such as its pH, viscosity and concentrations and nature of small and large biomolecules present in saliva (Feron & Poette, 2013, Ma & Chen, 2023). Ma and Chen's (2023) model of fat perception appears to be robust as a mechanistic theory for greasy perception and detection, while Feron and Poette's (2013) model may explain better the oil/fat perception below the point of greasiness. However, according to the former, emulsion breakdown during food oral processing is responsible for the fat perception, while the latter suggests that emulsion formation with saliva is the basis for fat perception. Further understanding of fat perception will allow for the development of more effective strategies for sustainably reducing fat content in food products.

5.2 Texture Psychophysics of Solid Foods

Ideal elastic materials obey Hooke's law, which describes a direct proportionality between the stress (σ) and the strain (γ) via a proportionality constant called modulus (G), i.e. $\sigma = G\gamma$ (Gunasekaran & Ak, 2000). Such materials deform with an applied load finitely and recovers upon removal of the load. The flow behaviour of real solid foods, however, represents a deviation from Hooke's law, and for decades, psychophysics has investigated how food responds to applied forces in the mouth during consumption. When food is compressed and fractured in the mouth, changes in shape, size and contact force are perceived, contributing to the sensory texture perception of the food (Shibata et al., 2017). It is important to quantitatively predict the relationships between the sensory magnitude of perception and the physical intensity of a material property to inform product design (Moskowitz, 2020). Generally, human beings are more sensitive to the change in the elastic modulus or hardness in solid foods ($n_p = 0.7$), than to the change in viscosity or thickness in liquid foods ($n_p = 0.4$) (Stevens & Guirao, 1964).

5.2.1 Softness–Hardness Continuum

Softness and hardness are importance texture percepts relating to the rheological properties of solid food materials. Yet, little is known about how to use tunable fracture mechanics, for example, to control mouthfeel and sensory properties (Tunick et al., 2013). The use of mechanical metamaterials for tunable food mouthfeel experience has so far been underexplored (Souto et al., 2022). Controlling sensory food texture experience is an important topic in food product design (Fuhrmann et al., 2020), since a food's internal structure modulates texture perception. For instance, Lee et al. (2019) reported a strong correlation between the chocolate volume ratio and perceived hardness ($R^2 = 0.72$).

Micro-aeration is one key technique that can be used in the example of chocolate manufacture to reduce hardness, enhance the sensorial tactile attributes such as crumbliness and smoothness, and to create a sophisticated sensorial profile (Haedelt et al., 2007; Rovers et al., 2016). This can be done by dissolving nitrogen gas into the chocolate mixture during manufacture, leading to a chocolate that is soft, smooth and brittle (Bikos et al., 2022). In solid foods, mechanical properties (e.g. Young's modulus, fracture stress and fracture toughness) determine how the material will perform during the first bite, and affect mastication parameters such as chewing speeds, mastication forces and rate of fragmentation (Witt & Stokes, 2015). Based on the Temporal Dominance of Sensation (TDS) method, Bikos et al. (2022) found that micro-aeration modified the psycho-rheological properties of the chocolate system, creating a softer, grittier and less sticky product that melts faster inside the mouth, and with constant sweetness perception, which was unexpected since the mass of sugar particles per unit volume was lower for micro-aerated samples (Bikos et al., 2022) (Fig. 10).

The chocolate structure was also influenced by the coefficient of friction, such that the *control chocolate* with high friction coefficient was

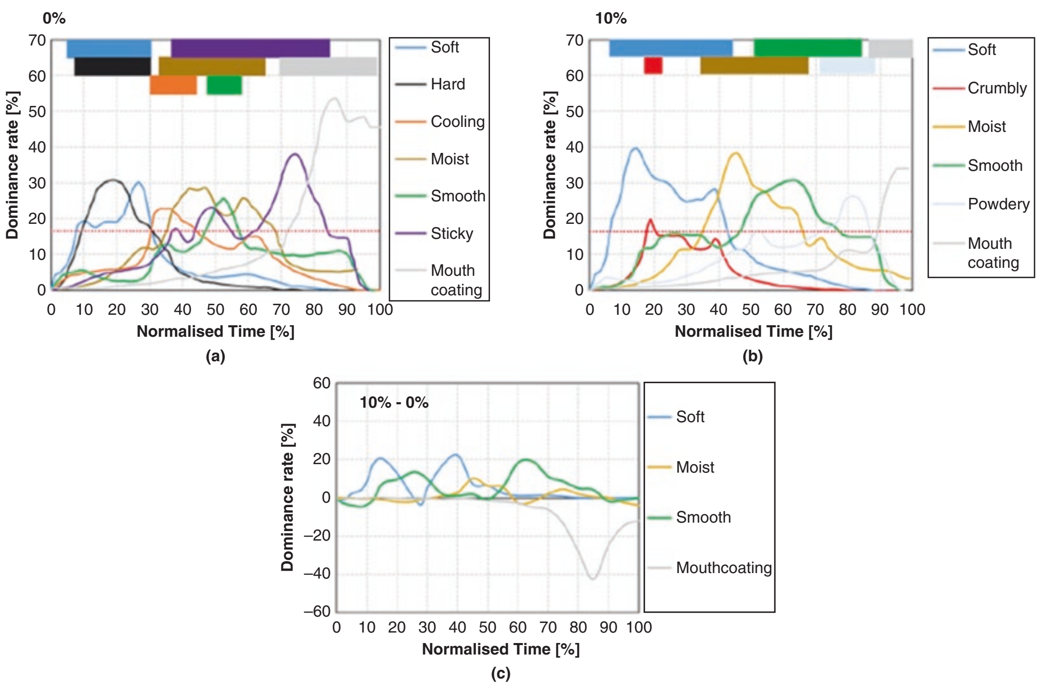

Fig. 10 TDS texture curves for (**a**) the non-aerated, (**b**) the 10% micro-aerated chocolate and (**c**) the difference in the curve between the 10% micro-aerated and non-aerated chocolates. The bars at the top represent the duration of each attribute. The red dotted line represents the significance line. Only significantly dominant attributes were shown in the TDS curve for the micro-aerated chocolate. (Reproduced with permission from Bikos et al., 2022)

perceived as having an oral 'stickiness' sensation, which significantly decreased in the micro-aerated product (Bikos et al., 2022).

Relating the mechanical measurements of foods with sensory attribute ratings, as well as tracking texture dynamics during oral processing, remains difficult (Srivastava et al., 2021). One example also related to chocolate is its melting behaviour in the mouth, which is a complex, dynamic process (Do et al., 2007). Sensory studies describe a melting rate as '*the time required to melt half of a chocolate square when chewed in mouth'* (Guinard & Mazzucchelli, 1999). This points to the temporality of food oral processing, and the urgency for use of temporal sensory methods in texture psychophysics. Recording temporal sensory responses to foods during consumption is important to establish realistic links between the effects of specific structure formation variables in the product and the evolution of sensorial attributes (Bikos et al., 2022). To illustrate this concept, Soltanahmadi et al. (2023) described the dynamic oral tribology during food consumption of a *phase change material* (PCM) exemplified with chocolate. A phase change often occurs through a sequence of dynamic interactions between the ingested food phase change material (PCM) and oral surfaces, starting with a *licking* stage, to a *saliva-mixed* stage at contact scales spanning micro- (cellular), meso- (papillae) and macroscales (Soltanahmadi et al., 2023). For chocolate, initial licking affords a direct contact between the tongue and a solid chocolate, followed by a gradual phase transition from a crystalline solid to a continuous molten fat phase containing suspended cocoa and sugar particles (Soltanahmadi et al., 2023). It has been shown that consumers generally prefer chocolates that *melt quickly* in the mouth, compared to *slow-melting* ones (Bolenz et al., 2000). The use of the terms 'quickly' and 'slow melting' emphasizes the dynamic/temporal nature of food texture processing and perception. However, the sensory perception of *melting* does not only depend on the rate/speed at which a chocolate melts and collapses in the mouth but also among other factors on the fluidity once melted (Do et al., 2007).

Arguably, technological innovations have made possible the design of tongue mimics with topographic filiform and fungiform papillae resembling real human tongues (Andablo-Reyes et al., 2020; Hu et al., 2020). This progress has facilitated our understanding of the micro- and nano-length scale phenomena during food oral processing. Nonetheless, the challenges of recreating the perceptual and psychophysical aspects of eating will probably persist into the future, even as opportunities for neuromorphic sensing and perception increase (Schuman et al., 2022; Bartolozzi et al., 2022). Understanding the temporality and dynamics of texture perception is of huge interest for food scientists who seek to investigate and model consumers' texture perceptions and sensorial experience of foods, based on changes in food structure during oral processing (Renard et al., 2006; Wilkinson et al., 2000; Srivastava et al., 2021).

Further psychophysical studies focused on food textures including cohesiveness, adhesiveness and springiness are recommended to better understand solid food texture perception (Lee et al., 2019). Tao et al. (2020) reported significant positive correlations ($R^2 = 0.85$) between stickiness measured by Texture Profile Analysis (TPA) method (adhesion) and stickiness scored by panellists. Adhesion is a measure of the maximum (negative) force, work or energy (negative area under the force–distance or force–time curve) required to detach a food sample from a surface (Fiszman & Damasio, 2000; Yu et al., 2019). Combining material science approaches/soft matter physics with temporal sensory profiling methods such as TDS, Temporal Check-All-That-Apply (TCATA) and Temporal Drivers of Liking (TDL) will create a clearer understanding of psycho-physical events and processes occurring when humans interact with food during oral processing. For instance, Santagiuliana et al. (2020) showed that the addition of granola pieces to a gritty quark increased liking significantly, potentially due to a hedonic compensation triggered by the introduction of more positive sensations. A prolonged dominance of positive, crunchy sensations was reported while the dominance of negative, gritty sensations was minimized. Similar strategies can be used to shift and increase dominance of positive and liked attributes to compensate for undesired texture sensations especially in novel food products, leading to an increase of overall liking even when some negative sensations may still be still perceived. When regressed with hedonic data, temporal sensory methods allow the product designer to gain a nuanced understanding of what texture attributes may require dominance to be enhanced and prolonged, at what stage, and which ones to subdue and shorten (even eliminate) during food oral processing.

On the other pole of the soft–hard continuum is softness, a perceptual correlate of compliance – defined as the amount of deformation caused by an applied force (Friedman et al., 2008). The capacity of humans to scale the magnitude of softness has not received enough attention (Friedman et al., 2008). For example, it is not known how the perceived magnitude of softness is affected by compressional force between the skin and the object, or what criteria are used to categorize an object as hard or soft (Friedman et al., 2008). Questions also remain unanswered about softness perception caused by friction-related product differences on the skin or skin-like materials (Arakawa et al., 2022). Most psychophysical experiments on soft perception have focused on the compliance of objects during pressing (often by the fingers and rarely orally-which could be more relevant to food), without involving sliding motions (Bergmann Tiest & Kappers, 2014). However, humans also feel friction-induced softness while rubbing surfaces, such that the smaller the friction coefficient of the surface, the softer it feels (Cavdan et al., 2021; Arakawa et al., 2022). Psycho-rheology could be a tool for the design of foods with ideal mouthfeel experiences, if coupled with an understanding of ingredient chemistry and material properties.

Overall, although the sensitivity of the somatosensory system may be influenced by multiple physiological and culture-related parameters, the link between tactile acuity, physiological and consumer characteristics is still unclear. In a study on the sensory sensitivity for thickness, firmness and sweetness between Dutch and Chinese adults, Ketel et al. (2022) found no differences in tactile sensitivities, confirming earlier results by Cattaneo et al. (2020), Komiyama et al. (2007) (between Belgian and Japanese consumers) and Santagiuliana et al. (2019) in grittiness thresholds between the Dutch and Chinese consumers. These findings suggests that texture sensitivity in general might be stable across populations from different geographical locations, cultural backgrounds and ethnicities (Cattaneo et al., 2020; Ketel et al., 2022). Future studies could explore the effect of cross-cultural differences on other texture attributes such as stickiness and chewiness, via the use of large-scale cross-ethnicity comparisons, to fully comprehend tactile sensitivity and consumers' characteristics (Ketel et al., 2022).

6 Food Texture Representation in the Brain

Food texture attributes such as viscosity play an important role in mouthfeel, flavour perception and food preference via the integration of somatosensory, gustatory and olfactory information in the brain (Colbert et al., 2022). Although human beings constantly interact with and experience the sensorial characteristics of different materials on a regular basis, empirical attempts to identify neural correlates of aesthetic/hedonic processing underlying active touch are hardly present (Marschallek et al., 2023). Studies on food texture processing, perception and hedonic responses are even more scant, and the mathematical or psychophysical models used by the human brain for sensory coding/representation remain unresolved (Chen et al., 2021). Fechner seemed to have had a clear notion of what had to be done to translate the study of outer psychophysics to the study of inner psychophysics, when he said (Fechner 1860, p. 56): '*Quantitative dependence of sensation on the [outer] stimulus can eventually be translated into dependence on the [neural activity] that directly underlies sensation—in short, the psychophysical processes—and the*

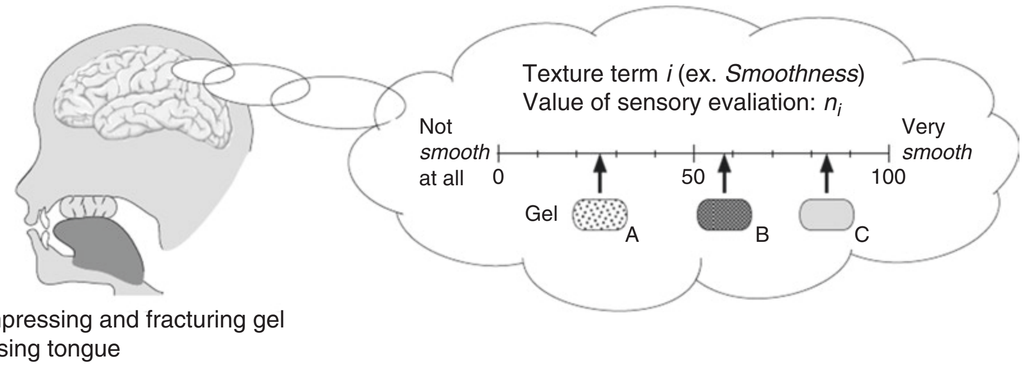

Fig. 11 Modelling how texture values of various gel-like foods are obtained by expert panellists through a sensory evaluation, for estimating the food texture. (Adapted from Shibata et al., 2017)

measurement of sensation will be changed to one depending on the strength of these processes' (Johnson et al., 2002).

It is now understood that human perceptual capabilities arise from the properties of some internal neural representations (Zhou et al., 2022). Inferences from psychophysical and neurophysiological studies indicate that food form/material properties and texture perception are linked via specific neural coding mechanisms (Connor & Johnson, 1992). Shibata et al. (2017) show a visual representation for the translation of the sensation of a food's mechanical properties into some psychophysical texture percept, through some internal neural coding processes during a sensory evaluation task (Fig. 11).

According to Carpenter et al. (2018), forces produced while sliding a finger along surfaces interact with the mechanoreceptors of the skin, to allow the brain to discriminate objects that differ only by surface chemistry, and this enables the sensing of texture perceptions such as the smoothness–roughness continuum. In terms of oral texture, very little is understood about its representation or coding process in the human sensory pathways and the brain (De Araujo & Rolls, 2004). However, we now know that when food is ingested, it triggers signals from the mouth to the brain to assess its eating quality (Paul et al., 2022). The deformation of food over the tongue surface during food oral processing creates clusters of different orotactile stimuli, which are perceived by the mechanoreceptors and then sent to the brain for further processing, including texture determination (Srivastava et al., 2021). Diverse tactile sensations received during eating are transmitted to the brain via the trigeminal nerves, which route through the jaw, tongue, teeth, and oral cavity, all contributing to how the food is texturally perceived (Schifferstein et al., 2020). The factors that influence touch perception are the characteristics of texture, the moving velocity of the exploratory system (finger/oral), and the normal load, among which the characteristics of texture are the most important (Chen et al., 2023).

Oral texture is represented in the brain areas that represent taste: the primary taste cortex, the orbitofrontal cortex (OFC) (Fig. 12, area 12) and the amygdala, with some neurons that show responses correlated with the subjective thickness of food (viscosity) (Rolls, 2020).

Tactile perception begins with the initial sensory and motor processing of the stimuli's characteristics (Gomez-Ramirez et al., 2016), followed by higher-order stimuli processing, such as comparison with previous tactile experiences (McGlone et al., 2012). The activations of the prefrontal regions, specific regions comprised the dorsolateral prefrontal cortex (dlPFC) (mainly in the left hemisphere), the mid-dorsolateral prefrontal cortex (mPFC) and orbital prefrontal cortices, have been related to evaluative judgment, either based on internally and/or externally generated information (Nadal, 2013; Marschallek et al., 2023). Activation of the prefrontal regions may be associated with fine-detailed discrimination and identification of stimuli characteristics

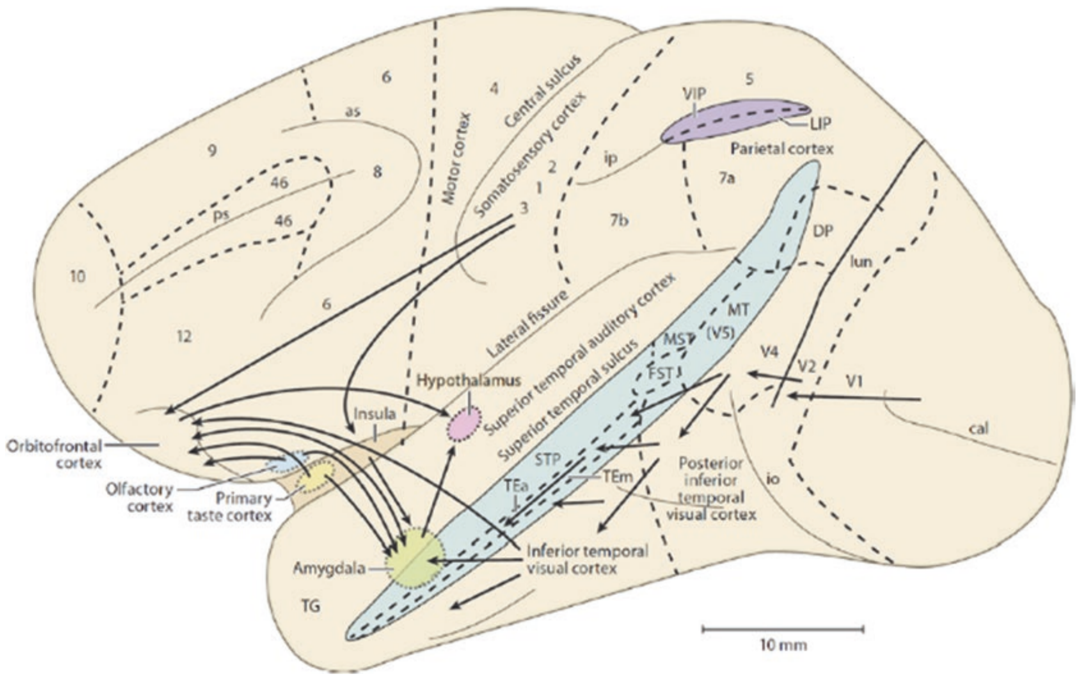

Fig. 12 Some pathways involved in processing food-related stimuli in the primate brain (macaque, lateral view). Numbers represent architectonic areas and their approximate functional equivalence: 1–3, somatosensory cortex (posterior to the central sulcus); 4, motor cortex; 5, superior parietal lobule; 7a, inferior parietal lobule, visual part; 7b, inferior parietal lobule, somatosensory part; 6, lateral premotor cortex; 8, frontal eye field; 12, part of orbitofrontal cortex; 46, dorsolateral prefrontal cortex. Connections from the somatosensory cortical areas 1, 2 and 3 that reach the orbitofrontal cortex directly and via the insular cortex and that reach the amygdala via the insular cortex are shown. as arcuate sulcus, cal calcarine sulcus, cs central sulcus, lf lateral (or Sylvian) fissure, lun lunate sulcus, ps principal sulcus, io inferior occipital sulcus, ip intraparietal sulcus (which has been opened to reveal some of the areas it contains), sts superior temporal sulcus (which has been opened to reveal some of the areas it contains). AIT anterior inferior temporal cortex, FST visual motion processing area, LIP lateral intraparietal area, MST visual motion processing area, MT visual motion processing area (also called V5), PIT posterior inferior temporal cortex, STP superior temporal plane, TA architectonic area including auditory association cortex, TE architectonic area including high-order visual association cortex and some of its subareas TEa and TEm, TG architectonic area in the temporal pole, V1–V4 visual areas V1–V4, VIP ventral intraparietal area, TEO architectonic area including posterior visual association cortex. Connections from the primary taste and olfactory cortices to the orbitofrontal cortex and amygdala are shown. Connections are also shown in the 'ventral visual system' from V1 to V2, V4, the inferior temporal visual cortex etc., with some connections reaching the amygdala and orbitofrontal cortex. (Reproduced with permission from Rolls, 2021)

to gather information that will guide subsequent aesthetic/hedonic judgment (Miller & Cohen, 2001; Marschallek et al., 2023). Marschallek et al. (2023) observed that when participants judged the surface of the stimuli as feeling good (as compared to feeling bad), the left prefrontal areas showed enhanced concentration changes in oxygenated haemoglobin, based on functional near-infrared spectroscopy (fNIRS).

Activation patterns in the orbitofrontal cortex (OFC) (Fig. 12, area 12) are thought to represent mainly analytical processes (e.g. intensity detection and discrimination) (McGlone et al., 2012). The stimulation of C-tactile (CT) afferent nerves mainly activates brain areas crucially involved in discriminative encoding: the detection, discrimination and identification of the stimuli (Case et al., 2016; Mcglone et al., 2014; Olausson et al., 2008; Perini et al., 2015; Marschallek et al., 2023). The activation of the (primary) taste cortex in the anterior insula was demonstrated to be proportional to the log of the viscosity of a

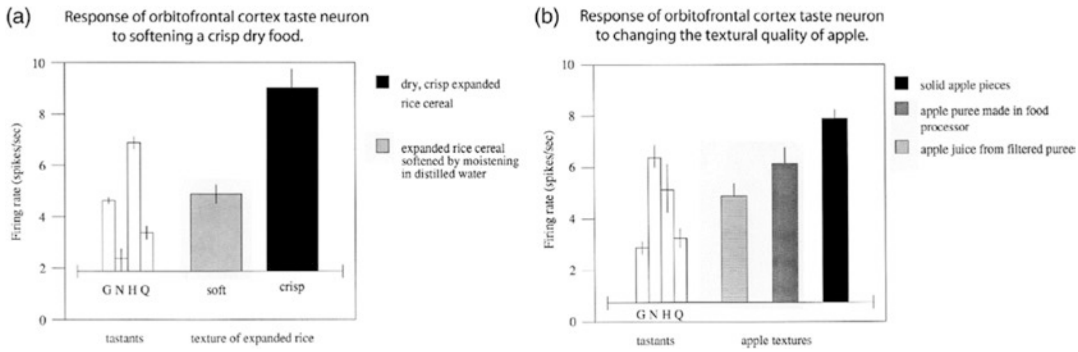

Fig. 13 Effects of altering the textural properties of foods on the firing rate of orbitofrontal cortex taste-responsive neurons: (**a**) A neuron that responded more to the texture of a crispy-dry expanded rice cereal than when it was made soft with water. (**b**) A neuron that responded more to a crisp slice of fresh apple than to a puree made from the apple, which in turn produced a larger response than the apple juice from the filtered puree. The responses of the neurons to 1 M glucose (G), 0.1 M NaCl (N), 0.01 M hydrochloric acid (H) and 0.001 M quinine are also shown. The responses are shown as changes from the baseline spontaneous firing rate of the neurons. (Adapted from Rolls, 2020)

cellulose stimulus (carboxymethyl cellulose) (De Araujo & Rolls, 2004; Kadohisa et al., 2005), indicating that this could be the brain area representing oral food viscosity. Increased activation co-varying with subjective ratings of smoothness and softness was also reported over the sensorimotor cortices using electroencephalography (EEG), following active touch exploration of different non-food textures with the index finger (Henderson et al., 2022).

In terms of affective, aesthetic and hedonic value representations, significant activity has been observed via fNIRS in the contralateral sensorimotor and prefrontal cortices during active fingertip exploration of non-food material surfaces, with smooth materials being perceived as more pleasant (cortical activity increased with perceived pleasantness, especially in the left prefrontal cortex) (Marschallek et al., 2023). Similar studies with food stimuli involving active food oral processing in addition to haptic touch would be important for confirmation. Besides viscosity, other oral textures encoded for (representations) in the insular taste cortex, the orbitofrontal cortex and the amygdala include grittiness and astringency (Schifferstein et al., 2020).

Regarding stickiness perceptual processing in the brain, relatively little is known about its neural mechanisms (Bensmaia, 2016). What is clear, though, is that when we touch a sticky surface with the fingertip, we perceive a sticky sensation when the skin begins detaching from the surface (Zigler, 1923). This perceptual flow tendency can be assessed through TPA or via extensional rheology. Emerging evidence from human neuroimaging studies (e.g. using functional magnetic resonance imaging, fMRI) reveals that surface stickiness, tactile perception and somatosensory information processing are represented in the posterior parietal cortex, supramarginal gyrus (SMG), the supplementary motor area (SMA) and the secondary somatosensory cortex (S2) (Bodegård et al., 2001; Kim et al., 2017, 2020; Lamp et al., 2019). Neural encoding patterns for stickiness perception were observed in the bilateral angular gyri (ANG) and the inferior frontal gyrus (IFG), suggesting that these are the brain regions representing stickiness perception, which also reflected in participants' intensity ratings (Kim et al., 2020). It is believed that these brain regions (mainly the somatosensory cortices, IFG, mid-ventrolateral prefrontal region including the IFG and the S2) represent the key parts of the tactile working memory network (Preuschhof et al., 2006; Spitzer et al., 2010), maintaining material tactile (stickiness) information as short-term storage memory to facilitate evaluative information processing and ratings by participants during sensory psychophysical tasks (Kim et al., 2020).

Neurons that respond to other aspects of texture such as the crisp fresh texture of a slice of apple versus the same apple after blending have also been reported (Fig. 13) (Rolls, 2020).

Regarding fatty mouthfeel, two distinct texture parameters are implicated in fat sensing: viscosity and sliding friction, corresponding to a food's thickness and lubricating properties respectively (Chen & Stokes, 2012; Laguna et al., 2017). Specific neurons in the brain encode fat in the mouth by its coefficient of sliding friction, and not by its viscosity or by its chemical properties (Rolls et al., 2018). However, a study by Huang et al. (2021) reflects that there are independent fat-sensing neurons that receive and respond to separate inputs from viscosity and sliding friction stimuli. The tribological basis for this sensing of lubricity in foods such as cream and milk containing fat is that these fat-responsive neurons respond similarly to hydrocarbons paraffin oil and silicone in the mouth (Rolls, 2020, 2021), evidence that their responses were mechano-specific, not chemo-specific.

Fat-like textures have been shown to reliably elicit fatty, creamy mouthfeel (Chojnicka-Paszun et al., 2012) and activate neural sensory and reward systems in macaques (Rolls et al., 2018) and humans (Grabenhorst et al., 2010; Grabenhorst & Rolls, 2014). Rolls (2020) found that the coefficient of sliding friction is the material property that is orally sensed by the fat-selective neurons in food and transmitted to the brain to provide an indication of the fat content and its pleasant texture in the mouth. Oral fat representation in the brain is frequently in terms of combinations of fat texture with other sensory aspects of food, including taste, other textures and olfactory inputs, and these combinations are important for understanding the cross-modal and multivariate, but full, gestaltic sensory impact of a food in the mouth on pleasantness (Rolls, 2020). This elucidation of the coefficient of sliding friction as the principal transduction mechanism for fat sensing could help the innovation of new and sustainable fat-substituted foods with the pleasant mouthfeel of fat, but better health-promoting nutritional properties. The coefficient of sliding friction (Rolls, 2020) and the degree or rate of evolution of a greasiness perception in the mouth during food oral processing (Ma & Chen, 2023) are some of the useful psycho-rheology measures to consider in the development of new and healthy foods with pleasant mouthfeel.

7 Challenges and Limitations for Food Texture Psychophysics

Opportunities abound for advances in psychophysics as a tool to improve the texture quality of food products. Nonetheless, there are some challenges to contend with. The first obstacle relates to the complex nature of food itself, the geometric nature of the oral system (including its confounding variables like saliva and oral enzymes) and the dynamic nature of oral processing. Changing a single food textural property without modifying other sensory properties, such as flavour, remains very difficult (Camacho et al., 2015). When real foods are used, the incidental modification and interference from other sensory stimuli would influence the holistic sensory perception, consequently affecting psychophysical outcomes and overall product preferences (Chen, 2014; Puleo et al., 2021a). For instance, viscosity is known to affect the psychophysics of sweetness, flavour and creaminess (Zahn et al., 2013; Forde & Bolhuis, 2022). Human beings detect many attributes of a food material simultaneously, making it hard to extract only one attribute without being influenced by other attributes (Nishinari, 2004). Moreover, most foods are non-Newtonian. For meaningful results it would be necessary to match shear rates applied in an instrumental test with those which might be experienced in the mouth, but this is often difficult (Deblais et al., 2021). Oral tactile and food texture sensitivities as predicted by the two-point discrimination, stereognosis or grating orientation tasks have also failed to adequately relate to the perceptions of real food texture, potentially because these measure represent single or limited dimensions of texture perception (Liu et al., 2022).

To control for some of the foregoing challenges as much as possible, the human mouth system has been modelled as two parallel plates (Kokini & Cussler, 1987), a biomechanics approach that is helping our understanding of sensorial signals produced by the food texture in the mouth (Li & Kleinstreuer, 2007; Rauh et al., 2012). Nonetheless, even with these assumptions, there is still a larger debate in the psychosensory field on how the 'strength' of an oral tactile sensation is realistically perceived by humans (Deblais et al., 2021). In terms of food matrix confounding factors, model food stimuli with Newtonian flow behaviour and fairly neutral or iso-intensive chemosensory stimuli are usually selected (e.g. maltodextrin solutions in a study by Camacho et al. (2015)). However, simple food models often fail to accurately describe the complex processes that real foods undergo in the mouth, making it difficult to provide a deeper understanding of the relationship between the mouthfeel of real foods and their rheological properties (Deblais et al., 2021). Additionally, psychophysical texture studies usually use a single attribute (e.g. smoothness) to limit confounding, but this makes them susceptible to biases like the dumping effect (Wang et al., 2022). While dumping effects may be eliminated by use of a trained sensory panel, an untrained consumer panel is considered more representative of the perceptions by consumers (high ecological validity) (Blok et al., 2020).

Instead of using model foods to assess sensitivity to viscosity changes and subsequent estimates of satiety, Pellegrino et al. (2021) prioritized ecological validity and investigated real foods with naïve consumer participants. Similarly, Janani et al. (2022) chose ecological validity and served matched weights of real foods to participants. The challenge of real foods usage, however, is the difficulty of determining the JNDs and Weber's fractions – fundamental quantitative parameters important in product design. Furukawa et al. (2019) used three types of test foods with different dominant textures, each comprising a series of stimuli with different ingredient concentrations, in a pairwise comparison discrimination test. Tests performed using the up-down staircase method revealed a significant correlation among the discrimination thresholds for three test foods, suggesting that acuities of texture perception correlated with each other across different textural attributes. Janani et al. (2022) recommended that future studies could vary texture attributes by an equivalent perceptual margin (JNDs) to ensure that the magnitude of differences between texture manipulations is scaled with the magnitude of perceivable texture differences. A study by Furukawa et al. (2019) proposed the use of discrimination tests for specific aspects of texture, using appropriate test foods as one method for evaluating oral texture perception ability.

Another challenge to food texture psychophysics is the multimodal nature of food texture perception. Just as texture is difficult to define, measures of its perception are elusive, and it is not possible to measure all food properties by only one measurement (Nishinari, 2004). Texture is not restricted to the sense of touch, but rather can be represented by means of vision and audition too (Blok et al., 2020). As Klatzky and Lederman (2010) put it, the 'language' of texture varies across the senses. Engelen (2018) described food texture as the perceived multisensory representation of a food's structure. Texture is also a sensory property with many interrelated facets as hardness, stickiness, cohesiveness, springiness and gumminess (Bourne, 2002), making its psychophysics complex. There is a need for the development of a more robust, next-generation psychophysics that can resolve the psycho-rheology of complex tactile perceptions including derived sensory properties.

Food texture psychophysics is also complicated by the fact that human subjects can have difficulty in disentangling one texture attribute from another (Foster et al., 2011). Although sensory lexicons used with psychophysical scales are useful, they may not be the best representation of the scientific nature of specific texture sensations (Howes et al., 2014). Translating instrumental texture terms such as viscosity, plasticity, elasticity, compressibility, cohesiveness and adhesiveness is subjective due to individual and cultural differences in interpretations (Nishinari et al., 2008). Human assessment of thickness is more experience-based, although the internal psychophysical analysis of the perceived texture like thickness could follow the same physical rules applied in rheometer analysis (Chen et al., 2021). Food psycho-rheology tests are also affected by the oral physiology of an individual, including the role of saliva during oral texture evaluation, and the size and nature of a sensory panel employed (Wang et al., 2022). These considerations make complete psychophysical understanding of important sensory tactile attributes like the perceived 'thickness' more challenging (Deblais et al., 2021).

8 Concluding Remarks

Psychophysics has become such a highly relevant food science discipline in modern times, due to consumers' demands for optimally textured foods, which can deliver good nutrition to targeted consumers in more sustainable ways. Food scientists can rely upon foundational psychophysics to meet these consumer needs. However, while the psychophysical underpinnings laid up by Fechner and others of the time have impacted how food textures can be designed, the principles remain partial, replete with their own limitations, breaking up in certain contexts (e.g. with complex/derived sensory attributes). Psychophysics of food texture has traditionally focused on one sensory stimulus at a time using model food systems, as opposed to multiple stimuli and the use of real foods, which would potentially generate psychophysical insights of high practical value. Psycho-rheological functions from simple model systems would likely deviate significantly from predicted values due to cross-modal interferences when transformed into real, complex and multivariate food products. One recommendation would be to augment the current psychophysical approaches in food (texture) studies, with use of artificial intelligence (AI), machine learning methods, computational modelling, big data analytics and multivariate methods. This will likely improve our understanding of the psychophysical functions between the techno-functional, material and composition properties/intensities of foods and food ingredients, and their corresponding human perceptions and liking responses. Such data-driven psycho-rheological models would relate a sensory perceptual output variable to many input variables and their interactions, for instance through computational and neural networks with capabilities to mimic stimuli processing and scaling in the brain (neuromorphic sensing and perception). Approaches as these would be important for the incorporation of new, complex ingredients into multi-attribute, sensory quality-optimized foods.

For the foregoing to be realized, and given the complex nature of food products, texture design and food value chains, it would be necessary to strengthen transdisciplinary efforts amongst disciplines including physics/material science, chemistry, physiology, psychology, neuroscience, computational science, behavioural science and food science, in the psychophysical investigations of food texture, and food psychophysics generally. Additionally, as the gap between psychophysics and sensory science continues to constrict, researchers need to consider working with (large) consumer panels in psychophysical tests where it is feasible. While certain psycho-rheological evaluations will require some degree of panel training for successful completion, general consumers of a product will have high ecological validity if the main aim is to predict the ultimate consumer perceptual response to the food product. Overall, despite some challenges in food texture psychophysics, limitless opportunities exist for high-impact applications in food science research and innovations to meet the economic imperatives of business, and the sensory and nutritional needs of consumers through ways that ensure a more sustainable global environment.

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Sensory Scaling and Measuring Techniques

Betina Piqueras-Fiszman

1 Introduction and Evolution

Texture, as any other sensory property, should be measured by human beings. Once in the oral cavity, each food piece is handled differently according to its structure and a series of other characteristics that give us clues on how to process it by evoking previous experiences. For example, we will chew a piece of meat repeatedly mixing it with saliva until forming a swallowable bolus. On the other hand, we will normally rub a scoop of ice cream with the tongue against the palate while perceiving how it slowly melts. All these actions, although voluntary, are done instinctively, based on previous oral processing experiences with such products. As is evident, the set of sensations that we can collect from the experiences with these two foods (meat and ice cream) is completely different; however, we are able to describe the "texture" of each food item as a single construct.

Moreover, we humans, as measuring instruments, tend to be variable over time as we are very susceptible to bias (Meilgaard et al., 2007). That is, our response to a stimulus is likely affected by other stimuli in the environment and by expectations from similar experiences. However, despite these "limitations," collecting information about human sensory perception is necessary as there are no machines able to *perceive* texture. Chen (2020) even questioned whether the information measured by machines should be referred to as "sensory property" or simply "material property," which can then aid in predicting sensory perception. At the end of the day, a product's success in the market is determined by how we, as consumers, actually perceive it. Consequently, a variety of standardized sensory testing methods have been developed to be able to measure human perception of food products, of which texture is a part. As such there are no specific methods developed exclusively for textural properties, but textural attributes can be placed at the focus, if the research so requires. Some recent examples will be provided throughout this chapter.

Sensory tests can be mainly classified as being either analytical tests or affective tests (which gather liking information). The scope of this chapter will be the former ones. Analytical tests are used to evaluate product samples in terms of differences or similarities and to identify and quantify certain sensory characteristics. Traditionally, the so-called expert or trained panels are used for these types of tests, but in the last decades methodologies, which also use naive people or consumers, have been developed and are widely accepted. Analytical tests can be divided into two categories: discriminative and

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descriptive. The first type aims at evaluating product samples in terms of similarities and differences, whereas the latter also quantifies these differences in terms of one or a variety of sensory attributes.

In the following sections, an overview of the analytical techniques will be provided, with a focus on the descriptive ones since with these methods one can quantify differences in sensory perception. Each method has a different approach and requires different levels of expertise or training, also with regard to the respective data analysis. However, describing data analysis techniques is not under the scope of this chapter.

2 Methods for Sensory Description

Sensory descriptive methods are among the most widespread methods in sensory science (Stone & Sidel, 2004). Their objective is to generate a thorough qualitative and quantitative description of the sensory aspects of food (and beverage) products. This is also referred to as the characterization of the similarities and differences among a set of products (Lawless & Heymann, 2010). Sensory description has been commonly applied in the food industry for some decades (Meilgaard et al., 2007; Stone & Sidel, 2004). It has been used for a wide range of applications, such as supporting and guiding new product development, tracking changes in formulation or production processes, understanding the changes in composition or structural characteristics that determine certain sensory characteristics, estimating sensory shelf life, correlating sensory characteristics, and physical or chemical measurements, as well as monitoring products in quality controls.

Over the last 70 years, a number of methods have been developed and classically used for sensory description. Some of these were thought for specific characteristics such as flavor (Flavour Profile®; Cairncross & Sjöstrom, 1950; Caul, 1957) and texture (Texture Profile®; Brandt et al., 1963; Civille & Liska, 1975), while others encompassed a mix, such as Quantitative Descriptive Analysis® (QDA; Stone et al., 1974; Stone & Sidel, 2004) and Spectrum™ (Muñoz & Civille, 1998; Civille & Lyon, 1996).

Nowadays, it is common practice to use generic descriptive analysis, which consists of an adaptation and combination of the basic features of Spectrum™ and QDA® (Lawless & Heymann, 2010) in order to suit the particular goals of the project. It should be performed with a selected and trained assessor panel and involves three basic steps: (i) descriptor generation, (ii) assessor training, and (iii) evaluation of samples.

Descriptive analysis should be performed with a panel of 8–20 trained assessors, being 8–12 the usual number of members (Lawless & Heymann, 2010). Being very familiar with a product category does not imply eligibility to belong in a trained panel. That said, the screening procedures to select the assessors should be kept relatively simple (Nachtsheim et al., 2012) as long as assessors are able to discriminate between similar samples accurately and/or are able to identify and rate the intensity of particular sensory attributes. Assessors are usually selected for having sensory capabilities above the average and could be screened for competence in the specific task needed for the characterization. For instance, during a selection of assessors for sensory characterization of gels, assessors could be screened for granularity sensitivity. It is equally important to ensure that assessors are motivated and interested in joining the trained assessor panel, as well as to keep the motivation throughout the whole process to ensure a good performance.

After the assessors have been selected, the main attributes that describe the products' sensory characteristics have to be defined by generating a complete list of descriptors. Usually, assessors are presented with a wide range of products that represent the perceptual space of interest. For instance, in the case of bread texture shelf life, it could include one that is as fresh as possible and another one that is very stale. They are then asked to individually generate a list of attributes that describe the differences among the samples. The attributes should be well understood, easily described and evaluated, and that they cannot include attributes with hedonic connotation (e.g., pleasant), although this is ultimately determined by the goal of the project. Then, by open discussion with the panel leader, the assessors agree on the attributes to be evaluated (Lawless & Heymann, 2010).

Once the attributes have been selected, the evaluation technique needs to be clearly defined and references can be selected to help the assessors identify and quantify each sensory attribute (Rainey, 1986). The panel has to be trained as well to use a common frame of reference that defines product attributes and their intensity (the reference points that assessors mentally refer to when assessing products). For this purpose, they are exposed to the range of products in the category of interest (Muñoz & Civille, 1998; Murray et al., 2001). Through this process, assessors acquire a common qualitative and quantitative frame of reference and are able to use a standard language to describe sensory concepts leaving behind their own reference frame, determined by their personal experiences. Note that the evaluation of products is bound to the context of all those products tested during the term generation and concept formation sessions (Murray et al., 2001). It is also common the use of other foods not related to the tested category; for example, during an evaluation of a set of biscuits, one could use the sound of potato chips to convey to the panelists the crispy perception and the sound of almonds to explain the crunchy attribute (Laguna et al., 2013). This part of the training should be as extensive as needed to reach a panel alignment and a thorough understanding of all the attributes being measured.

Once the attributes have been generated and the panel has been aligned, assessors should be trained in attribute recognition and quantification (Stone & Sidel, 2004). Usually, attribute intensity is quantified using 10- or 15-cm unstructured line scales anchored with words such as "slight" and "intense" or "low" to "high" at the extremes, usually called "anchors" (Fig. 1). The use of more than two anchors would tend to reduce the line scale to a category (or partitioned) scale, which is not necessarily desired. When evaluating a product, assessors should place a mark along the line scale considering that the distance from the left extreme of the line to the mark correspond to the intensity the attribute being evaluated. In generic descriptive analysis, scales are not necessarily referenced, although reference marks could also be provided in some cases if needed, for example using references for the anchor points.

Fig. 1 Example of an unstructured scale to evaluate the intensity of an attribute

During successive training sessions, assessors are presented with different sample sets and are asked to quantify the intensity of the selected attributes. These sets should vary in intensity and difference levels between samples, starting from clearly different samples (with easily quantifiable differences), ranging to samples sets whose differences are more difficult to assess. Training continues until the panel is capable of providing reliable information about the sensory characteristics of the products (valid and reproducible). The end of the training is determined by the evaluation of the individual performance of each assessor, as well as the performance of the entire group (Labbe et al., 2004). In this final stage, each assessor should be able to consistently rate the intensity of all the attributes, to discriminate between products, and to evaluate them, on average, as the rest of the trained panel (Mandel, 1991). Panel performance is evaluated taking into account individual and global repeatability, reproducibility, and discrimination ability (Bi, 2003) by using analysis of variance and multivariate statistical techniques (Brockhoff, 1998; Latreille et al., 2006; Dahl et al., 2008; Derks, 2010).

The training would normally last from 10 to 120 hours, depending on the complexity of the products and the number of attributes selected to characterize the products (Dairou & Sieffermann, 2002; Meilgaard et al., 2007). After the assessors have been trained, they can start evaluating samples, which is usually performed in duplicate or triplicate (Lawless & Heymann, 2010). Data from descriptive analysis are statistically analyzed using univariate and multivariate techniques and usually graphically represented.

3 Alternative Methods for Sensory Characterization

While descriptive analysis is still one of the most widespread methods in industry because of the reliability, reproducibility, and level of detail of the data (Meilgaard et al., 2007; Stone & Sidel, 2004), it is usually expensive and time-consuming, which becomes a challenge to implement in many everyday situations where there are constraints in terms of time and resources (Labbe et al., 2004). The fact that assessors have to complete an exhaustive training process and that the evaluations require several sessions has led to many food companies to maintain separate panels, since a single panel is not able to handle the evaluations of all the product categories produced (Lawless & Heymann, 2010).

Moreover, interest grew in gathering sensory information directly from the target consumers of food products instead of from the more technical descriptions provided by trained assessors (Faye et al., 2006; Varela & Ares, 2012). Several researchers have used a hybrid approach; that is, they have used a simplified descriptive analysis method with consumers. This can be successfully achieved, and the results can be reliable if, for instance, the vocabulary (list of attributes) is kept relatively simple or provided the definitions, if the instruction in terms of rating on intensity scales is clear, and if the panel of consumers is large enough. An example of such approach can be read in Aguayo-Mendoza et al. (2020).

In this context, several cost-effective methods for sensory characterization have been more recently developed and have been reported to be a good option for gathering information about the sensory characteristics of food products using less time. These methods do not require training and can be performed by trained, semi-trained, or even untrained assessors. There are basically four types of methods: (1) attribute-based methods, (2) temporal methods, (3) holistic methods, and (4) open-ended questions.

3.1 Attribute-Based Methods

Attribute-based methodologies rely on the evaluation of specific attributes, as in conventional descriptive analysis. Their main feature is that they reduce the steps related to descriptor generation and panel training. In this chapter, three methodologies will be discussed: free-choice profiling, flash profiling, and check-all-that-apply (CATA) questions.

3.1.1 Free-Choice Profiling

Free-choice profiling was developed in the 1980s to overcome some of the drawbacks of descriptive analysis (Arnold & Williams, 1986). It is based on the assumption that assessors differ not only in the way in which they describe the sensory characteristics of products (Jack & Piggott, 1991) but also in the characteristics that they consider relevant. For this reason, each assessor develops an individual set of sensory attributes and evaluate them using line scales, according to their own personal criteria (Williams & Langron, 1984).

Descriptor generation is usually performed using the repertory grid method (RGM; Kelly, 1955), which enables to overcome the difficulties faced by many untrained assessors to generate sensory attributes to characterize the products (McEwan et al., 1989). Once each assessor has generated their individual list of sensory attributes, these are placed together in a list next to unstructured scales. Then, assessors are asked to evaluate the products by rating the intensity of their own set of sensory attributes. Therefore, each assessor evaluates their own set of sensory attributes, which are considered the most relevant for describing the products, according to their own individual experience and familiarity with the product.

Due to the fact that free-choice profiling does not require consensus descriptor generation and panel training, it can be applied with both trained and untrained assessors, being quicker and less expensive than descriptive analysis (Gains & Thomson, 1990; Lawless & Heymann, 2010).

3.1.2 Flash Profiling

Flash profiling has the same initial steps as free-choice profiling with regard to attribute generation. However, the products are not rated one by one but compared to each other for each attribute and ranked (Sieffermann, 2000). The methodology is based on the assumption that comparing products is easier and more natural than evaluating them using intensity scales (Delarue & Sieffermann, 2004). It is thought to rapidly profile products according to their most salient sensory attributes responsible of the differences between the tested samples. As an example, Laguna et al. (2020) used this method to understand how different hydrocolloids influence oral structure breakdown of starch-based systems, and how this is related to mouthfeel sensations.

Flash profiling is structured in two main steps. Initially, assessors are presented with the whole set of products and are asked to generate their individual set of sensory attributes, which differentiate the products, avoiding hedonic terms (Lawless & Heymann, 2010). Then, assessors are presented again with all the products and are asked to rank them according to their intensity of each of the attributes in their individual lists. Three replications of the ranking session are recommended (Dairou & Sieffermann, 2002). Fig. 2 shows an example of a ballot for the attribute creaminess.

The main advantage of flash profiling is that sensory characterization is performed in a short time due to the fact that familiarization with the product space, attribute generation, and evaluation are merged into a single step (Delarue & Sieffermann, 2004). Considering that each assessor uses his/her own vocabulary to generate the list of sensory terms, the methodology allows a diversity of points of views (Dairou & Sieffermann, 2002). Moreover, the fact that assessors have simultaneous access to the whole product set forces them to focus on the differences they perceive in order to generate attributes that allow discriminating between samples (Veinand et al., 2011).

3.1.3 Check-All-That-Apply Questions

The check-all-that-apply (CATA) or checklist method is a multiple-choice question, which has been extensively used in marketing research (Driesener & Romaniuk, 2006). It consists of a list of words or phrases from which respondents should select all they consider appropriate to describe a product (Fig. 3).

Regarding the list of words or terms included in the CATA question, the selection is performed by the researcher and, therefore, care must be taken to ensure that all the relevant sensory characteristics are included. These could be selected based on the researchers' knowledge about the product sample from experience, so from descriptors used by trained assessors to characterize the products or using results from previous focus groups or other consumer studies.

Products are presented to assessors in a monadic balanced order (as with descriptive analysis) and are asked to check all the terms that they consider appropriate to describe each of the samples, without constraints on the number of attributes that could be selected by the assessors.

CATA questions have been reported to be an easy, simple, and quick method to gather information about the sensory characteristics of food products (Ares et al., 2010, 2011; Dooley et al.,

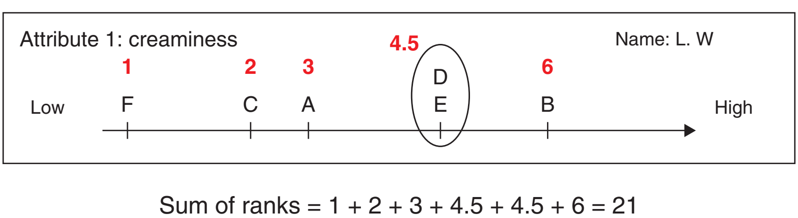

Fig. 2 Example of a ranking scale along which six products (A–F) have been placed. The numbers indicate the score that each ranked product would receive, a tie in the fourth position resulting in two products having a score of 4.5. With six products the sum of ranks is 21

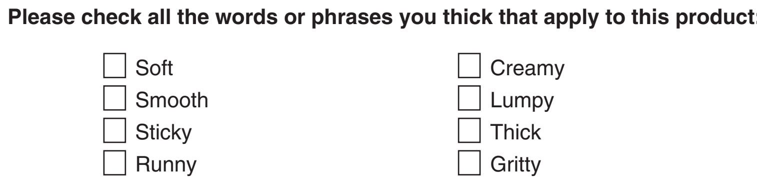

Fig. 3 Example of a check-all-that-apply (CATA) question

2010; Giacalone et al., 2013). Selecting words from a list does not require much cognitive effort for assessors compared to intensity questions. Some publications have suggested that the sensory maps generated by CATA questions are very similar to those from descriptive analysis with a trained assessor panel (Dooley et al., 2010; Ares et al., 2010; Bruzzone et al., 2012). However, it is important to take into account that the frequency of mention of the terms should not be interpreted as intensity of perception, since consumers are limited to assess only whether a term is appropriate to describe a product or not. That said, it has been reported to be closely related. A limitation of CATA questions is that it requires a relatively large number of assessors due to the fact that data are binary instead of quantitative. Moretton et al. (2023) used this method recently to identify the desirable sensory and mechanical properties in bread targeting elderly consumers (see Merino et al., 2021, for an example on people with dysphagia). A variety of CATA in which assessors rate the attributes that apply was also developed (see Oppermann et al., 2017 and Santagiuliana et al., 2018 for examples applied particularly to investigate textural properties of gels and semisolid foods).

3.2 Temporal Methods

A couple of methods have been widely used for product categories where the dynamicity of the sensory characteristics plays an important role in the overall perception or acceptance of the product. The most applied one is temporal dominance of sensations (Pineau et al., 2009; Schlich, 2017) where, via a software, assessors select the most dominant attribute they are perceiving one at a time. Therefore, with this method, a profile of a product is obtained whereby only the dominant attributes are highlighted in a linear way. It is simple and easy to understand, therefore feasible for consumers with very little training.

A variant of CATA was developed, called temporal check-all-that-apply (TCATA). In TCATA, multiple attributes can be selected and unselected throughout the evaluation, and this is recorded by the software giving as output the dynamic perception of the attributes during oral processing (Castura et al., 2016). The idea behind this other method is to allow for several attributes to be selected in parallel, so in other words to report simultaneous perception of more than one attribute at a time and therefore not the dominant one. A question is whether assessors, and mostly those naive ones, are able to actually perceive several attributes simultaneously and keep up with selecting and unselecting them during the task. One would expect different oral processing (and time) compared to having only to select the most dominant attributes as in temporal dominance of sensations (TDS). For some examples applied particularly in studies investigating textural properties of foods; see, for example, Nguyen et al. (2018).

3.3 Holistic Methods

Holistic methodologies are often used when a detailed profile of products is not needed. They are based on the assessors' perception of the global similarities and differences among the products, so on the global perception of the products rather than on the analytical evaluation of specific sensory attributes. This consists of a first advantage of the methods since those aspects that are difficult to verbalize or defined are not overlooked by assessors. The disadvantage is precisely the lack of individual profiles of the products (and scores), so the type of data obtained is "messier" compared to the other more structured methods using scales. The most popular methodologies are sorting and projective mapping (Varela & Ares, 2012).

3.3.1 Sorting

Sorting tasks have been reported to be a good alternative to gather information about the sensory characteristics of food products in sensory and consumer science (Schiffman et al., 1981; Lawless et al., 1995). The idea behind a sorting task is to measure the global degree of similarity between pairs of samples within the product sample set by grouping the samples according to their similarity. Assessors receive the entire sample set and are asked to sort the samples into groups according to their similarities and differences, using their own personal criteria. Two samples should be put in the same group if they are similar enough, whereas two samples that are clearly different should be placed in different groups. In addition, assessors are usually told that they should sort the samples in at least two groups in order to avoid the trivial response of having all samples in the same group. Once the sorting has been completed, a verbalization task is added, and assessors are asked to provide descriptors for each of the groups they formed (Lawless et al., 1995; Cartier et al., 2006; Popper & Heymann, 1996). A typical classification provided by an assessor in a sorting task is presented in Table. 1.

3.3.2 Projective Mapping

Projective mapping is based on the quantification of the individual perception of overall similarity and dissimilarity among samples (Risvik et al., 1994). Assessors are asked to provide a two-dimensional representation of the samples, according to their own criteria (Risvik et al., 1997). In this representation, the Euclidean distance between the samples is a measure of their dissimilarity, in such way that the smaller the distance separating two samples, the more similar they are.

All samples are presented simultaneously to assessors, who are asked to place them on a bidimensional space (*"nappe"* in French means "tablecloth," which gave the name to Napping®). The space in Napping® is usually a white sheet of paper (60 cm by 40 cm, or a rectangular space of those proportions if the study is conducted digitally; see Fig. 4). Samples should be arranged by the participant according to their perceived global similarities or dissimilarities among them. Assessors are told to complete the task according to their own criteria and that there are no right or wrong answers. The criteria used by assessors to locate the samples in the sheet are chosen on an individual basis, which makes projective mapping a flexible and spontaneous procedure. In Napping the x-axis is the longer side, since it considers the possibility that humans psychologically use the x-axis to spread the main differences and the y-axis to express secondary differences in a space.

A description phase usually follows this positioning task to identify the sensory characteristics responsible for the similarities and differences among samples (Pagès, 2005). Assessors are asked to provide a description of the samples once they are placed on the white sheet, a method generally known as ultra-flash profiling (Perrin & Pagès, 2009; Perrin et al., 2008). A repeated sample within the set is generally used as a panel performance check, whenever it is possible, and the sample is not recognized by its appearance.

Table 1 Response of an assessor to a free sorting task with six samples. In this example, the assessor has formed three groups: the first one consists of two products and can be described as being crunchy brittle and salty; another group consists of three products characterized by being hard, crunchy, and dull; and a third group consists of two products, which are mainly soft and rancid

Group	Samples	Description
1	456, 336	Crunchy, brittle, salty
2	349, 971, 023	Hard, crunch, dull
3	194, 248	Soft, rancid

3.4 Open-Ended Questions

Open-ended questions are a branch of techniques, which have been around since long ago (and well-known in other fields, such as marketing and psychology), but their application to gather sensory data is still quite novel. In sensory science,

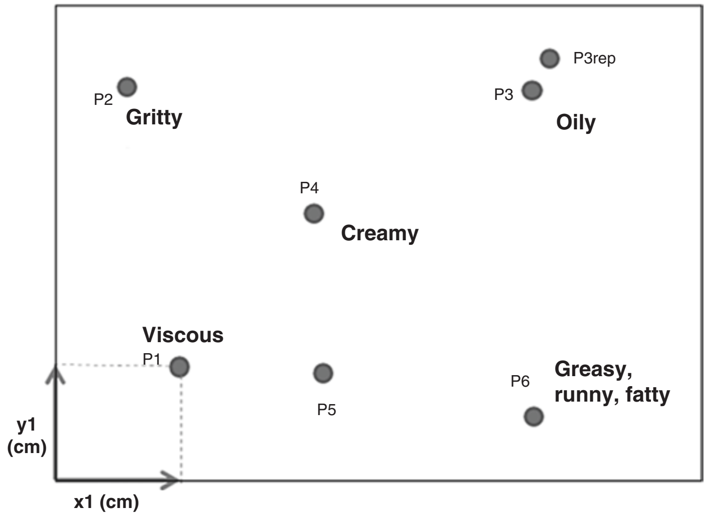

Fig. 4 Example of sample representation of a single assessor in a Napping® task. The space represents the positioning of the products made by this assessor

techniques that let consumers "express themselves," such as open-ended questions, are used to understand the main characteristics that determine consumer perception of products and especially what motivates their liking scores (Piqueras-Fiszman, 2015). In this approach consumers are asked to describe each product in their own words. This type of question provides insights (in an unbiased way) about issues that were not anticipated in setting up the more structured parts of the survey. Also, the responses are more spontaneous, and in many cases they explain the subjects' responses to other closed questions. The disadvantage of these techniques is that the data are difficult or complex to interpret, code, and tabulate, so while data can be collected rather quickly, the treatment thereof required longer times compared to the quantitative methods.

4 Conclusions

While instrumental measures of food products are essential for food developers, a crucial aspect of food science is how humans perceive, describe, and respond to foods' various sensory properties. It is wrong to believe that data provided by humans are mere opinions that differ widely (though unfortunately this belief still persists among some academics). As has been discussed throughout this chapter, there is an array of techniques, which can be used to measure and collect a food's sensory description, both from experts (or trained panels) and from consumers who have been proven to be robust and reliable. In the context of this book, the methods are not specific to characterize textural properties, but of course, depending on the purpose of the research, the textural attributes can be the focus, as the many examples showed. In this chapter, an overview (nonexhaustive) of some of the most oft-used procedures and test methods has been provided. It is really the responsibility of the sensory scientist to select and implement the proper methodologies to successfully address the research objective. What is key is that food technologists collaborate with experts in sensory science, or consult the original references to the methods in case a collaboration is not possible, to conduct the research. Applying these methods in a "quick and dirty" fashion with staff who have shallow knowledge can lead to errors and false conclusions. Together with affective data (such as liking/hedonic scales) or using some methods that combine sensory and affective information, insights into how products can be improved to satisfy the majority or a target group of consumers can be achieved. Some of these methods require advanced statistical skills, which are not described in this chapter, but there are several textbooks available (Le & Worch, 2015). Some commonly occurring industrial applications in which these techniques are used include: new product development, product matching, product improvement, process change, cost reduction, quality control, storage stability, product grading, selection and training of a panel, and correlation of sensory and chemical/physical measures.

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The Meaning of Sensory and Consumer Terminology

Arantxa Rizo and Amparo Tárrega

1 Introduction

Food texture comprises sensory properties related to food structure and how it behaves (deformation, breakage and flow) when manipulated or consumed. Texture includes multiple sensations perceived by the human senses of touch, vision, hearing and kinesthesis (Bourne, 2002; Szczesniak, 2002). Although texture depends directly on food properties, it is finally determined by the perception and integration of human senses, which makes its verbal description complex and diverse (Varela et al., 2013).

Texture terminology/lexicons/vocabulary are sets of words that describe the texture characteristics of food products. They allow the understanding and communication of texture and are an essential tool for industry and research to apply new product development processes, quality control, product improvement and shelf-life control, as well as manufacturing and marketing.

The type of texture vocabulary differs depending on the purpose and the user; analytical sensory evaluation product developers, sensory professionals and trained panellists use precise, specific and technical terms to describe texture. Descriptors are selected for the product category and well defined regarding the stimuli and procedure of evaluation for the same understanding among individuals. In contrast, consumers use a free and personal vocabulary influenced by associations, memories and experiences. Similar sensory attributes can be used or understood differently due to differences in perception, culture, language, training or familiarity (Fiszman et al., 2015; Lawless & Civille, 2013; Suwonsichon, 2019). Sensory perception complexity may also explain differences in vocabulary use. As recently proposed by Chen et al. (2021), most sensory attributes are derived from a complicated combination of two or more primary perceived features that come from physical stimuli. For example, creaminess or fattiness perception seems to involve different physical primary stimuli, such as colour, aroma and texture. Similarly, viscosity and thickness are two closely linked terms, which result from primary sensory stimuli related to force and displacement. Viscosity is a precisely defined rheological property, while thickness is a term more commonly used by consumers. Texture has a great influence on consumer hedonic perception of food products, thus the knowledge of words that consumers use to express texture sensations is highly relevant to the industry (Szczesniak, 2002). The study of differences in the vocabulary of consumers is used to understand the perception of texture and differences across cultures, to avoid misunderstandings in language translations of texture

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lexicon for texture characterisation and to improve the design of food products that meet consumer needs (Kumar & Chambers, 2019a).

This chapter describes the approaches where the meaning of texture terminology is relevant for sensory evaluation and consumer research with a focus on describing methodological aspects (Fig. 1).

2 Analytical Sensory Terminology

Texture vocabulary, or terms specifically defined and described, is required for sensory evaluation methods such as quantitative descriptive analysis, texture profile analysis, or Spectrum™ based on quantifying the intensity of attributes. The lexicon, in these cases, includes the terms described, evaluation of the procedure and references or examples of the intensity levels to train panellists in a congruent and repeatable evaluation. The lexicon used in a descriptive analysis of texture can exist (previously developed and validated) or be adapted to ensure that all relevant attributes are included for the products being evaluated. Alternatively, the lexicon can be specifically developed; for this, consider the following suggestions of Lawless and Civille (2013) in a review about lexicon development procedures. They include reviewing protocols, generating terms and definitions that describe the products, selecting references that clarify the terms and a final selection and reduction of terms using statistical methods (ISO 11035:1994; ISO 13299:2016).

Different lexicon standards for texture description are currently available based on the pioneer studies of Alina Szczesniak on texture evaluation using instrumental techniques and sensory description by panels and consumers (Szczesniak et al., 1975, 1963; Szczesniak, 1963). These studies classified texture attributes into three main classes (mechanical, geometrical and other characteristics) (Table 1). The dynamic nature of texture perception is also considered, and the stages of consumption (first bite, chewing, swallowing and oral clearance) are included in the description of texture attributes. Each attribute should be evaluated in the precise stage, so they are more evident and easier to detect.

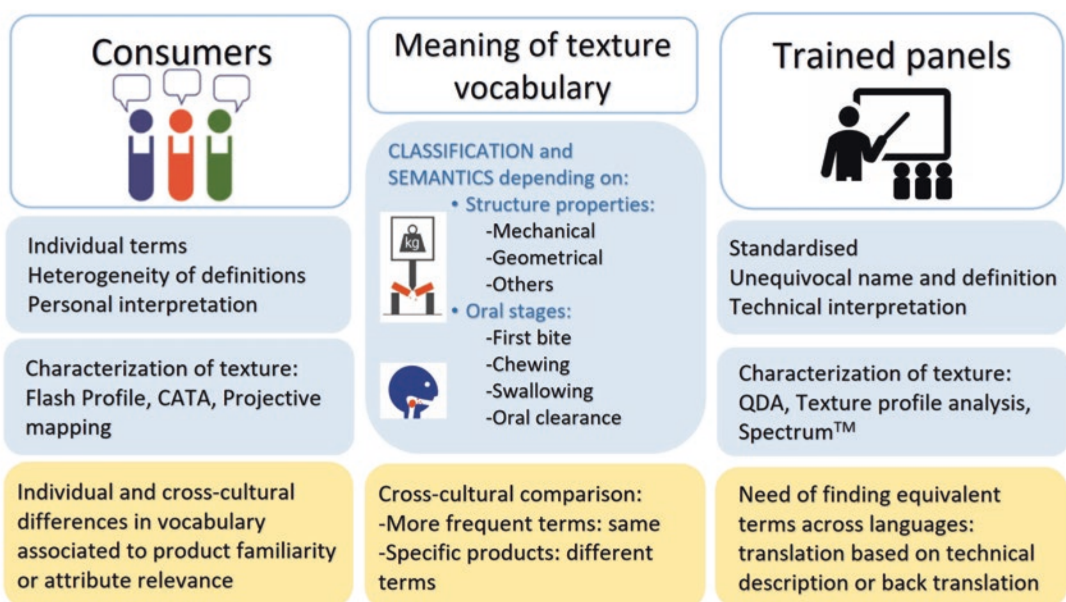

Fig. 1 Texture vocabulary meaning: classification and characteristics depending on the use

Table 1 Textural characteristics related to terms used by consumers to describe these sensations (Szczesniak, 1963)

Mechanical	Primary properties	Secondary properties	Terms used by consumers
	Hardness		Soft → Firm → Hard
	Cohesiveness	Brittleness	Crumbly → Crunchy → Brittle
		Chewiness	Tender → Chewy → Tough
		Gumminess	Short → Mealy → Pasty → Gummy
	Viscosity		Thin → Viscous
	Elasticity		Plastic → Elastic
	Adhesiveness		Sticky → Tacky → Gooey
Geometrical	**Class**		**Examples**
	Particle size and shape		Gritty, grainy, coarse, etc.
	Particle shape and orientation		Fibrous, cellular, crystalline etc.
Other	**Primary properties**	**Secondary properties**	**Terms used by consumers**
	Moisture content		Dry → Moist → Wet → Watery
	Fat content	Oiliness	Oily
		Greasiness	Greasy

The ISO standard for texture profile analysis (ISO 11036:2020) describes texture attributes, mainly mechanical terms related to the response of food structure to an applied force and usually associated with parameters of instrumental measurements (*hardness, viscosity, springiness, adhesiveness, fracturable, cohesive in mass*). It also includes other guiding descriptors, such as those related to geometrical properties (*smooth, chalky, grainy, gritty and coarse, fibrous, cellular, crystalline, puffy and aerated*) and properties related to moisture (*dry, moist, wet and juicy*) and fat content (*oily, greasy and fatty*). Another lexicon standard for sensory analysis is of the American Society for Testing and Materials (ASTM) and includes 133 descriptors of texture with their definitions and the techniques used to evaluate them. Recently Bondu et al. (2022) developed a general lexicon of texture vocabulary (in English) from literature and food science databases, including categories and intensities represented as a texture wheel with synonyms and definitions, which can be updated by adding new concepts, thanks to an open access database.

In the development or adaptation of the lexicon to a specific category, new terms and descriptions must be included or created. Civille and Seltsam (2014) outlined the steps and the most important aspects to adequately define a texture attribute: Assessors who describe attributes or characteristics when assessing products and assign an unequivocal name, definition and technique of evaluation. The importance and approaches for developing a texture vocabulary with unique meanings and definitions and for finding equivalent terms across languages are discussed in some previous papers (Nishinari et al., 2008; Jowitt, 1974; Zannoni, 1997).

Additionally, lexicons developed by trained sensory panels for the texture evaluation of specific products can be found in the food science literature. Kumar and Chambers (2019b) developed a texture lexicon for various snack and snack-type foods (e.g. crackers, chips, vegetables and yogurt) in various languages (English, Spanish, Chinese and Hindi). Other lexicons include those developed to evaluate the texture of almonds (Civille et al., 2010), cashew nuts (Griffin et al., 2017), long dried pasta (Irie et al., 2018), tomato (Hongsoongnern & Chambers IV, 2008), peaches (Belisle et al., 2017), quinoa (Wu et al., 2017), turron (Vazquez-Araujo et al., 2012), caviar (Baker et al., 2014), bread (Estévez-López et al., 2021) and chocolate (De Pelsmaeker et al., 2019).

3 Terminology of Consumers

3.1 Understanding Texture Perception from Consumer Terminology

The study of the words that consumers use to communicate specific texture sensations they feel in response to food stimulus and what they mean to them is relevant for understanding texture perception. Some research on terms used by consumers highlights that the use of the same term in different studies does not guarantee that the same sensory concept is measured, especially when the same term is used for different food products. Likewise, different terms can refer to the same concept (Roudaut et al., 2002).

This is the case for *crunchiness and crispiness*, which are considered important quality factors determining consumer acceptance for food categories such as fruits and vegetables, snacks, or bread. They are complex sensory attributes that provide information on the freshness of the product and combine a wide range of perceptions related to fracture characteristics, sound, density and geometry (Szczesniak, 2002; Varela & Fiszman, 2012). There is controversy among consumers about using crispy and crunchy words when referring to the same sensory concept or not (Rohm et al., 1994; Fillion & Kilcast, 2002; Tunick et al., 2013). Varela et al. (2008) studied the meaning of the terms *crispness* 'crujiente' and *crunchiness* 'crocante', used by Spanish and Uruguayan consumers. Both *crunchiness and crispiness* were related to resistance to applied forces for hard, resistant and solid foods. They also refer to sound emission and fracture mechanics when breaking or eating. The terms *crispy* and *crunchy* had different meanings and perceptions depending on the country, and only Uruguayan consumers differentiated between *crunchy* and *crispy* terms with food. For them, *crunchy* foods were harder than *crispy* ones and needed more mastication, in addition, a mixture of elements with different textures and consistency was described during the chewing of *crunchy* products, plus a repetition of sound during chewing because the hard elements crunched. In other studies, specific to fruits and vegetables with native English speakers (Fillion & Kilcast, 2002), the term *crunchy* for consumers was mostly defined as mentioning *hardness* and sound and was more used than *crispy*. The definitions of *crispy* attributes were more diverse and were a combination of a snap clean break, a light texture and a sound, as well as with freshness, moistness and brittleness for some consumers. *Crispy* was associated with a sound like 'walking on snow or frost,' whereas *crunchy* was associated with a sound like 'walking on gravel or dry leaves', as well as a 'crackly noise like a fire'. *Crispness* was less understood and its use by consumers was more ambiguous than *crunchiness*.

Other attributes in the relevant study of consumer vocabulary to understand perception are mainly related to tactile sensations such as *creaminess*, *mouthcoating*, *astringency*, or *roughness*, among others. They are properties usually not perceived as an isolated sensation, as they are usually felt together (Laguna et al., 2021).

Creaminess is an important driver of consumer liking, critical for semi-solid foods such as dairy products, soups and sauces. The meaning of *creaminess* and its perception in food products has been studied, and although it is still not fully understood, it is considered a multi-sensory term perceived because of the integration of the senses (smell, taste, sight and touch) and has been related with the presence of fat (Kokini & Cussler, 1983; de Wijk et al., 2006; Upadhyay et al., 2020). Although the sensation of *creaminess* is usually easily identified by consumers, some studies have revealed that they associate *creaminess* with tactile aspects related with *smoothness* and *thickness* (such as *smooth*, *soft*, *thick*, *slippery*, *lumpy, melting*, *liquid* and *solid, unctuous*, *greasy*, '*creamy texture'* opposite to '*watery texture'*), but are also related with the manipulation in mouth (*mouth* and *palate*), flavour (*vanilla, dairy, fat-related flavour, bitter, sour and sweet*), appearance (*yellow, white* and *homogeneous*) and pleasantness (*pleasant*) (Tournier et al., 2007; Antmann et al., 2011a, b); they rarely distinguish between them (Kirkmeyer & Tepper, 2003).

Astringency is also a complex sensation attributed to the interaction of astringent compounds (tannins, proteins, alums and acids) with mucopolysaccharides and the precipitation of salivary proteins that causes a decrease in saliva lubrication ability. As indicated by Bajec and Pickering (2008), the literature is unclear in deciding whether *astringency* can be a single perceptual phenomenon or as a compound term encompassing several tactile sensations. It is mainly described as the sensation of mouth drying and puckering, but also as oral friction and roughness sensations. According to Childs and Drake (2010), *astringency* was not a term consumer freely elicit when describing texture sensations of whey protein beverages, using instead the terms 'dry' and 'mouth drying'. Similarly, the terms used by consumers to describe astringency in red wine (Vidal et al., 2015) were limited compared to the vocabulary of the 'Mouth-feel wheel' design by experienced wine tasters for red wine (Gawel et al., 2000). Consumers described astringency in wine in terms related to *dryness* and *roughness* sensations, such as *dry*, *rough*, *harsh, hard, smooth* and *sandpaper*.

4 Classification and Use of Texture Terms in Different Languages

Language is closely related to cognition; thus, how consumers organise or associate texture concepts in their minds is strongly related to their sensory perception experiences (Varela et al., 2013). Therefore, the classification of texture terms is necessary to understand the appreciation of texture (Hayakawa, 2015; Szczesniak, 2002). Classification of terms has been useful to understand and relate the concepts they convey and to make texture descriptions easily understandable at an international level.

The first attempts to identify, classify and define texture terms were conducted by Szczesniak in the early 1960s, who studied the degree of texture consciousness and other attributes through a word association test from food names, in which participants were employees of the General Foods Corporation (Szczesniak & Kleyn, 1963) or consumers (Szczesniak, 1970). The researchers concluded that texture is a discernible attribute and that for certain foods, it may be more important than flavour. The highest number of texture responses was associated with products bland in flavour or had crispness characteristics. The terms generated were limited for most people, with different degrees of hardness, ease of fracture and moisture most often mentioned. Women and people of higher economic level showed more texture awareness. In other work, Szczesniak and Skinner (1973a) studied the meaning of texture words for consumers. Using word association tests, participants named food items that came into their minds from food texture terms. This study gave an association of descriptive texture words with specific food products, useful to illustrate the meaning of a given texture word to people unfamiliar with the terms, e.g. when training texture profile panels in different countries. Based on this knowledge, the definition and classification of basic texture terms were proposed with parameters divided into three main classes (mechanical, geometrical and other characteristics) and compared to the terms consumers use to express the same sensations in their daily lives (Table 1). Most of the popular terms for texture used by consumers correspond to degrees of increasing intensities of the same descriptive term. This is the case of *hardness* used in descriptive analysis that, for consumers, would be *soft, firm* or *hard* depending on the intensity of the sensation perceived; *crumbly*, *crunchy* and *brittle* are degrees of the characteristic of *brittleness*; and *dry, moist, wet* and *watery* are terms denoting different levels of moisture (Szczesniak, 1963; Szczesniak & Skinner, 1973b).

Similar classification research studies have been conducted for texture vocabulary in different languages and cultures, showing that the semantic organisation of texture terms differed little among them, indicating a similar perceptual experience. Consumer textural classifications are often related to the physical structure and the mechanisms that underlie its perception and manipulation in the mouth. Lawless et al. (1997)

studied the classification of 70 English and Finnish texture terms by professionals or consumers using sorting, multidimensional scaling and cluster analysis. A similar classification was obtained for both languages and groups with little variation. The categories were related to geometric, particles, degree of open structure, firmness/compressibility, thickness and adhesiveness, deformability and elasticity, moisture terms, oiliness and presence of effervescence. Classification of 37 texture terms by Spanish speakers (Varela et al., 2013) using a sorting technique, showed that besides the attributes groups already described in the initial Szczesniak studies (related to resistance to deformation, particles, surface properties and water content), other groups related to the difficulty to manipulate in the mouth or to sound emission were included. The classification of 445 Japanese texture terms (Hayakawa et al., 2013) according to similarities between pairs of terms included new subgroups for each of the already established groups; six groups of mechanical attributes ('toughness', 'fracture at low strain', 'low cohesiveness', 'deformability', 'adhesiveness and sliminess' and 'fluidity and smoothness'). Six groups of geometrical attributes ('air', 'particles', 'smoothness and homogeneity', 'roughness and heterogeneity', 'thinness' and 'denseness'). Furthermore, terms related to other attributes (moisture and fat content) were classified into three groups ('fat content', 'dryness' and 'moisture content').

The terms elicited by consumers to describe the texture of foods and their frequency have also been collected in studies focused on a specific language; Japanese (Yoshikawa et al., 1970), English (Szczesniak, 1970) and Spanish (Antmann et al., 2011c); or by comparing different languages such as Japanese, English and German (Rohm, 1990). The terms mentioned most frequently, considered those more relevant and more commonly used by consumers to describe texture, were similar in all studies. The lists of words used by the participants to describe texture in five languages are shown in Table 2.

Cross-cultural differences in texture vocabulary or descriptors are more relevant when focusing on specific products. Comparison of sensory terminologies is useful to find equivalent terms for the evaluation of products that must be tested and marketed internationally. Cross-cultural studies have been conducted for a variety of products, such as jellies and soy yogurts in France and Vietnam (Blancher et al., 2007; Tu et al., 2010); cooked rice in France, Japan, Korea and Thailand (Son et al., 2012); and snack foods in nine countries speaking English, Hindi, Mandarin and Spanish (Kumar & Chambers, 2019a). Despite some terms being consistently used, there are also differences in understanding and use of some texture terms attributed to the context, culture and previous experience with the food product. Therefore, texture terms developed by trained descriptive panels and translated at a scientific level may produce consistent information across panels for different countries. Using back-translation approaches (the already translated terms are translated back into the original language by a different translator) also helps to confirm that the meaning was maintained (Monteiro et al., 2017; Kumar & Chambers, 2019b). For consumers, however, direct translation of texture terms from one language to another may be problematic and does not ensure the same meaning, as some terms are specific to products and may change between product categories. Kumar and Chambers (2019a) found that translating English terms to Hindi, Mandarin and Spanish resulted in divergent understanding and usage among countries. To avoid potential misunderstanding and inconsistencies when using translated terms for consumer sensory evaluation, pre-tests are recommended to check an understanding of translated vocabulary. Another alternative is to use the vocabulary developed by consumers in each country. Recently, the textural characteristics of typical foods have been described in all major regions worldwide (Nishinari, 2020). More detailed information on the classification of texture terms and cross-cultural studies can be found in the chapter by Hayakawa (2015).

Table 2 Texture terms that are most frequently used in different languages

Language	English	German	Chinese	Japanese	Spanish	Spanish	Spanish
Country	USA	Austria	China	Japan	Argentina	Spain	Uruguay
Subjects	115 consumers	208 students	Panels from Beijing, Shanxi, Shanghai and Guangdong	140 female students	110 consumers	107 consumers	120 consumers
Terms generation method	word association	word association	free answer questionnaire	word association	free listing task	free listing task	free listing task
Food stimulus	29 foods names	50 foods names	No	97 foods names	No	no	no
Paper	(Szczesniak, 1970)	(Rohm, 1990)	(Hayakawa et al., 2004)	(Yoshikawa et al., 1970)	(Antmann et al., 2011c)	(Antmann et al., 2011c)	(Antmann et al., 2011c)
Terms	crispness	knusprig (crispy)	crunchy	hard	cremoso (creamy)	cremoso (creamy)	cremoso (creamy)
	crunchy	hart (hard)	hard	soft	suave (smooth)	duro (hard)	suave (smooth)
	smooth	weich (soft)	sticky	juicy	duro (hard)	blando (soft)	áspero (rough)
	juicy	knackig (crunchy)	pliable	chewy	áspero (rough)	crujiente (crispy)	duro (hard)
	creamy	saftig (juicy)	crispy	greasy (oily)	rugoso (rugous)	suave (smooth)	blando (soft)
	soft	klebrig (sticky)	soft	viscous	blando (soft)	líquido (liquid)	fibroso (stringy)
	sticky	cremig (creamy)	thick	slippery	fibroso (stringy)	áspero (rough)	crocante (crunchy)
	stringy	fettig (fatty)	tender	creamy	untuoso (unctuous)	pastoso (pasty)	líquido (liquid)
	fluffy	wäbrig (watery)	slimy	kori-kori (crisp)	crocante (crunchy)	fibroso (stringy)	arenoso (gritty)
	tender	zäh (tough)	chewy	kari-kari (crunchy)	crujiente (crispy)	gelatinoso (gelatinous)	grumoso (lumpy)
	dry	trocken (dry)	oily	brittle	líquido (liquid)	rugoso (rugous)	seco (dry)
	chewy	dickflüssig (viscous)	fine and smooth	torori-to-shita (melting)	tierno (tender)	grumoso (lumpy)	liso (even)
	hard	kernig (firm)	rough	nuru-nuru (slippery)	seco (dry)	granuloso (grainy)	granulado (granulated)

5 Terms for Consumer Characterisation of Texture

In the past, consumers have traditionally only been considered to evaluate food attributes using hedonic or affective tests, where they are asked how much they like a product or what product they prefer. Consumers did not evaluate the intensity of attributes because the terminology in sensory profiling methods was too specific and technical and cannot be easily understood without previous training (Bachour et al., 2016; Lawless & Heymann, 2010). For a long time, it has been considered that only these analytical methods – which require extensive training with a panel to generate, understand and learn to evaluate with specific texture attributes – can objectively describe products that provide detailed, reliable and reproducible information. Since the 2000s, extensive investigation has focused on the development and validation of sensory evaluation without trained assessors and it has been demonstrated that consumers, although using a different and less technical vocabulary, can describe texture sensations and discriminate or describe the texture of food products effectively (Ares & Varela, 2017). In techniques such as free-choice profile, flash profile, open-ended questions and holistic methodologies (like projective mapping), consumers generate texture sensory terms, freely, to describe samples using their own words (Tarrega & Tarancon, 2014). Using check all that apply (CATA) questions, consumers describe texture using a unified list of texture terms previously generated by consumers (Ares & Jaeger, 2015). Consumer vocabulary used to describe texture can be rich and extensive but redundant terms, the lack of definitions and heterogeneity of individual descriptions and the subjection to personal interpretation make analysis and interpretation of consumer sensory terms difficult (Antmann et al., 2011a; Ares & Varela, 2017). However, this lack of homogeneity in the consumer's use of words to describe their sensations can be overcome with appropriate statistical approaches – as the words used usually converge on similar concepts – using techniques such as generalised procrustes analysis or multiple factor analysis (Tarrega & Tarancon, 2014). In these studies, consumers usually use hedonic terms to describe products and can be considered a limitation, but can be useful to relate sensory characteristics with marketing features and consumer preference. Today, descriptive methods performed with the untrained vocabulary are of great interest (Ares & Varela, 2017).

Different approaches have been used to facilitate the generation of sensory vocabulary, especially useful when working with consumers. These methods describe a set of samples (Piggott & Watson, 1992), free listing (Hough & Ferraris, 2010; Antmann et al., 2011c; Vidal et al., 2015), word association technique (Antmann et al., 2011a; Luckett & Seo, 2015), focus groups (Cardinal et al., 2003; Bachour et al., 2016; Kumar & Chambers, 2019a; Talavera & Sasse, 2019; Foguel et al., 2021), descriptions of individual samples using open-ended questions (Ares et al., 2010), comparison of samples sets (Fiszman et al., 2015) and repertory grid method (Thomson & McEwan, 1988; Gomez et al., 1998; Jaeger et al., 2005; Tarancon et al., 2013; Fiszman et al., 2015). The simplest way to generate natural texture vocabulary is by presenting samples or a representative set of samples to the participants and asking them to describe them. The instruction given varies depending on the study: 'note any attributes or associations', 'describe the samples using all the necessary terms', 'describe the differences between products' or 'choose the descriptive terms which make the products different'. In the free generation of attributes, the participants usually generate few attributes, and thus, there is a risk that certain differences between samples are not considered. Therefore, numerous researchers prefer to use a more structured sample evaluation, in which terms are generated by describing the differences or similarities between certain groups of samples (pairwise or triad comparisons). Another more structured option is the repertory grid method (RGM). This comprises the presentation of products in several triads that represent the main variations in the texture characteristics of a group of products. In each triad, participants are asked to describe the similarities and differences between the two of them with the third. Although the use of RGM supposes spending more time generating the vocabulary, it is a more structured procedure that not only facilitates the task of the consumer, increasing the number of terms generated but also ensures that all the possible differences between samples have been explored and covered (Tarrega & Tarancon, 2014). Fiszman et al. (2015) compared the performance of a repertory grid, the comparison of the entire sample set and the individual sample description to generate a sensory vocabulary of satiating foods. The methods differed in their ability to encourage consumers to verbalise their sensory perception in detail, which influenced the total number of terms generated and the frequency with which consumers generated some terms. However, the most frequent terms related to texture were similar in the three methods, indicating that the three are reliable. The lowest number of terms was found when consumers described similarities and differences in texture for comparison of the whole sample set, which differed from the other two methods because they described the samples only once. The RGM often provided more detailed information than the individual sample description, as it made consumers focus their attention on more detailed or subtle differences. With individual descriptions, consumers are asked to describe samples; whereas in RGM, they must compare samples. The authors considered that the cognitive processes behind individual description and RGM are different, as individual description is more suitable for studying consumers' vocabulary. However, if the idea is to discriminate among samples (such as free-choice or flash profile), RGM can provide more detailed information.

6 Conclusions

The meaning of texture vocabulary is crucial for evaluating texture and understanding its perception. The semantic classification for the texture terms, similar across countries and cultures, is based on two main dimensions: food structure properties and the stage of consumption where perceived. However, the use and understanding of terms differ among individuals and cultures which make difficult a unique interpretation. For many years, food texture research and evaluation has been based on analytical texture descriptors, precisely defined for a consistent understanding across trained panellists. In the recent years, advances in sensory evaluation methods allow for characterising texture by consumers using their own vocabulary to provide insights about how different consumers perceive and describe the same sensation.

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Consumer Perception of Food Texture in Relation to Preferences and Food Intake

Quoc Cuong Nguyen and Paula Varela

1 Food Texture and Its Implications for Consumer's Perception

Succinctly but clearly defined by Szczesniak (2002): 'texture is a sensory property'; a multidimensional, complex perception, only subject to description by humans in its totality and which plays an important role in the interactions with food. Texture drives acceptance and rejection, influencing food selection and food intake (i.e. portion size estimation). It is a key element for food choice thinking throughout the entire life journey, often related to picky responses in children (Chow et al., 2022), as well as presenting difficulties in old age, when hard or fibrous textures are difficult to handle in the mouth (Vandenberghe-Descamps et al., 2018). Highly pleasurable textural contrasts have been used in high cuisine to create exciting sensations (Mielby & Frøst, 2010). Nevertheless, texture perception has been historically understudied, when compared to other sensory properties as taste or smell. More recently, it has gained new attention, as per its role in oral processing and satiety perception, closely linked to societal issues such as obesity, and it has even been suggested as one of the drivers for overeating when it comes to ultra-processed foods (Gibney, 2022).

In this chapter, we address the relation between food texture perception and consumer responses in terms of liking and satiety expectations, refer to the most important methods to measure and model this relation and conclude with an illustrative case study.

1.1 Oral Processing and Texture Perception

Food oral processing is an essential step in the eating process, preparing the food for swallowing and digestion, yet also playing a key role in sensory perception (Foster et al., 2011) and food palatability (Jourdren et al., 2016), which in turn influence preferences and food intake. During oral processing, the structure of food is broken down by teeth and/or tongue (mechanical breakdown) and lubricated (hydrated or dissolved) with saliva until a swallowing threshold is reached (Pascua et al., 2013). The process was modelled by Hutchings and Lillford (1988) with three dimensions: degree of structure (rheological behaviour), degree of lubrication (secretion of saliva) and time, Fig. 1.

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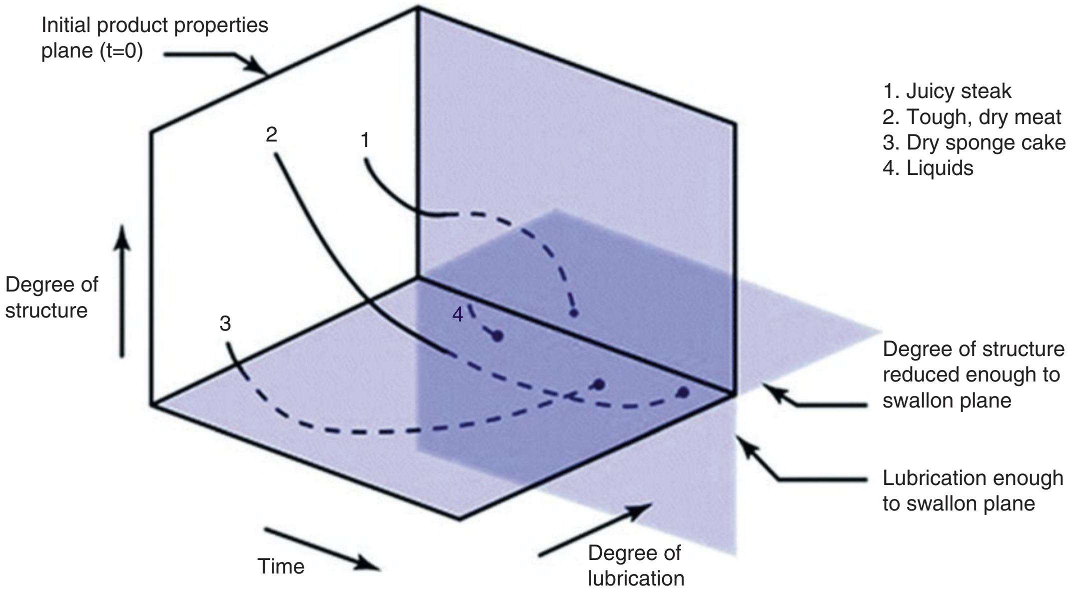

Fig. 1 Hutchings & Lillford philosophy of breakdown path. (Reproduced from Devezeaux de Lavergne et al. (2017) with permission from the Royal Society of Chemistry)

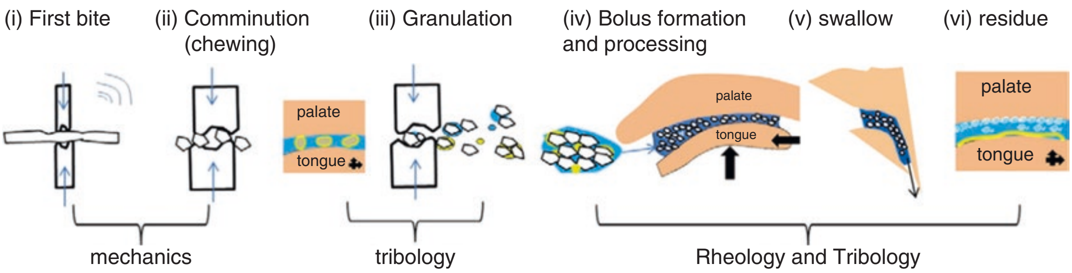

Fig. 2 Stages during oral processing of solid food. (Reproduced from Stokes et al. (2013) with permission from Elsevier)

Oral processing has been split into the following six stages (Fig. 2): (1) first bite, (2) comminution, (3) granulation, (4) bolus formation, (5) swallow and (6) residue (Foster et al., 2011; Stokes et al., 2013).
In this process, at early stages, breaking and large deformation dominate, and the sensation of food texture is mostly related to food fracture and mechanical properties. With the decrease in particle size and/or thinning down with saliva, at later stages of oral processing, surface friction and lubrication (i.e. tribology properties) become the dominating mechanism for texture perception. Sensory properties perceived are linked to the dominating mechanisms of oral sensation, thus rheology-tribology transition is very important (Chen & Stokes, 2012).

1.2 Texture and Consumers' Preferences

There is no doubt that food structure plays a key role in the pleasure of eating (Chen, 2015). Several recent reviews have emphasised that understanding the formation of food bolus is essential to explain people's eating behaviour, sensory perception, consumers' acceptance and liking of foods (Chen, 2015; Koc et al., 2013; Stieger & van de Velde, 2013; Witt & Stokes, 2015). Food texture plays a pivotal role in how foods and beverages are perceived (Bourne, 2002; Schiffman, 1977) and whether food is liked or disliked (Moskowitz & Krieger, 1995; Scott & Downey, 2007; Szczesniak, 1991). Texture is important to product liking (and disliking), preference and perceived food quality (Jeltema et al., 2019). Texture can be a major reason for food rejection (Drewnowski, 1997) and one of the strongest drivers of food aversion (Scott & Downey, 2007). Regarding pleasure, surprising textural experiences and textural contrasts are used in gastronomy for creating complex highly liked products (Palczak et al., 2020) with even the upcome of a new discipline, 'gastrophysics', based on the traditions gastronomy and food physics (Pedersen et al., 2021).

1.3 Texture, Food Intake and Satiety Perception

1.3.1 Definition and Factors Influencing Satiation and Satiety

Satiety comprises two processes: satiation (intra-meal satiety) and satiety (post-ingestive satiety or inter-meal satiety). The former is defined as the process that leads to the termination of eating, and, therefore, controls meal size; the latter, on the other hand, is the process that leads to inhibition of further eating, decline in hunger and increase in fullness after a meal is finished (Blundell et al., 2010).

According to Blundell et al. (2010), three factors influence satiety assessment, *metabolic factors* based on human long-term energy status, *sensory factors* that drive food choice and *cognitive factors* that shape our eating (Pribic et al., 2017). These factors play different roles during the meal (satiation) and post-meal period (satiety) in food reward regulation (Zheng et al., 2009), which might provide a rationale for the observed differences in food factors affecting satiation and subsequent satiety (Ni et al., 2021). Foods' sensory properties, particularly texture, play a functional role in moderating the way food is eaten and influence the total amount of food consumed within an ad libitum meal (Forde, 2016; Green et al., 2000).

Two foods of equal nutrient content may have different effects on appetite. This is because aspects of food consumption, other than the metabolic effects of nutrients in the gastrointestinal tract, contribute to appetite control (Chambers, 2016). The 'Satiety Cascade' (Blundell et al., 2010) describes that both expected satiation and satiety of foods rely on sensory attributes of foods. Among sensory dimensions, texture imparts expectations of satiation and satiety to a larger extent than flavour (Chambers, 2016; Hogenkamp et al., 2011). Food texture can influence food intake at several levels.

Texture plays a critical role in satiation or satiety through oro-sensory exposure. Longer time in the mouth and higher intensity of sensory signals are linked to higher satiation (Blundell et al., 2010; Bolhuis et al., 2011). For instance, due to their fluid nature, liquid foods require less oral processing time than semi-solid and solid, leading to a reduction in oro-sensory exposure, which is important for the development of satiety-related perceptions (McCrickerd et al., 2012; Tang et al., 2017). In principle, a high mastication number means longer oral exposure and stronger sensory signals, contributing to higher satiation (Blundell et al., 2010), but it can also result in more, smaller and homogenised particles in the food bolus, reducing the volume of digesta in the stomach (Jalabert-Malbos et al., 2007), resulting in limited gastric distension and low satiation. The direct link of texture to satiation is thus still unclear (Tang et al., 2017). There is an independent role played by texture itself in the satiation response that is independent of oral processing time (Larsen et al., 2016; Tang et al., 2016).

From a cognitive perspective, people generally perceive solid foods as more satiating than liquid foods, and that solid foods will contain more energy than liquid foods, without necessarily reflecting their actual calories (de Graaf, 2012). Texture perception plays an important role in the development of satiety related expectations: expected satiation and satiety are influenced by the structure of the food and learned through exposure, thus used by subjects to decide on prospective portion size and amount eating (Brunstrom, 2011). In this sense, texture-based reformulation has been highlighted as a promising tool to manage portion size, in the fight against overeating (McCrickerd et al., 2014; Nguyen et al., 2017).

1.4 Individual Differences in Oral Processing and Texture Perception

Oral processing is both a physical process modulated by the mechanical and geometrical properties of the food and a physiological process controlled by the central nerve system (Woda et al., 2006). Thus, bolus properties at the end of mastication depend on both food and subject characteristics, as well as on the oral strategy of the subject eating this specific food product (Panouillé et al., 2014; Yven et al., 2012). In fact, the subjects change their chewing activity according to sample textures (Tarrega et al., 2008), and their physiological characteristics play an important role in the oral processing (Chen, 2014).

When considering individual differences in oral processing, it can be assumed that subjects have different eating styles, but they all aim at producing a bolus suitable for swallowing (Mishellany et al., 2006). Jeltema and colleagues (Jeltema et al., 2014, 2015) developed a tool, JBMB®, to classify individuals into four major groups of mouth behaviour (MB): *chewer*, *cruncher*, *smoosher* and *sucker* in response to their preferred way to manipulate food products in their mouths. In practice, consumers are asked to select the image that 'best describes you, most like you'. These images are shown in Fig. 3. In principle, *cruncher* and *chewer* would be those who like to use their teeth to break down foods, whereas *sucker* and *smoosher* preferred to manipulate food between the tongue and roof of the mouth. This self-assessment has been later correlated to chewing sequence and jaw movements (Wilson et al., 2018). Jeltema et al. (2015) hypothesised that individual oral processing behaviours may drive preferences for specific food textures. However, not all studies using the JBMB tool manage to identify the different groups (see, e.g., Nguyen et al., 2020b), while others agree that individual differences are found in texture preferences but refute the idea that fixed texture-liking subgroups exist (Kim & Vickers, 2020).

Individuals use different mechanisms for the oral breakdown of food so that at any point, different groups of individuals would experience the samples differently (Brown & Braxton, 2000). Oral processing has been found to be consistent across several eating occasions, suggesting that individuals have a characteristic eating style (McCrickerd & Forde, 2017). Individuals can be characterised as slow or fast chewers regardless of the test food being used (Fontijn-Tekamp et al., 2004). Devezeaux de Lavergne et al. (2015) observed that eating speed (fast vs. slow) leads to differences in dynamic textural perception.

It is noteworthy that consumer characteristics such as age or gender may also influence oral behaviour (Ketel et al., 2019). Elderly consumers have longer consumption times and lower eating rates than young consumers for liquid, semi-solid and solid foods (Kohyama et al., 2002; Mioche et al., 2004; Peyron et al., 2004). With respect to the influence of gender on oral processing behaviour, males have larger average bite size for liquid, semi-solid and solid foods and higher eating rate for solid foods than females (Hill & McCutcheon, 1984; Ketel et al., 2019; Park & Shin, 2015). Additionally, Rosenthal and Philippe have found that when men and women chew at different stages within their oral residence time, women tend to chew at the start of oral processing, while men progressively increase the amount of chewing towards the point of swallow (Rosenthal & Philippe, 2020).

The concept of an individual's manner of oral processing, such as 'fast chewers, thorough chewers and suckers' (Carvalho-da-Silva et al., 2011) or 'crunchers, chewers, suckers and smooshers' (Jeltema et al., 2016) suggests that textures may have an individualised aspect to their perception. Additionally, different ways of

Fig. 3 Graphic MB typing tool. (Reproduced from Jeltema et al. (2016) with permission from Elsevier)

managing food in the mouth can influence preferred textures and key drivers of liking and other expectations (Brown & Braxton, 2000; Jeltema et al., 2016); those individual differences in eating behaviour and texture perception may in turn influence preferences, diet, satiety perception and food intake (Laureati et al., 2020; Varela et al., 2021).

2 Sensory and Consumer Measurements of Texture in Relation to Food Preferences and Satiation

To understand the textural characteristics of food products and link them to the generated expectations of satiety and food intake consequences, it is important to consider the whole sensory experience during the different product oral processing stages. Many studies have used instrumental measurements as a proxy, others used sensory characterisation with trained panels and later correlated to consumer expectations or have measured both aspects with the same consumers, using consumer-based descriptive methodologies (Stribiţcaia et al., 2020).

2.1 Static and Dynamic Sensory Methods

Traditionally, sensory methods with trained panellists (e.g. QDA®) have focused on static judgements, measuring the averaged intensities of textural sensations instead of temporal dimensions (Di Monaco et al., 2014). Also, various sensory studies have obtained static sensory data from untrained consumers to understand their perception of products more directly. Among consumer-based methods for sensory characterisation, check all that apply (CATA) questions

(Adams et al., 2007) have become one of the most popular methods for sensory characterisation with consumers because of their simplicity and versatility (Ares & Jaeger, 2015). In this approach, consumers are presented with a set of products and a CATA question to characterise them. Consumers are asked to try the products and to answer the CATA question by selecting all the terms that they consider appropriate to describe each of the samples, without any constraint on the number of attributes that can be selected. Nguyen et al. (2017) combined the CATA approach using consumers with a dynamic sensory evaluation with a trained panel showing good complementarity.

It is noteworthy that as the perceived intensity of the sensory attributes changes from moment to moment during consumption, dynamic descriptive methods seem the best adapted to capture the changing nature of food sensations (Nguyen et al., 2017), as static methods do not consider the temporal aspects may miss crucial information for understanding consumer preferences (Lawless & Heymann, 2010). Various temporal methods have been developed for dynamic sensory characterisation (Cadena et al., 2014). Particularly relevant to textural perception, capturing temporal sensory changes has long been an objective of researchers seeking to obtain a more complete understanding of how food products are perceived (Cliff & Heymann, 1993; Holway & Hurvich, 1937; Jellinek, 1964). The processes involved in eating, for example mastication and salivation, are dynamic processes (Dijksterhuis & Piggott, 2000). Some models have been proposed to explain the breakdown pathway of food during oral processing that emphasised the dynamic and complex nature of sensory perceptions during the continuous transformation of food from first bite to swallowing (Hawthornthwaite et al., 2015; Hutchings & Lillford, 1988; Koc et al., 2013).

Temporal dominance of sensations (TDS) is a relatively recent method that describes the evolution of the dominant sensory attributes during consumption. Egon Peterii Köster, at the Centre Européen des Sciences du Goût (CESG) in France, initiated TDS in 1999 and the method was presented at the Pangborn Symposium in Boston (Pineau et al., 2003). TDS is well established in the sensory domain now and has been applied to many product categories. The applications of TDS have been reviewed by Di Monaco et al. (2014) and Schlich (2017). This method consists in presenting to the assessors a pre-selected list of attributes, and the assessors are asked to assess the dominant one; when the assessor considers that the dominant attribute has changed, they select the new dominant sensation (Labbe et al., 2009; Pineau et al., 2009). Only one dominant attribute can be selected at a given time; owed to this, the concept of 'dominance' has been controversial, issues highlighted were around how attributes are selected, the drivers of transitions between attributes, the competition of sensory modalities, and how some phenomena like dumping or dithering could happen at some stages in TDS (Varela et al., 2018).

Conventionally, the characterisation of the dynamic sensory properties of products has been the domain of relatively few trained assessors (Ares & Varela, 2018; Lawless & Heymann, 2010). Training is used to ensure task familiarity and/or to ensure that the panel is aligned in their understanding and competent in their identification of attributes. Trained assessors have been suggested unrepresentative of consumers in their characterisation of products, as consumers might perceive the products in a different manner (ten Kleij & Musters, 2003). Nevertheless, supporting evidence has shown that trained assessors and untrained consumers will often provide similar information, and consumer results are reproducible (Husson et al., 2001; Worch et al., 2010).

Temporal check all that apply (TCATA), the temporal extension of CATA developed in recent years, could potentially overcome the abovementioned 'dominance' issue. TCATA enables the evaluation of more than one attribute at each time, resulting in a more detailed description of the sensory characteristics of products over time (Ares et al., 2015; Castura et al., 2016). Other alternatives would be to implement TDS in separate steps (M-TDS); that is, assessors are asked to perform TDS for one sensory modality (e.g. flavour) and then followed by another sensory modality (e.g. texture) avoiding the competition of modalities in assessing dominance (Agudelo et al., 2015; Nguyen et al., 2018). However, these methods are based on different conceptual aspects and are not necessarily substitutes (applicability in TCATA vs. dominance in TDS). Consequently, the choice of method should be considered in a specific situation depending on the purpose of the study. If researchers look for information about the attribute that draws the most attention, TDS is recommended. In contrast, TCATA is a better method when more detailed descriptive information is required. To identify the sensory attributes which influence satiety perception, TCATA has been recommended to capture a most detailed picture of the dynamic perceptions over time (Nguyen et al., 2018).

2.2 Measurements of Satiety and Satiation

As mentioned above, there are various expectations and perceptions linked to the management of food intake (how much we eat and how often), satiety and satiation, also linked to a complex cascade of physiological and psychological signals (Blundell et al., 2010). How to measure them and relate them to food structure and texture perception will be key in designing reformulation and product development approaches to manage overeating and tackle obesity problems.

2.2.1 Actual Measures of Satiation and Satiety

To quantify satiation, the experimenter should record the total ad libitum weight (in grams) or energy (in kcal or kJ) consumed to fullness within a meal (Chapelot, 2013). To quantify satiety objectively, it is necessary to measure the time to the next meal and/or the amount of energy consumed at the next meal (Forde, 2018).

Satiety can therefore be measured by (1) tracking changes in subjective need states over time (i.e. hunger/fullness/desire to eat) or by (2) measuring the duration between the treatment and the next meal and the intake at the next meal following the experimental treatment. Based on this, there are multiple outcomes used to measure satiety feelings, including *subjective feelings* or *objective measures* of inter-meal duration and later food intake.

Subjective appetite feelings can be measured via:

- *Scales* such as 100 or 150-mm visual analogue scale (VAS) scale (Flint et al., 2000; Stubbs et al., 2000), categorical scale (Almiron-Roig et al., 2009; Jeon et al., 2004), satiety labelled intensity magnitude (SLIM) scale (Cardello et al., 2005)
- *Time Course*, that is changes in appetite sensation over time for a specific stimulus
- *Indices of Satiety Sensations* such as satiating power (Blundell et al., 1987), satiety index (Holt et al., 1995), satiety quotient (Green et al., 1997), satiety ratio (de Castro & Brewer, 1992)

Objective measurements:

- To serve the test treatment as a *preload* and record the *intake of energy* at a meal following a predefined time gap (Forde, 2018).

For a satiation trial, the ad libitum meal is the test variable, and the experimenter is interested in how intake changes across different variants of the ad libitum meal (Forde, 2018).

Despite suggested limitations, the single--course ad libitum test meal provides a reliable and reproducible measure of quantitative energy intake from a single meal when correctly applied (Arvaniti et al., 2000; Gregersen et al., 2008). Current methods for measuring eating behaviours and recording food intake away from the laboratory are less accurate than laboratory-based methods so controlled laboratory trials are recommended to achieve representative data for causal inference (Gibbons et al., 2014).

2.2.2 Expectations Measurements

In human subjects, food is emptied into the duodenum for absorption at a rate of only about 10 kJ/min (Carbonnel et al., 1994). This greatly constrains the opportunity for physiological adaptation and the detection of energy as a meal proceeds. Thus, people often use their prior experience to moderate their intake: meal size is decided before a meal begins (via learned expectations of satiation and satiety) by the prospective volume of food to be consumed rather than its actual energy content (Brunstrom, 2011). Actually, people have very precise expectations about satiety and satiation that foods are likely to confer (Brunstrom & Rogers, 2009; Brunstrom & Shakeshaft, 2009; Brunstrom et al., 2008). Then expectations of satiation and satiety without consuming a whole portion have been used to measure satiation and satiety in many studies (de Graaf et al., 1992; Fiszman & Tarrega, 2017; Nguyen & Varela, 2021; Nguyen et al., 2017).

Expected satiation can be quantified by selecting the amount that would be required to feel full (Forde et al., 2017) or the satiation imparted by a fixed portion, whereas expected satiety can be quantified by asking the participant to imagine consuming the portion of food and rate how long they would expect to be full (Forde, 2018). Ideal portion size can be assessed by selecting the amount that they would typically consume or would like to consume at that moment (Wilkinson et al., 2012).

2.2.3 The Influence of Liking and Palatability in Food Intake

It is important to note that expected satiation, satiety and preferences influence each other and the selection of portion size (Nguyen et al., 2020a, b). Nevertheless, the ways in how these expectations (i.e., expected satiation, satiety, preferences) are related are still unclear; some studies (Bobroff & Kissileff, 1986; Rogers & Schutz, 1992) observed that increased liking increased feelings of satiety or satiation; however, others (Hill et al., 1984; Holt et al., 1999) observed that increased liking decreased feelings of satiety or satiation. While Karalus (2011) and Warwick et al. (1993) found participants felt less hungry after the more-liked meal, Rogers and Blundell (1990) found that participants felt more hungry after the more-liked meal.

Liking may be predictive of initial motivation to eat, but not of the total amount of energy consumed (de Graaf, 2005). Palatability has been shown to influence the amount of energy consumed for satiation but not influence satiety (De Graaf et al., 1999). Hedonic processes are affected by acute nutritional need states and may modulate food intake through their interaction with other physiological processes involved in satiation and satiety (Berthoud & Morrison, 2008). While some studies showed that if people eat food they greatly enjoy, they experience more pleasure, satiation and satiety (Bobroff & Kissileff, 1986; Mattes & Vickers, 2018; Rogers & Schutz, 1992), others observed that increased liking decreased feelings of satiety or satiation (Hill et al., 1984; Holt et al., 1999).

The role of palatability in the prediction of portion size has been debated in different studies. Some studies indicated that reducing palatability should result in reduced food consumption (Yeomans et al., 2004), while increases in palatability lead to short-term overconsumption (Cooke & Wardle, 2005; Yeomans, 2007). Nevertheless, others found that palatability was not associated with the selection of portions (Brunstrom & Rogers, 2009). Recently, the question whether ‘quality can replace quantity’ has been raised in some studies, proposing that food reward, an immediate sensation of wanting and liking a food when it is eaten and as a longer lasting feeling of well-being after a meal, could be used to predict the behaviour. Further, Varela et al. (2021) found that different groups of consumers reacted differently: when confronted with different isocaloric products varying in consistency and particle size, for some consumers liking and intake were correlated, while others ate more of what they liked less, driven by textural changes in the matrix.

2.3 Understanding Individual Differences in Food Preferences, Satiety and Food Intake

The role of liking as a contributor to meal size, as other factors, such as satiation and satiety, has been debated in many studies. These factors when considered separately, explain a relatively small amount of the total variance in food intake (de Castro, 2010). Therefore, the integration of liking, satiation and satiety via multivariate statistical techniques can be regarded as a good approach to better understand this issue. These types of data could be modelled by PLS path modelling as proposed by Wold and colleagues (Wold, 1975a, b, 1985) and an alternative approach, namely SO-PLS path modelling (Næs et al., 2011).

2.3.1 PLS Path Modelling (PLS-PM)

Recently, Nguyen et al. (2020b) have investigated and modelled the relations between different aspects of consumer expectations, that is liking, satiation and satiety using PLS-PM approach. In this study, eight yogurts were prepared from an experimental design of three factors viscosity (thin/thick), the particle size of oat flakes added (flake/flour) and flavour intensity (low/optimal). Consumers (n = 101) were asked to rate liking on a labelled affective magnitude (LAM) scale (Schutz & Cardello, 2001), expected satiation on a satiety labelled intensity magnitude (SLIM) scale (Cardello et al., 2005) and expected satiety on a 6-point scale from 1 = 'hungry again at once' to 6 = 'full for five hours or longer'. For ideal portion-size, they chose the extent to which they would consume as compared to the normal amount of commercial yogurt. To investigate the individual differences, consumers were classified based on their mouth behaviour (MB) using the JBMB™ typing tool, which sorts people in four groups (*cruncher*, *chewer*, *sucker* and *smoosher*) as defined by Jeltema et al. (2015) and Jeltema et al. (2016).

This study revealed some important findings: *For relations between consumer expectations*, an increase in liking leads to an increase in prospective portion size. In addition, a higher liking could produce greater satiety as a consequence of a greater satiation, being compatible with the results of the previous studies (De Graaf et al., 1999; Johnson & Vickers, 1992; Yeomans, 1996); *for individual differences*, the path diagrams of different consumer eating-styles were similar in general, but the difference in the relation Liking-Portion (when viscosity is under consideration).

2.3.2 SO-PLS Path Modelling (SO-PLS-PM)

From a statistical viewpoint, in the case of sensory and consumer data, PLS-PM approach has violated the assumption of unidimensionality of the different blocks. Then, the new study reports further development of the path modelling in which SO-PLS-PM approach is proposed to use instead of PLS-PM approach (Nguyen et al., 2020a).

The SO-PLS-PM path diagram shows three main/significant relations based on the direct effects: liking-portion, liking-satiation and satiation-satiety with the 'path coefficients' (i.e. explained variances) 20.64, 10.45 and 19.23, respectively. These results are consistent with those of PLS-PM, which emphasise the relations liking–portion, liking–satiation and satiation–satiety (Nguyen, et al., 2020b). Although there were differences in the numerical absolute values, the two approaches (i.e. PLS-PM and SO-PLS-PM) showed the same main trends: Liking was the essential regressor of expected satiation and portion size; and expected satiation mainly predicted expected satiety.

3 Case Studies

3.1 Case Study 1: Understanding the Role of Dynamic Texture Perception in Consumers' Expectations of Satiety and Satiation. A Case Study on Barley Bread

3.1.1 Background

This study (further detailed in Nguyen et al. (2017)) aimed to explore the role of texture of solid foods in consumers' perception and expectations of satiation and satiety; in particular, the role of dynamic perception during oral processing, with barley bread as a case study. Eight barley bread samples were manufactured using the same formulation and ingredients but manipulating the texture of the final products by changing process parameters (i.e. barley type, barley size, treatment, fermentation). This resulted in products varying in texture and being equi-caloric.

Eight bread products were first characterised by a trained panel using TDS method, and then four products (Table 1) were selected for a static descriptive task via QDA.

In a consumer test, consumers were asked to taste each sample and rate their liking on a labelled affective magnitude (LAM) scale (Schutz & Cardello, 2001), expected satiation on a satiety labelled intensity magnitude (SLIM) scale (Cardello et al., 2005), and expected satiety on a 6-point scale from 1 = 'hungry again at once' to 6 = 'full for five hours or longer'. Finally, consumers answered a CATA question including sensory and non-sensory attributes.

Table 1 Bread products with different levels of oat flakes, treatment and fermentation

Sample	Oat flakes	Treatment	Fermentation
Bread3	Flour	Scalding	Yes
Bread5	Flour	Scalding	No
Bread6	Flakes	Soaking	Yes
Bread7	Flour	Soaking	No

3.1.2 Main Results: Sensory Drivers of Liking and Expectations of Satiety for Each Time Interval

For analysing temporal sensory description, time duration was split into three time intervals: *beginning*, *middle* and *end*. Multiple factor analysis (MFA) was applied on the time interval data to obtain sensory maps, being able to characterise the relationships between products and temporal dynamic attributes during three stages of the mastication (Fig. 4).

The first component separated products in terms of *dough-like* dominance perception (from beginning to end of consumption), *juiciness* at the beginning and middle (*b.juicy*, *m.juicy*) and *stickiness* perception in the middle of the eating period (*m.sticky*). The second component separated products being dominantly *crumbly* (both in the beginning and middle) and *dry* in the beginning vs high dominance rates for *coarse* (during the whole consumption) and *m.chewy*.

In the correlation map (plot on the right in Fig. 4), one can see that expected satiation and expected satiety were driven by *chewy* dominance (mainly at the beginning of consumption, but also partially during the rest of the mastica-

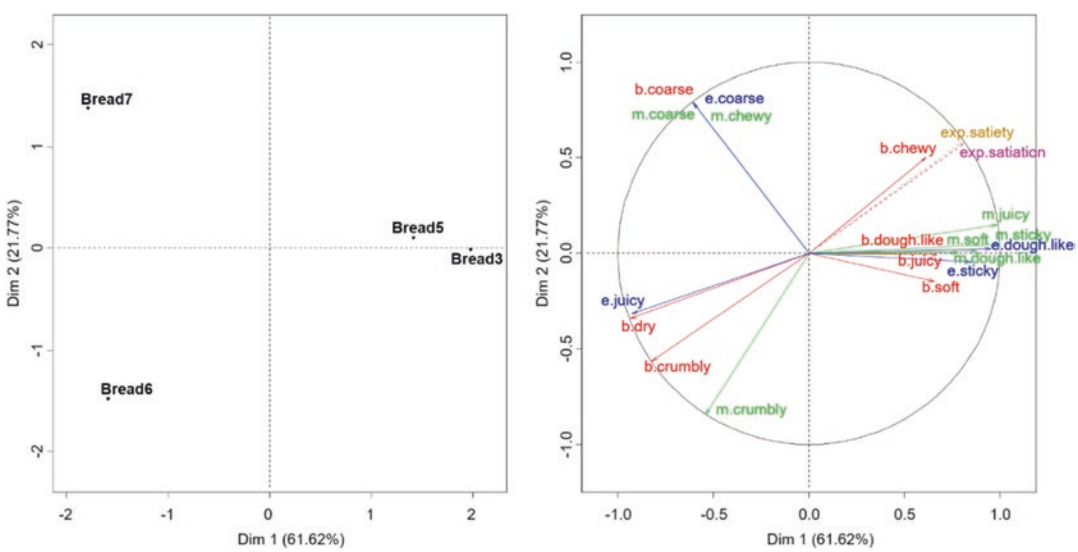

Fig. 4 Representation of the bread samples (left) and the dynamic sensory attributes (TDS data, right) across all oral processing intervals on the first two dimensions of the MFA. Codes: b., m. and e. were the notation of beginning, middle and end time intervals; expected satiety and satiation were plotted as supplementary variables

tion) and negatively correlated to *crumbly* (beginning and middle), *b.dry* and *e.juicy*.

Chewiness and *coarseness* dominance differentiated bread 7 from bread 6, which was expected to be less satiating by consumers. A more satiating barley bread would then be either dominantly *coarse* throughout the mastication and *chewy* in the middle stages or else dominantly *chewy*, *sticky* and *dough-like* throughout the mastication; on the contrary, a barley bread that is not perceived as *chewy* is dominantly *crumbly* in the first stages of the mastication and is *dry* in the beginning will be perceived as less satiating. *Juiciness* might be a driver of higher expectations of satiety in the beginning and middle of the eating period, but not in the end.

3.1.3 Implications

Chewiness dominance, mainly in the first stages of mastication, and *coarseness* throughout the mastication were drivers of enhanced satiety perceptions, whereas a dominant perception of *dryness* and *crumbliness* at the beginning were linked to breads less expected to be satiating.

The results demonstrated that manipulating the texture of (semi)solid products looks as a promising way to develop food products perceived as more satiating and lower in calories.

3.2 Case Study 2: Identifying Temporal Drivers of Liking and Satiation Based on Temporal Sensory Descriptions and Consumer Ratings

3.2.1 Background

Nguyen and colleagues highlighted that dynamic sensory perception was key in defining satiety expectations (Nguyen et al., 2017) and that consumers with different eating styles would have different reactions to textural changes (Nguyen et al., 2020b). Further, Varela et al. (2021) highlighted that different groups of consumers were driven by distinct textural attributes when assessing liking and satiety, differently influencing their intake. Therefore, it is important to see how individual differences may influence the relations between consumer ratings and dynamic sensory perceptions.

In the present case, a way of modelling together temporal sensory data and consumer ratings is proposed by splitting temporal data into CATA-coded data for each time point, applying penalty-lift analysis sequentially to each split data in order to identify sensory drivers and, finally, combing these drivers to draw temporal driver curves (for further details, see Nguyen and Varela (2021)).

Eight yogurt samples, with the same calories, composition and ingredients, but with different textures were prepared by using different processing strategies. The design parameters of the full factorial design were yogurt viscosity (thin/thick), cereal particle size (flakes/flour) and flavour intensity (low/optimal vanilla level). The details of design parameters were shown in Table 2.

A trained panel (n = 10) was used to evaluate the samples according to the TCATA method (Castura et al., 2016) with the pre-defined list of sensory attributes (*acidic, bitter, cloying, dry, gritty, sandy, sweet, thick, thin, vanilla*). Regular yogurt consumers (n=101) were recruited from Nofima's database (73 females and 28 males, age ranging between 18 and 77). General information (age, gender, BMI, consumption and usage) was collected, as well as and consumer attitudes to health and taste by Roininen et al. (1999). Consumers tasted each sample and rated their liking on a labelled affective magnitude (LAM) scale, 0–100 as in Schutz and Cardello (2001), and expected satiety on a 6-point scale, in which 1 = 'hungry again at once', 2 = 'full for up to one hour', 3 = 'full for up to two hours', 4 = 'full for up to three hours', 5 = 'full for up to four hours' and 6 = 'full for five hours or longer'.

3.2.2 Main Results: Temporal Drivers of Expected Satiety and Liking

Clustering around latent variables (CLV) approach was used to determine consumer segments according to different patterns of expected satiety. For each cluster, penalty-lift analysis (PLA) was carried out to identify if certain attri-

Table 2 Yogurt samples with different levels of viscosity, cereal particle size and flavour intensity

Sample	Viscosity	Cereal particle size	Flavour intensity
TnFkL	Thin	Flakes	Low
TkFkL	Thick	Flakes	Low
TnFrL	Thin	Flour	Low
TkFrL	Thick	Flour	Low
TnFkH	Thin	Flakes	High
TkFkH	Thick	Flakes	High
TnFrH	Thin	Flour	High
TkFrH	Thick	Flour	High

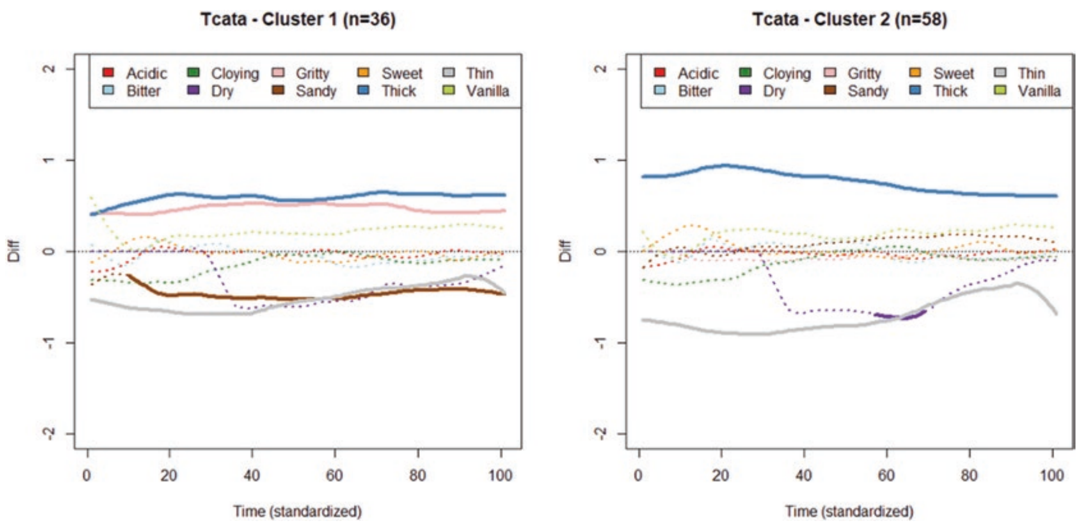

Fig. 5 Temporal changes of expected satiety for clusters 1 and 2. Solid lines: Differences in expected satiety (when an attribute is checked vs. non-checked) are significant at test level of 0.05. Dashed lines: Differences in expected satiety (when an attribute is checked vs. non-checked) are not significant at test level of 0.05

butes affected the changes in liking (or expected satiety) significantly over time, i.e. temporal drivers of liking (or expected satiety).

Temporal drivers of expected satiety are shown in Fig. 5; highlighting *thick* as a positive driver of expected satiety, while *thin* results in lower expected satiety for both clusters.

The main differences between clusters were regarding the influence of particle size (*gritty* vs. *sandy*). Cluster 1 associated gritty texture with higher satiety and sandy texture with lower satiety, but this association was not found in cluster 2. It is worth noting that they were significant overall consumption time (i.e. from the beginning to the end of the eating process). In cluster 2, *dry* was found to be a negative driver during T55-T70. These results, based on the time continuum, demonstrate that consumers in cluster 1 considered both thickness (*thick*) and particle-size (*gritty*) variables when they rated expected satiety, whereas consumers in cluster 2 focused on thickness only when they rated their expected satiety.

Temporal drivers of liking are shown in Fig. 6, where the thickness was the major driver of liking for the two clusters; particularly, *thick* increased whereas *thin* reduced hedonic ratings. Like the expected satiety results, the influence of thickness (*thick* vs. *thin*) on liking occurred throughout all the eating process.

For cluster 1, *gritty* and *sandy* led to high and low hedonic ratings, respectively. *Gritty* was a strong driver of liking from the middle to end of

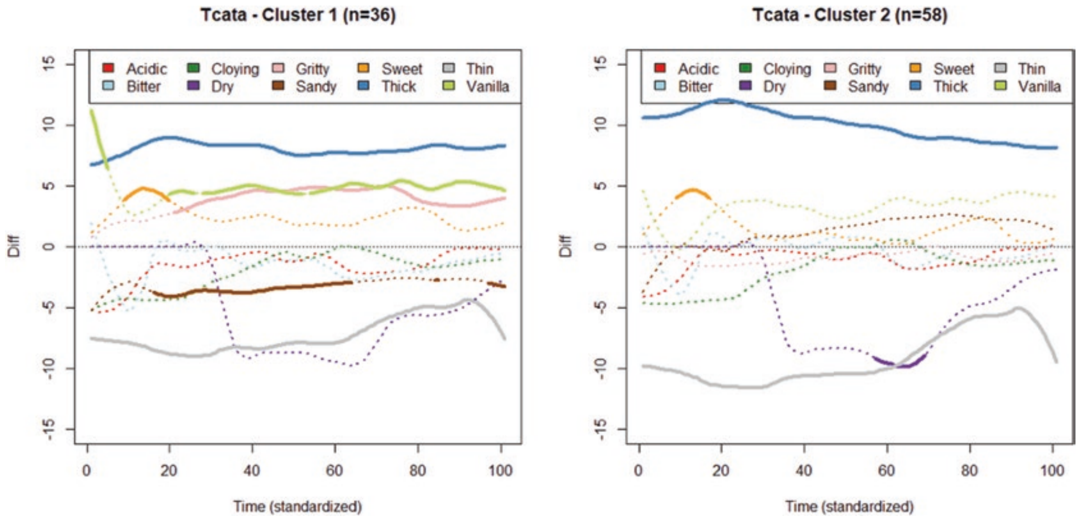

Fig. 6 Temporal changes of liking for clusters 1 and 2. Solid lines: Differences in expected satiety (when an attribute is checked vs. non-checked) are significant at test level of 0.05. Dashed lines: Differences in expected satiety (when an attribute is checked vs. non-checked) are not significant at test level of 0.05

the evaluation (T20-T100), while grittiness at the beginning was not significantly associated with a higher liking (T0-T20). Meanwhile, *sandy* showed up as a negative driver in the middle only (T20-T60), decreasing the liking if present during this time. At the end of the evaluation, *sandy* appeared as a negative driver at some time points. Regarding flavour attributes, liking was associated with sweet perceptions (*sweet*, *vanilla*). As can be seen, the effect of *vanilla* on liking was strongest at the beginning and gradually declined until T10. After that, *sweet* appeared as the main taste that increased liking (T10-T20). Finally, *vanilla* appeared again as a positive driver of liking until the end of the consumption. In general, both *sweet* and *vanilla* can be considered as positive drivers of liking. For cluster 2, the drivers of liking were quite clear. In addition to *thick*/*thin* attributes as positive/negative drivers over time, it was shown that *sweet* increased liking only at the beginning (T10-T20) similarly to cluster 1. Unlike cluster 1, in some time points at the middle (T55-T70), dry was a negative driver of liking.

Considering expected satiety or liking in the present study, particle size attributes (gritty vs sandy) were found to be important attributes that sorted consumers into 2 clusters. Cluster 1 could be seen as a high grittiness sensitivity group where consumers perceive the difference in terms of grittiness, or else they give enhanced importance to it, and differently rate expected satiety and liking between the products based on those perceptions. Cluster 2, however, could be described as a low grittiness sensitivity group including consumers who either do not perceive the difference in terms of grittiness or perceive it but do not give importance to this attribute to rate expected satiety and liking between the products tested.

3.2.3 Implications

The results suggest the important role of tactile sensitivity (grittiness in this case) in determining drivers of consumer liking and satiety-related perceptions. While the importance of texture in food preferences is well documented, there is limited understanding of how physiological individual differences in sensitivity would influence texture perception, which in turn impacts consumer preferences, expectations of satiety and food intake. More research should be performed to investigate these relations and how those are related to dynamic sensory perceptions.

The approach based on the full-time continuum allowed us to see the evolution of sensory drivers over time while maintaining the temporality of the data and allowing for a more detailed interpretation. Coupled with the clustering of consumers, this approach can provide new insights for better understanding of how temporal perception influences consumers' choices.

Furthermore, in a time where personalisation is increasing in focus, this type of information could be particularly interesting for food industries that want to develop products with particular temporal sensory profiles for specific consumer groups, with different objectives (e.g. product optimisation, products aimed at reduced intake, or products for elderly to increase their calorie intake or certain nutrients).

4 Closing Remarks and Future Perspectives

This chapter reviewed the relation among food texture perception, consumer preferences and satiety expectations, the most important methods to measure and model this relation, as well as presented two case studies. The authors highhighlighted the fact that these relations are not the same for all consumers and the importance of studying individual differences as there are groups of consumers that react differently to the textural changes.

Texture perception has regained strong attention in the last decade. Important areas of new knowledge are related to the role of texture in oral processing, satiety perception and food intake. More recently, the relationship with the degree of food processing also has been suggested, highlighting that structural and textural changes may be one reason underlying overeating (Gibney, 2022), potentially contributing to the important societal problem of obesity and related diseases.

To be able to assess food texture and mouthfeel in a systematic way and across all food categories, more research is needed also from a sensory descriptive perspective, where there are many studies but very scattered, regarding vocabulary applied to different food categories, and particularly for novel products (e.g. plant-based meat and dairy analogues). A first effort towards this has been the recent paper by NguyenBondu et al. (2022) trying to gather, classify and organise textural terms in a general ontology. Larger studies in this area are still needed, probably comprising interlaboratory studies for validation and the linkage to consumer perception.

The study of individual differences in texture sensitivity (i.e. oral tactile sensitivity) and its relation to eating behaviour, preferences, satiety perceptions and food intake is also in its infancy. A recent review (Liu et al., 2022) notes several gaps in knowledge and proposes that the sensitivity to specific texture attributes might predict texture perception and related preferences. Particularly, the study of mouthfeel perception as related to oral tactile sensitivity and product physical properties (rheological and tribological properties) has been very scarce. This will be an important area of study in the coming years.

Finally, there is still a way to go in the study of texture perception in a dynamic way and to model its complex relations among expectations, perceptions and important consumer variables (physiological measures, psychological traits, attitudes), without losing sight onto individual differences, so more sensometric developments are to be expected in this area.

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Part III

Food Texture, Instrumental Analysis

Texture Analysers

Katie Plummer

1 What Is a Texture Analyser?

A Texture Analyser is a specific type of Universal Testing Machine optimised for use in the food industry. At their simplest, Texture Analysers are instruments that use a sequence of movements to compress, stretch or bend a sample. A travelling arm or 'crosshead' is fitted with a load cell, recording the force response of the sample to the deformation that is imposed on it. Users are able to adjust test settings, such as target forces or distances, test speeds and test modes (e.g., tension, compression or cyclic loading). Force, distance and time data are collected and presented as a curve on a graph which, when analysed, indicates the texture of the sample.

Texture Analysers provide the operator with the ability to measure the textural properties of solid and semi-solid food samples. Depending on the manufacturer, they may be fitted with a wide variety of probes and fixtures that have been optimised to measure a specific range of properties. Texture Analysers provide instrumental quantification of traditionally sensory properties, such as crispness, stickiness, firmness and stretchiness of food samples. They are used in both the research and development process for the creation of new products, as well as for monitoring the properties of samples in production.

Unlike traditional fundamental test methods used in the metals, ceramics or polymer industries, food texture tests are commonly designed to be imitative, mimicking the action carried out by the consumer during use or consumption. The aim here is to imitate the conditions imposed on a food sample during manufacture, handling or consumption, giving insight into the real-life physical properties of a product. Mechanical results are dependent on the type of probe used and may give comparative rather than fundamental results (Estellé et al., 2006), although some operators use their Texture Analyser for more traditional analysis methods.

As well as the measurement of force, distance and time, modern instruments may be capable of simultaneously measuring other data types, such as acoustic, video, temperature and humidity.

This chapter reviews current Texture Analyser technology, outlining force application and measurement, displacement measurement and instrument accuracy and sensitivity. Probes and fixtures are discussed, along with the suitability of Texture Analysers for various food applications. The use of computers for collecting and analysing data is then described, including the measurement of auxiliary data, and the future of Texture Analysers.

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2 The Origin and Growth of Texture Analysers

Texture Analysers were born from the Universal Testing Machine, an instrument designed to perform tensile compressive and bending tests. They were named after the wide variety of stress states that may be applied to a sample during their use (Davis 2004), as previous instruments focussed on one function and were only able to perform a tensile, compressive or penetration method.

The very first instrument of this type was most likely a penetration-based instrument. Penetration tests are a quick and simple test to perform on many food samples. Puncture testers were manufactured as early as 1861, when Lipowitz developed the earliest recorded model. This instrument involved the application of lead shot to a disk placed on the surface of gelatin in a beaker. The total weight of the rig and shot required to cause penetration of the disk into the jelly was used as a measure of consistency. The measurement of gelatin puncture force is still used today. This apparatus evolved into the Bloom Gelometer (Bourne, 2002).

Commercial tensile testing equipment became available in the late 1800s. The earliest equipment used manual methods such as hand cranks to apply load, with an 1890 patent registered by Tinius Olsen. By 1891, Olsen produced the first autographic instrument capable of producing a stress–strain diagram (Davis, 2004).

Texture Analysers have evolved from these basic, hand-driven designs to advanced electromechanical instruments containing advanced electronics and microcomputers. Electronic circuitry and microprocessors have increased the reliability of experimental data while reducing the time it takes to perform a measurement and analyse results (Davis, 2004). This progress has enabled the rapid quantification of an enormous number of textural properties of food, from raw ingredients through to the final product.

Decades of development by Texture Analyser manufacturers and academic researchers, as well as the evolution of microprocessors and rapid progress in the way we work with software, has led to the generation of computerised, customisable instruments we see today which enable digital archiving, retrieval and comparison of data.

3 Texture Analyser Construction

3.1 Key Components

Each brand of Texture Analyser will have a unique construction, with variations between models within a brand depending on their intended function, for example, heavy duty or low force use. However, there are components common to all Texture Analysers. These major components include (Bourne, 2002):

1. A drive mechanism to provide vertical movement to the loading arm. This is driven most commonly by a screw, chain or hydraulics.
2. A system to measure and record force-distance-time data during a test.
3. A probe or fixture to deform the sample in a known and controlled way (e.g., tensile grips, flat test platform or a compression platen).

Fig. 1 shows a schematic diagram of a Texture Analyser, including the main components of interest to most operators. This is to be used as an overview as Texture Analysers have large variations in their construction.

3.1.1 Column

The supports used to provide rigidity to the instrument, either in the form of a single or double column. These supports may also be referred to as the 'frame'.

3.1.2 Instrument Arm

The arm (or 'crosshead') on a Texture Analyser is the major moving part used to deform samples during a test. It moves up or down at a constant speed (although it can sometimes be programmed to move cyclically, sinusoidally or to maintain a constant force). The load cell is usually located in the arm but may be located in the instrument base in some models. Probes and rigs are attached to the load cell, with a component also attached to

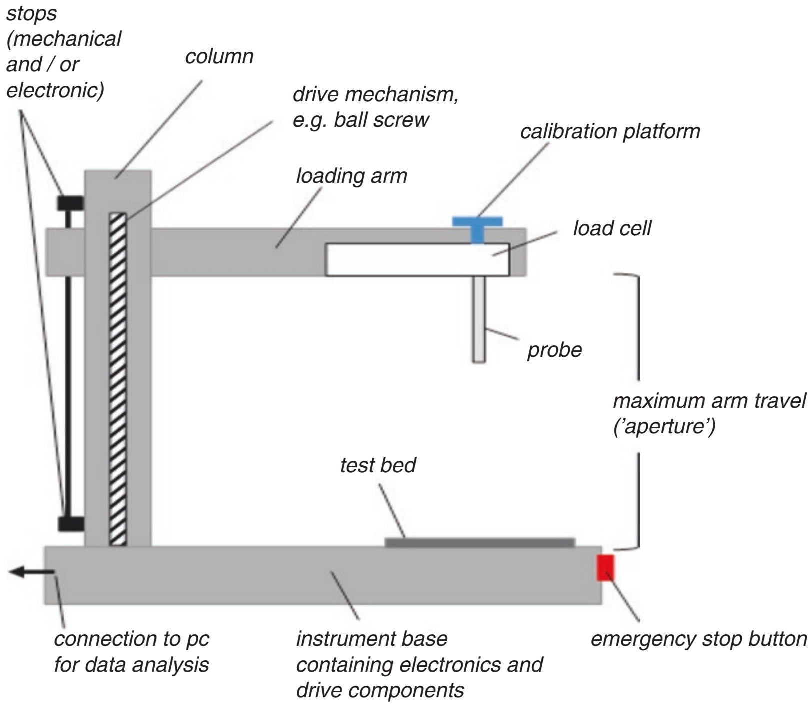

Fig. 1 Schematic diagram of a Texture Analyser, containing key components. Partially redrawn from [1]. Some Texture Analysers may have a different construction

the base when composite setups are used (such as Tensile Grips). The arm is carefully reinforced by the manufacturer to prevent excess compliance.

3.1.3 Test Aperture

The aperture (or 'maximum travel') of a Texture Analyser is the distance between the underside of the arm at its maximum height and the instrument bed. Aperture values are in the range of hundreds of mm.

The aperture determines the maximum arm displacement possible during a test. If the aperture is too small, certain tests may not be possible. For example, melted cheese extensibility testing and tensile testing of samples such as liquorice laces can result in large displacements. Some Texture Analyser manufacturers offer an extended height model to overcome this difficulty. The drawback is that these models are more expensive to manufacture due to the need for greater frame reinforcements.

In some cases, a sample of lower initial length may be used to reduce overall extension. Alternatively, higher strain rates may be used to encourage earlier rupture in viscoelastic samples.

3.1.4 Drive Mechanism

The drive mechanism is a series of parts used to move the Texture Analyser arm up and down through specific displacements at specific speeds. The choice and quality of parts used in this system determine the accuracy and precision of the arm's movement. The drive mechanism in a modern Texture Analyser is typically made up from a motor along with a series of gears, pulleys, ball screws and drive belts, although the exact mechanism is typically kept confidential by the manufacturer.

The arm and drive mechanism are coupled with reinforcement such as linear rails, guide rails and bearings to provide further stiffness to the frame and encourage vertical movement, preventing side loading of the sample under test. Some systems with more than one column containing ball screws use screws of opposite-handed thread to further eliminate twist (Davis, 2004).

3.1.5 Displacement Measurement

Most tests involve either the control or measurement of displacement or deformation of a sample. A Texture Analyser requires a means to measure this. This displacement is measured with the use of known movement of certain components in the drive system. The details of displacement measurement are generally kept confidential by the manufacturer.

3.1.6 Load Cell

Load cells are force transducers present in every Texture Analyser. They are used to measure force and are available in a wide range of capacities.

3.1.7 Electronics

Electronics are a key component of a motorised Texture Analyser, determining the type and quality of data that is recorded. The electronics receive information from force, distance and time inputs (in some systems, time is inferred from distance), as well as (in some cases) auxiliary data streams, including sound, video, temperature, resistivity, humidity or pressure. The various channels of synchronised data can then be recorded and stored for subsequent analysis. These input data are converted to a format usable for the software (or touchscreen, when software is not available). The firmware installed on a Texture Analyser enables the instrument to work as intended by the manufacturer.

Most Texture Analysers have a series of push buttons available for the operator to manually control arm movement. This is helpful when positioning a probe before a test or height calibration or moving the arm out of the way for cleaning or swapping samples.

3.1.8 Safety Mechanisms

Another key feature of electronics is the emergency stop button. This is present for rapid termination of movement by immediately cutting power to the Texture Analyser. This is an important safety feature on an instrument with the potential for rapidly moving parts, sharp components and high forces.

Some Texture Analysers come with the option of a safety screen that cuts power to the arm when open and allows movement when closed. Alternatively, instruments may be enclosed mechanically by a static shatter screen that is put in place before a test begins.

Mechanical and electronic stops are also used to protect the instrument itself. These prevent the loading arm moving past the end of its intended travel. For load cells, as well as overload and underload force limits programmed into the unit, stops are sometimes included in the load cell housing, preventing the load cell from damage.

3.2 Calibration

3.2.1 Force Calibration

A force calibration is required to enable the system to calculate the relationship between the signal from the load cell and force. The load cell measures an electrical resistance proportional to force. This is then measured by an Analogue to Digital converter, which converts these values to a useful format.

A force calibration is carried out by recording the input voltage at zero load and after the application of a known calibration weight. The relationship between these two values is calculated and used as the force-voltage response until the next calibration.

Force calibrations are generally carried out after a change of load cell, when the instrument is used and when the load cell has been overloaded.

3.2.2 Force Verification

Rather than performing a full calibration, a user may prefer to perform a 'force verification'. This is often used to determine whether or not the force measured from the load cell is linear. To do this, the user applies loads of varying magnitude and confirms that the forces are measured correctly by the load cell.

3.2.3 Zero Height

A 'zero height calibration' sets a specific arm position to zero. It enables the measurement of absolute distance and product height as well as strain and can help to speed up the testing process. A zero-height calibration is carried out by attaching the intended probe to the load cell, then driving the arm down until a target force is exerted through the probe into the test platform. Once this target has been reached, the current position of the arm is set to 'zero height'.

The target force used in this calibration is specified by the operator and is generally larger for larger probes to ensure full contact.

3.2.4 Unit Convention in the Food Industry

The standard unit of force is the Newton (N). However, gram-force, shortened to grams (g) are more widely used for force measurement in the food industry. Displacements are generally measured in millimetres (mm) as the most convenient scale for food tests, during which test displacements range from approximately 0.1 mm for the fracture of hard, brittle products such as a biscuit breaking up to tens of centimetres for the tensile measurement of very extensible products, such as the extension of some types of confectionery.

3.3 Frame Deflection

When a Texture Analyser is subjected to a force, the whole system experiences some degree of deflection, including the frame, load cell, probe or grips, couplings and the sample undergoing measurement.

Steps are taken by the manufacturer to reduce this movement as far as possible within the bounds of budget and weight. Reinforcement methods include low flexure structures used in castings (corrugation in extrusions, reinforcement bars or reduced length of cantilever components), linear rails used to prevent torsion, careful choice and installation of load cell and appropriately tightened internal bolts.

Most Texture Analysers are of the single column type, but some manufacturers offer a twin column model. The use of two columns significantly reduces frame compliance, expanding the available load capacity. This type of instrument comes at higher cost and is bulkier, so it is generally only used when the enhanced capacity is required. Food texture applications generally require the stiffness and capacity of a single column, and so this is the setup of choice for most food-specific researchers.

3.3.1 Frame Compliance Correction

Deflection is proportional to the load applied through the instrument arm. The Texture Analyser software measures displacement, and this displacement is the sum of the total system deformation. To determine the displacement of the specimen only, machine compliance (deformations associated with the load frame, load cell and grips) must be removed from this measurement. Frame compliance is specific to each system and is dependent on the forces subjected to a given system (Instron, 2010).

While this deflection is relatively minor, some operators may need to correct for it. Texture Analyser manufacturers may offer the means to compensate for bend deflection using methods including:

Single-point correction – uses a calculated force-displacement bend gradient. Non-linearities are not removed but this is still an improvement.

Multi-point bend correction – several thousand points of force-bend data plotted across an appropriate force range. This method accounts for any non-linearity that may be present with particular probe configurations, but to maintain accuracy, it must be calibrated more frequently.

When performing a bend correction, the test speed and probe or rig setup are identical to those used for a real test (Estellé et al., 2006). This process may be performed with either no sample or a dummy sample, which should be infinitely stiff compared to the stiffness of the sample being tested, so it deforms very little at the maximum force (Instron, 2010). This process must be repeated when the probe or load cell is changed, as frame stiffness is influenced by every component in contact in parallel. Fig. 2 is a schematic representation of a force-displacement graph before and after frame compliance correction.

Frame compliance correction is most important in applications that require a high force and

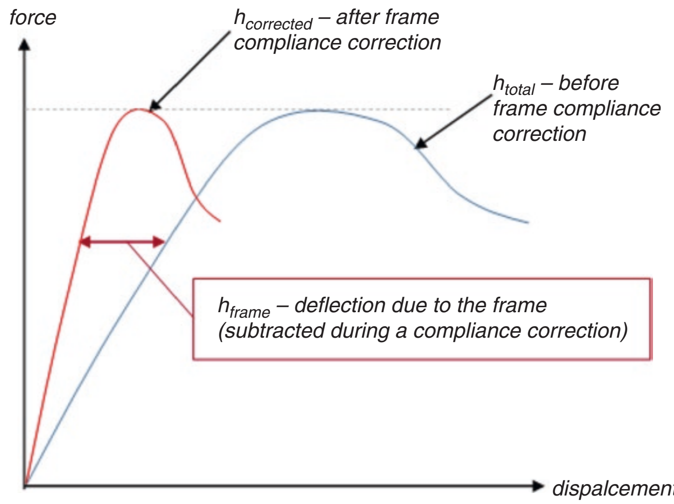

Fig. 2 A schematic representation of a force-displacement graph before and after frame compliance correction

the measurement of low deflection, such as in the fracture of powder compacts. In this application, small movements are measured while the Texture Analyser compresses a rigid sample. The compliance of the Texture Analyser is significant compared to the movement of the tablet and so must be removed. The same applies to 'squeeze flow' tests, during which a thin layer of liquid is compressed between parallel plates. However, this is not the case for most food applications. Food samples are generally compliant themselves and require smaller forces for their measurement. Consequently, frame compliance correction is not generally carried out when food testing.

For each value of applied force, the corrected displacement is equal to the frame displacement (measured during a frame correction) subtracted from the total displacement measured by the load cell:

$$h_{\text{corrected}} = h_{\text{total}} - h_{\text{frame}} \tag{1}$$

$h_{\text{corrected}}$ = corrected displacement
h_{total} = total displacement measured by the load cell
h_{frame} = frame displacement measured during the frame compliance correction procedure

Each of these values is a function of the force applied through the loading arm – the higher the force, the greater the deflection of both the frame and sample. All of these displacements are generally measured in mm. For applications in which it is necessary, frame compliance correction is carried out in tension as well as compression.

3.4 Load Cells

All Texture Analysers contain a load cell for force measurement. Load cells are components that convert a mechanical force signal into an electrical signal. They work by deforming in response to the applied force (the deformation being well below the elastic limit of any component materials). In most load cell designs provided by Texture Analyser manufacturers, deflection is measured by strain gauges bonded at points on the load cell, although piezoelectric load cells are also available. The strain gauges provide an electrical signal proportion to the applied load.

3.4.1 Capacity

The maximum force reached during the test must not be greater than the load cell capacity or an overload (in compression) or underload (in tension) will occur. On the other hand, the expected maximum force must not sit in the lower end of the load cell force range, as sensitivity may decrease in this region.

3.4.2 Accuracy and Precision

Load cell accuracy can be affected by non-linearity, hysteresis, creep and temperature effects on output and zero (Hardy, 2011). An improperly applied load (twisting or bending off-axis) causes the load cell to experience strain and send a signal change proportional to the twisting rather than the load's weight.

Consequently, rigs and probes are generally designed to ensure vertical loading. Manufacturers advise customers on correct load cell handling.

Many manufacturers have guidelines in their load cell specification for an expected degree of accuracy and precision, generally varying with applied load and dependent on capacity.

3.4.3 Format

As well as capacity, strain gauge load cells vary by form. These include S-beam, cantilever and button load cells. Different formats can produce varying force-distance responses due to the variation in components used in their construction.

In the past, some Texture Analysers were supplied with a built-in load cell of a fixed capacity. Many modern Texture Analyser manufacturers provide interchangeable load cells, so the user may change the load cell capacity depending on their current application. Load cells are generally fixed in place by screws or bolts.

3.4.4 Non-linearity

Non-linearity is the maximum deviation from a straight line of the load cell calibration curve, starting at zero load and ending at its maximum rated capacity. This represents the error in force measurement over the load cell's entire operating range. The smaller the change in weight applied to a load cell, the smaller the error resulting from non-linearity (Hardy, 2011). A schematic diagram showing non-linearity on a load cell calibration curve is shown in Fig. 3.

Due to this non-linearity characteristic, force calibration is advisably carried out over the range of expected use. For example, a 10 kg load cell should not be calibrated using a 10 kg weight, then used to measure forces of a few grams. The measured force will divert from the calibration line at this lower end.

On the other hand, a 100 kg load cell should not be calibrated with a 100 g weight, then used to measure tens of kg. The calibration line plotted between 0 and 100 g may not be representative of the behaviour of the whole range of the load cell.

Some mechanical factors influence the linearity of the load cell. These include the choice of fixing screws used to attach the load cell to the Texture Analyser and the torque to which they are tightened. When loading to high forces, a load cell that is not fixed in place correctly may provide variable results. Consequently, the use of a torque wrench is helpful in maintaining uniformity of behaviour. Some manufacturers provide a torque wrench for use in the field, instructing operators to tighten the screws to a specific torque.

3.4.5 Hysteresis

Any given load cell has a certain amount of hysteresis in its load–unload behaviour when known weights are applied or removed as shown in Fig. 3. This is the difference in the output force reading for the same applied load in the following situations, using a target force of 5 kg as an example:

1. Increasing the load from zero to 5 kg
2. Decreasing the load from a larger applied load to 5 kg (Hardy, 2011)

Hysteresis is seen on a load–unload graph as a mismatch between the loading and unloading curves.

3.4.6 Temperature Effects

Temperature changes can cause a variation in load cell measurements. This can be compensated for re-calibrating the load cell after any large temperature changes. Further to this, many load cells have a degree of built-in temperature compensation. This is achieved by built-in temperature compensation resistors and careful design of the analogue components around the strain gauges (Hardy, 2011).

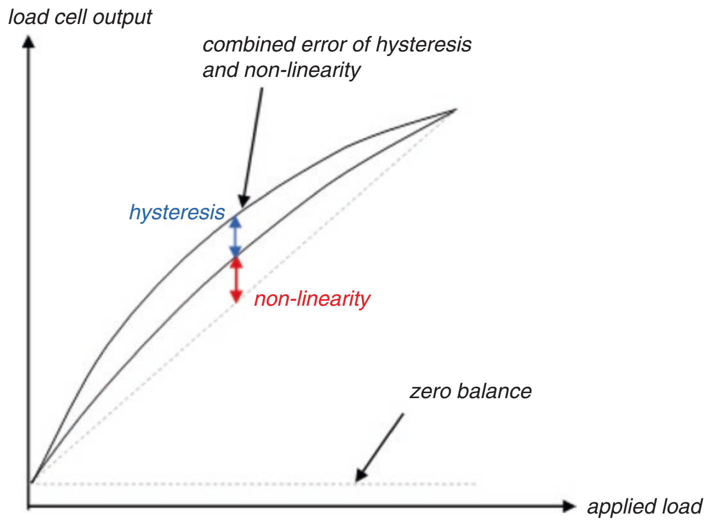

Fig. 3 Schematic diagram showing non-linearity and hysteresis on a load cell calibration curve. This may take other forms depending on the Texture Analyser and load cell used

3.4.7 Response Time

Load cells used in Texture Analysers generally have a fast response time. However, as their overall behaviour is that of a stiff spring, when a load is quickly applied, the load cell will oscillate for a very short settling period. This is on the scale of tenths of a second or less in free air. Specifying the settling time is difficult for a generic situation, as the sample being tested can dampen the oscillation, changing the resonance of the load cell. While generally not a significant effect, it is important to be aware of this when performing tests that involve rapid movements.

4 Software

Most modern Texture Analysers are sold with a software package to be used with a separate computer, although some instruments are limited to a built-in touchscreen that simply displays settings and results. There are many benefits of dedicated texture analysis software. Software allows for features otherwise not obtainable, such as allowing the user to zoom in on specific regions of graphs, perform manual graph measurements and adjust axes with ease. It also enables the user to add parameters such as sample weight and test method details to graph files and project notes for future reference.

4.1 Test Setup and Customisation

Many software packages provide the means to create bespoke test sequences to suit the needs of individual users. This may involve creating a test sequence to precisely follow a standard method or to perform an unusual sequence of movements of the test arm to imitate a physical situation such as chewing or a particular manufacturing process. Speeds, positions, target forces and hold periods are some commonly adjusted parameters in the test customisation process. Test customisation can also provide the means to adjust the data acquisition rate (sampling rate, or points recorded per second) to suit the test in question.

Texture Analyser software allows for the rapid location of folders and files associated with testing. Projects and analysis methods may be loaded quickly using the file explorer, and the location for future tests also specified with ease.

The provision of software also allows for data capture from other sources to be set up, such as temperature data from thermal cabinets.

Texture Analyser manufacturers generally specify a recommended temperature range of operation, on the order of 0°C (Stable Micro Systems TA.XTplus, Brookfield CTX) to 40°C (Stable Micro Systems TA.XTplus, Brookfield CTX, Shimadzu EZ-Test).

Similar considerations should be made for the humidity control of the environment. Humidity conditions may be specified by the Texture Analyser manufacturer with the condition that the instrument is to be used in a non-condensating atmosphere.

4.1.1 Environmental Temperature and Humidity

Another consideration must be made, and that is the operating temperature of the Texture Analyser as a whole. Below the dew point, there is a risk of condensation forming on key electronic components, bearing in mind the interior components of the Texture Analyser generate their own heat and so raise the local temperature. If the temperature is lowered even further, ice will begin to form. Both of these effects may cause damage. On the other hand, above a certain temperature, some components may begin to fail. A Texture Analyser cannot, therefore, be used in a walk-in freezer or in an excessively hot bakery.

4.2 Analysis

Many manufacturers provide automated data analysis of graphs. A major benefit is the ability for previously tested samples to be analysed at a later date.

Data analysis can involve the calculation and plotting of specific axes (such as engineering stress and strain specific to the test setup in question). A large part of data analysis in the measurement of food samples relates to calculating food-specific properties.

These physical properties aim to be highly correlated with the human sensory evaluation of food, but are often loosely based on traditional materials science parameters. For example, the hardness of a metal may be calculated by Vickers indentation, and hardness calculated as the ratio of applied load in Newtons to the cross-sectional area of the residual indentation. In food testing, indentation (or 'penetration') testing is a widely used technique due to its speed, simplicity and repeatability of setup. 'Hardness', in this case, may be recorded as the load in grams required to reach a specified displacement with a cylinder or ball probe, and so it is a simplified version of the traditional hardness calculation (Lis et al., 2021).

Some tests are more complex in their setup, but calculation is kept as simple as possible. For example, the measurement of 'spreadability' of semi-solid and viscous liquid products may be carried out by the total displacement of a product contained in a female cone by a male cone of the same geometry, resulting in a uniform thin film. A Spreadability Rig is shown in Fig. 4a, with an example measurement showing spreadability profiles of two cream cheese samples in Fig. 4b.

This does not reflect a traditional materials science measurement, but is widely used due to its correlation with the properties experienced by a consumer during use. The stress state of the sample undergoing measurement is complex, and computer modelling would likely be required for the extraction of stress and strain data. Consequently, the analysis of spreadability parameters simply involves the calculation of the absolute maximum force and the area under the positive region of the curve. Adhesive parameters may be calculated from the negative region of the curve recorded during withdrawal of the probe. These do not exactly reflect a traditional adhesive test, most commonly carried out using a flat probe applied to a substrate, but the properties correlate well to the sensory experience.

On the other hand, complex analysis may be applied to simple test methods. For example, analysis macros are widely used to calculate the parameters in the Texture Profile Analysis (TPA) double bite test method on samples such as meat (Liu et al., 2022) or fruit (Roque-Velásquez & Cesia, 2022), and some researchers perform complex stress analysis on simple compression (Marquez-Cardozo et al., 2012) and bending (Saleem et al., 2005) measurements.

4.3 Help

Most software packages provide a comprehensive help file. This may include sample projects with details of test setups, sample preparation advice, analysis methods and an explanation of

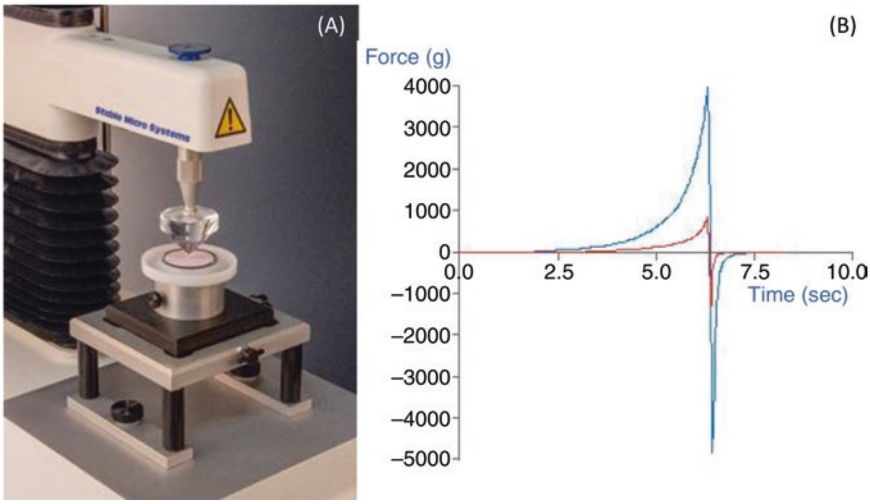

Fig. 4 (**a**) Spreadability Rig; (**b**) spreadability profiles of two cream cheese samples (Stable Micro Systems)

the stages that occur during a test. The help file may also contain detailed information on the rigs and probes available from the Texture Analyser manufacturer, with advice on their optimal use, care and maintenance and parameters such as maximum and minimum applied forces they will safely withstand to prevent damage.

5 Suitability of Texture Analysers for Different Food Applications

Texture Analysers have historically been widely used in the food industry. Consequently, over the decades they have been in action, they have adapted to meet the requirements of most food products. The choice and quality of several key components used in a Texture Analyser will affect the accuracy, precision and resolution of its measurements. Force, displacement and time are the key data channels from which others such as stress and strain are calculated.

When testing a food sample, the quality of a measurement is crucial in enabling comparison between batches or within batches over varying time periods. Some food texture measurement methods rely heavily on a high resolution in all data channels.

5.1 Force

An immediate limiting factor for food testing is load cell capacity. For example, a marshmallow compression test should use a load cell in the range 1–5 kg, depending on the intended extent of deformation. A bulk compression test on hard cereal pieces should use a load cell of capacity in the range 50–250 kg.

A 10 kg load cell would overload if used to compress bulk cereal pieces. A 250 kg load cell would be capable of measuring a marshmallow compression, but the electronic noise of the load cell and non-linearity in this region may be more evident on the resulting graph.

Load cells with a low force capacity may be used to successfully measure forces as small as a few grams, providing the ability to measure delicate properties such as the wettability of liquid food samples, although Texture Analysers are not advised for the measurement of samples of very low viscosity unless the method used acts to provide a large mass movement of the liquid, increasing the measured force. Back extrusion is a widely used measurement for samples such as honey (Chen et al., 2021) and yoghurt (García-Gómez et al., 2018), providing a quick, simple and repeatable measurement of consistency as well as adhesive properties. Rheology methods are optimised for the measurement of non-viscous liquids.

Load cells of very low capacity are fragile in nature due to the delicate components required to measure very small forces. At the lower end, load cells have a maximum capacity of a few hundred grams, for example options include a 100 g load cell on the Brookfield CTX, 200 g load cell on the Mecmesin MultiTest-i or a 500 g load cell on the Stable Micro Systems TA.XTplus and the Lloyd-Ametek TA1 series.

A higher capacity load cell should not be used to measure forces at the lowest end of their working range. For example, a 30 kg load cell would not successfully measure forces of a few grams. The electronic noise present in every load cell scales with its capacity. At some point, when using a load cell of high capacity to measure very small forces, this noise becomes visible on the test graph, and in extreme cases will cause erroneous results. This effect is demonstrated in Fig. 5, an illustration of a typical load cell response.

Additionally, load cells may have a small non-linear section at the very start of their loading curve. It is ideal to stay away from this section.

As an approximation, load cells should be used to measure forces from around 10% to 100% of their capacity.

The upper limit of load cell capacities available on the market generally exceeds the requirements of most food applications (5000 kg on the Mecmesin MultiTest-I and Instron 6800 dual column, 750 kg capacity on the Stable Micro Systems TA.HDplus, 500 kg on the Lloyd-Ametek TA1 series, Shimadzu EZ-Test and Zwick-Roell zwickiLine).

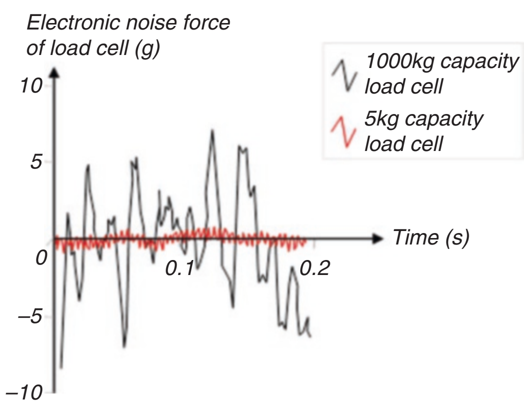

Fig. 5 Example electronic noise levels of a high force load cell and a low force load cell

Food measurement methods that can expect a higher measured force include bulk compression measurements of hard samples. The forces measured during these tests may be in the region of several kg to several tens of kg, and so higher force load cells are required.

The methods used at the higher end of a Texture Analyser's capacity may be limited. Reinforced compression platens and tensile grips are amongst the only fixtures that will withstand load of hundreds of kg. Many of the more intricate food-specific rigs will have a force limit an order of magnitude lower than this.

5.1.1 Force Sensitivity

Resolution is particularly important when small behavioural differences are used to tell two or more samples apart. For example, this may be the case when monitoring the effect of varying raw ingredient batches of flour in a sponge cake. The firmness of samples in compression may be similar, but small differences indicate inconsistencies in the final product.

Load cell choice is the main determinant of force data quality. The accuracy of the load cell generally varies with applied force, as a percentage of load cell capacity – the error quoted by the load cell manufacturer is likely to be a percentage of the reading. Any offset error in load cells is negated by taring the force, so the zero point should not be affected by an error. Resolution (the smallest force division available for measurement output) will be determined and specified by the load cell manufacturer and is generally provided in grams.

5.2 Speed

Texture analysis techniques are frequently designed to be imitative, with the test setup based on a real-life situation in many cases. For example, the Volodkevich Bite Jaws use a pair of blunt wedges with the aim of simulating the biting action of the front incisor teeth. This method is used to measure the bite hardness of cheese or the tenderness of meat. Other imitative tests include three-point bend testing of biscuits, imitating the snapping motion performed by consumers before they are eaten, the use of a Warner-Bratzler Blade on sausages to imitate the forces experienced during consumption, or the tensile measurement of a piece of pizza to imitate the process of pulling with the teeth.

Consequently, the test settings in many cases aim to imitate the process as much as the experimental setup does. The results of many texture analysis measurements are influenced by the test speed used, including those measured during Texture Profile Analysis (Rosenthal, 2010). The velocity of the jaw during a standard chewing cycle, for example, ranges approximately from 0 to 50 mm s^{-1} (Throckmorton et al., 2001), and so the test speeds used in the majority of cases sit somewhere in this range.

Other food properties of interest to the researcher or manufacturer do not centre around the chewing process, and instead focus on other aspects of the cooking or eating experience. For example, bundles of dry spaghetti and chocolate bars are frequently snapped in the hands before use. The sensory aspects of this process are important to the consumer's perception as well as those during consumption, and so tests are used to imitate these actions. The associated speeds are moderate, and still within the range of 0 to 50 mm s^{-1}.

Food properties that are completely separate from the user experience are also of interest to the food manufacturer. These may be related to transport and storage longevity, or as part of the process to reduce manufacturing costs (assessing the use of a cheaper ingredient alternative, for example). Tests in this area include adhesive tests, examining the reliability of an adhesive for securing coatings to a food sample, or measuring the stickiness of dough during the bread baking process in a factory.

Adhesive tests often combine two very different speeds – a slow speed used to apply a force to the adhesive in a controlled manner (for example, 0.05 mm s^{-1}), and a fast speed to pull away (for example, 40 mm s^{-1}). These methods are more likely to test the limits of a Texture Analyser's speed capabilities than standard food testing. Crosshead speeds can reach 50 mm s^{-1} (Zwick-Roell zwickiLine) and 40 mm s^{-1} (Stable Micro Systems TA.XTplus Connect, Brookfield CTX).

5.3 Displacement

5.3.1 Displacement Sensitivity

Displacement resolution is an important consideration for situations in which subtle changes in distance infer significantly different properties. This is the case in applications such as the stringiness of a food adhesive (Fig. 6) or the distance to fracture of a brittle sample, such as a cracker, for which each significant figure of a distance value is important.

The accuracy and precision of displacement measurements are determined by the drive mechanism and motor used. Displacement accuracy also depends on the compliance of the mechanical system; this factor may be reduced by performing a frame compliance correction.

5.4 Time

5.4.1 Time Sensitivity

When performing crispness measurements on a bulk sample such as a breakfast cereal, thousands of small fractures may occur in a short test period. The frequency and magnitude of these fractures are used in part to determine sample crispness. If a system has a low data acquisition rate, for example, 20 pps (points per second), many of these fracture events will not be registered on the graph, and so two samples of different crispness may not be as easily differentiated from one another than if a higher acquisition rate was used, for example, 2000 pps.

Fig. 7 illustrates the importance of choosing the correct data acquisition rate for a test with a rapidly changing force response. The topmost

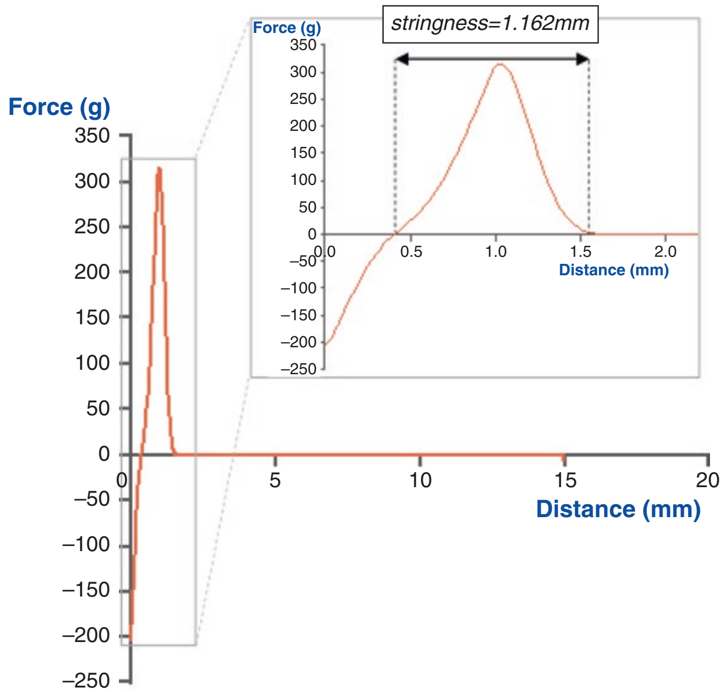

Fig. 6 Stringiness measurement of a food adhesive

graph demonstrates a force signal recorded at 2000 pps. The following three graphs show the equivalent test recorded at 1600, 800 and 200 pps. The decreasing data acquisition rate corresponds to an increasing period of time between data point collection. For 200 pps, the Texture Analyser records a data point every 0.005 seconds. Using this example, the force is only recorded at times 0, 0.005, 0.01 and 0.015 seconds, hence the crude graph form. As the data acquisition rate is increased, points are collected more frequently, and more detail becomes available on the graph output with each increase.

Tests with long hold times or very slow test speeds may require a reduced data acquisition rate during hold periods, or even a period with no data collection, to optimise the use of computer memory. These include creep and relaxation tests. High acquisition rates are generally reserved for periods of tests that contain rapidly changing data that needs to be recorded, including fracture and adhesive tests. For those tests containing a rapid succession of events, it is imperative to collect data at the highest data acquisition rate available, ensuring the collection of all detail.

The storage capacity of the computer being used to interface with the Texture Analyser may provide a limit to the data acquisition rate. Some slower computers, or computers lacking memory, may crash if a test is carried out over a long time period at a high data acquisition rate. Consequently, it can be valuable for the manufacturer to provide the option of varying data acquisition rate during a test sequence. In the example above, the data acquisition rate would be very low at all stages apart from true sample deformation (such as when the probe is moving through the air to contact the sample and when the probe is being unloaded). Data capture may alternatively be switched off during insignificant test periods.

The accuracy of time measurements is dependent upon the accuracy of the clock on which the time measurements are based. Time data is generally derived from a crystal oscillator that produces high precision pulses that drive the sample system. This is used to feed time data from the Texture Analyser to the graph viewed by the user.

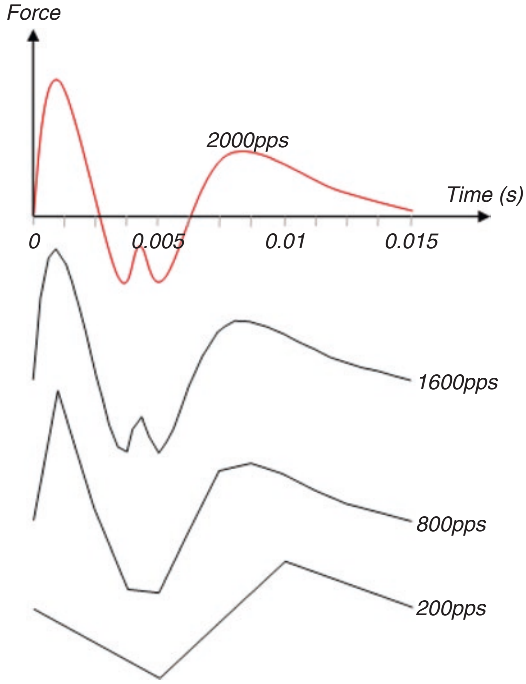

Fig. 7 A schematic diagram showing the importance of choosing the correct data acquisition rate for a test with a rapidly changing force response. The topmost graph demonstrates a force signal recorded at 2000 pps, with a loss in detail in the three following graphs (1600, 800 and 200 pps)

The resolution of time data corresponds to the number of data points per second on the final graph. This is controlled by the data acquisition rate.

5.5 Hold Control

The measurement of some properties requires the ability of the Texture Analyser to perform a hold period. This involves the application of either a specified force or specified probe position for a set period of time. Force hold periods are usually controlled by a PID (proportional, integral, differential) feedback loop, with PID settings adjustable by the user for the optimisation of the hold plateau, making it as smooth and uniform as possible. Fig. 8 shows graphs recorded from two adhesive tests carried out with optimised and non-optimised PID control settings. After optimisation, the hold period is distinctly more uniform, giving a more reliable hold force.

Properties that rely on these actions include the measurement of stress relaxation (a deformation is applied to a sample and held, and the change in force over time recorded) and creep (a force or stress is applied to a sample and held, with the deformation recorded over the hold period).

Hold periods also make up one stage in a more complicated test sequence. For example, food ingredient powders may be tested using an Unconfined Yield Stress measurement to investigate the effect of applied load on their flow properties, relevant to the manufacture, transport and storage phases of their lifetime. During one stage of this method, a force is applied to the powder surface and held for a specified time period. The stability and accuracy of the hold force has an influence on the measured properties of the powder compact. The same applies to any other test sequence containing a holding period.

6 Probes and Fixtures

Probes and fixtures available on the market range from the simplest compression platen to complex setups that imitate specific procedures such as chewing, frictional measurements or cheese grating. The most common probes and fixtures use a combination of compression, tension, penetration, cutting, bending and shear. Samples may be tested singly, in small groups or in bulk, depending on the application.

Probes and fixtures can be used to conform to standard methods, or more frequently in the food industry, tailored to suit the requirements of the user in question.

A range of intermediate methods also exists. These are methods used so frequently in industry they are almost considered standards, but not registered as such. The settings used in these methods (such as speeds, target forces and displacements) are not standardised, but published work is frequently used as a starting point.

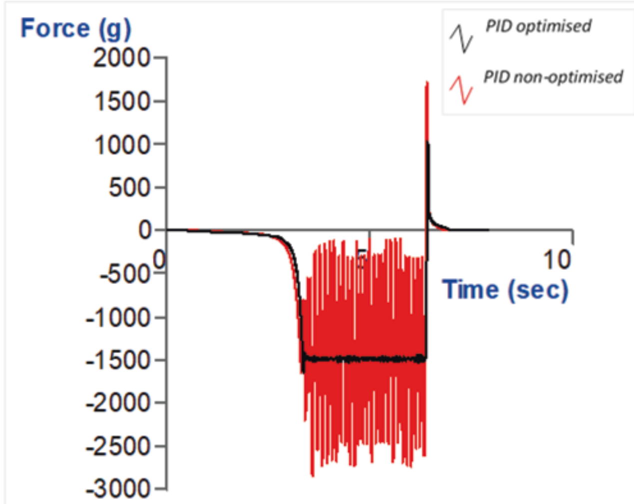

Fig. 8 Adhesive graphs before and after the optimisation of PID control settings

Additionally, many institutions have a set of 'Standard Operating Procedures' or SOPs. These are the methods specified by the company or research group and used by all Texture Analyser operators. This allows the comparison of food characteristics over a long time period with tests not dependent on the user in question.

When international standards are not being followed, food manufacturers have a certain amount of freedom when it comes to selecting the probes and fixtures for their test methods.

7 The Future of Texture Analysers

Texture Analysers began their life as a basic load-distance measurement system. With the research and modernisation that has taken place over the past few decades, their abilities have expanded well beyond force and distance measurement. Tests are now saved onto computers or locally on the instrument, and results can be viewed, and graphs analysed at any later date.

Auxiliary data input channels have expanded to include the following parameters, offered by various Texture Analyser manufacturers. In most cases, the data is not a single point measurement, but is instead collected simultaneously and synchronised with the data capture rate of the main test. This allows the changes in the following properties to be monitored throughout the whole test period.

7.1 Temperature and Humidity

Temperature is a key variable to take into account when food testing. Unlike materials such as metals or ceramics, whose properties vary over the scale of hundreds of degrees Celsius, food materials undergo phase changes, chemical changes and variations in their physical and mechanical properties over relatively narrow temperature bands. This is reflected in the experience of chocolate melting in the mouth, and the everyday process of cooking food.

Temperature must, therefore, be carefully controlled when testing certain food samples, or at least be kept within a suitable range and recorded. Texture Analysers may be supplied with temperature control and measurement options such as Peltier plates and cabinets, thermal cabinets and temperature probes. Temperature has a smaller effect on some products than others – dry pasta will not have a large variation in properties over a 10°C span, whereas ice cream can fully melt over this scale of temperature change.

The ability to either control or at least measure temperature and display it on the secondary y-axis to show the effects of temperature on force measurement is crucial to some applications. These include measurements of melted cheese extensibility, chocolate bending characteristics or ice cream hardness.

Additionally, some samples are highly dependent on the humidity of their surroundings. These include baked goods and powders. Powder flow measurements are particularly sensitive to changes in humidity, and so it should be measured or, ideally, controlled.

7.2 Acoustic

The sound emissions created during the consumption of food are key to the perceived and real quality and acceptability of the food in question. Some manufacturers now offer the ability to measure both the volume of sound emissions (sound pressure level, in dB), as well as the frequency characteristics of the sound, in the form of a WAV file. Acoustic emissions are particularly important in the measurement of food crispness in products such as breakfast cereals placed in milk (Dias-Faceto & Conti-Silva, 2022) or deep-fried batter and breaded coatings (Voong et al., 2018).

7.3 Video

As well as acoustic data, the ability to record synchronised video data is offered by some manufacturers. The video can be played back at any time after testing has concluded. Each frame of the video is synchronised to the force-time graph, allowing the operator to step through frames that cover a significant event that may not have been seen by the naked eye in real time. Graph events can then be related to visual events during the product's deformation. This capability is useful for monitoring fracture behaviour and crack propagation as well as the compression behaviour of food samples (Kohyama et al., 2019).

In some systems, it is possible to synchronise both acoustic and video data for a full audio-visual analysis of a sample's deformation behaviour. This is shown in Fig. 9, which illustrates three of the stages that occur during the fracture induced by a three-point bend test on a cracker.

7.4 Extensometer

Some operators may choose to directly measure the deformation of a food sample (particularly when performing tensile tests). This negates any need for frame compliance correction. Extensometers allow for this measurement and may be used alongside certain models of Texture Analyser.

7.5 Powder Flow

Dynamic powder flow measurements are particularly important methods for manufacturers of food powders as flow properties are key to a powder's behaviour during handling, transport and storage and have a large influence on a final food product. During a powder flow test, a flow is imposed on a powder using a known geometry, and the resulting force is measured, providing the characterisation of the sample under those controlled conditions. Measured properties include cohesion, caking, bridging, bulk density, compressibility, relaxation, stiffness, elastic recovery and powder flow speed dependence.

Although dedicated powder flow testers are available on the market, some Texture Analyser models may be fitted with a purpose-designed powder flow measurement system.

7.6 Automation

Automation is available to some extent on most Texture Analyser models. This may include automated test runs used in quality control, performing a set number of tests automatically, so the user does not have to set up a test each time, offering efficiency in sample throughput.

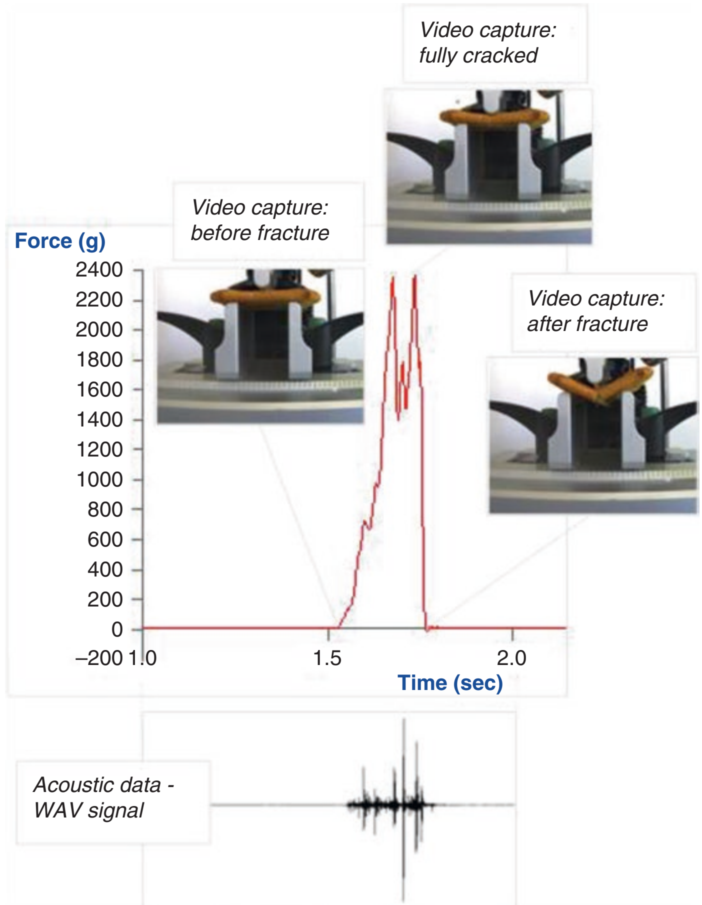

Fig. 9 Acoustic, video and mechanical data showing three of the stages that occur during the fracture induced by a three-point bend test on a cracker

Automated sample movement systems are also available from some manufacturers, including 1D and 2D raster plates, and in some cases, automated probe cleaning.

7.7 Modernising Texture Analysis

As well as expanded data acquisition potential, many manufacturers are also offering online capabilities. In some circumstances, tests may be run remotely providing an internet connection is available. This may be possible using an internet browser or through an organisation's internal network.

Texture Analysers have been through enormous changes since the first very basic models were made available several decades ago. Instruments have better accuracy, precision and resolution, higher capacities and more rapid data capture. Software has expanded with automated test sequences and analysis methods provided by the manufacturer. In the future, processors will continue to increase in performance and their power consumption will continue to fall. Software algorithms will continue to mature and the user interfaces will improve in their clarity and intuitiveness. Mobile and untethered devices will become more mainstream and voice commands will become a useful control mechanism.

Test equipment is no longer limited to simple tension or compression, but instead complex fixtures are available to measure almost any textural property of a food sample. And recorded data is no longer limited to force, distance and time, but includes a full spectrum of information regarding a sample's behaviour during deformation.

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Rheometry and Rheological Characterisation

Shona Marsh and Florian Rummel

1 Food Rheology History and Fields of Application

Rheology is the science of deformation and flow of materials. Foods are often complex materials where rheology plays a key role in food science and engineering. This applies to the entire value chain, including cultivation of raw materials, processing, storage, cooking through to eating and digestion of food.

1.1 Historical Aspects of Food Rheology

The importance of rheological properties have been recognised dating back to ancient history, even though the term 'rheology' was not yet in existence (Weipert et al., 1993). In the last few centuries, specific techniques for different types of food have been designed in order to measure their physical properties, such as characterising cereal products (dough), fruit-based products (pectin) or meat (gelatine) (Weipert et al., 1993).

The characterisation of food is of fundamental relevance since its physical appearance does not just provide an indication of processability or sensory perception. It is also crucial in the sense that insights into the physical appearance of food allow conclusions to be drawn on food safety (e.g. rope spoilage in bread from bacterial contamination). The simplest measurement methods are based on human senses, such as kneading and feeling bread dough with your hands, the visualisation of phase separation in a salad dressing or the smooth sensation of melting chocolate when the tongue moves against the palate. From a historical perspective, there are setups and geometries dedicated for specific types of food. These setups enable characterisation of special parameters, e.g. the bake-ability of rye flour suspensions using an instrument known as a viscoamylograph (see chapter 'Starch, Modified Starch and Extruded Foods'), low viscosity Newtonian fluids with an Ostwald viscometer or characterisation of gels (pectin-based) using a Lipowitz penetrometer (Weipert et al., 1993). In today's world of industrial processes, mass production is often internationally standardised with complex customer and supplier relationships that also need navigation. Therefore, there is a need for standardised and quantitative measures of food materials and hence a demand for technical instrumentation.

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1.2 Fields of Applications in Food Rheology

Currently, the rheological properties of food materials are relevant for designing the steps in the food processing value chain. Rheological properties can influence the manufacturing and processing of food and their raw materials. This makes rheology important for the development of products, processes, design of machines and quality control. Typical scenarios and applications are:

- Mouthfeel of foods: By meeting the required yield stress and shear rate dependent viscosity. Typical shear rate during food intake is approximately 50 s^{-1} (Chojnicka-Paszun, 2009)
- Medical conditions: Dysphagia (swallowing difficulties) requires establishing appropriate viscosity of substances to aid in eating and drinking. Depending on the bolus and the individual, the shear viscosity in the pharynx can be slightly higher than 50 s^{-1} (Stading et al., 2019; Qazi et al., 2019).
- Digestion of food: Where shear rates are below 0.5 s^{-1} at the small intestine villi (Lim et al., 2015).
- Design of machines in manufacturing: Optimising the residence time distributions in mills or heat exchangers which considers the shear rate dependent flow behaviour of the product.
- Optimising operating conditions: Such as in positive displacement pumps in order to overcome the viscosity generated pressure drop in a production plant.
- R&D and quality control:
  - Eliminating sedimentation of chocolate pieces in cake batter by producing a solid-like or sufficiently highly viscous mixture
  - Stability of foam confectionary while coating with molten chocolate by optimising the viscoelastic properties of the foam
  - Control extrudate swelling by tailoring normal stresses of the material.

Food rheology is relevant over 16 orders of magnitude in terms of time and length scales (Fischer et al., 2009). An overview of different time scales and deformation rates for relevant food processes are shown in Fig. 1.

Figure 2 illustrates how rheology is used to understand and improve processes and products. Processing typically changes the structure of the food ingredients and can be studied using rheological techniques. Results from rheological measurements can be applied together with the use of appropriate models in order to understand the material's behaviour and how it's affected by processing. The insights from rheological studies are used to improve the processes along with the food value chain.

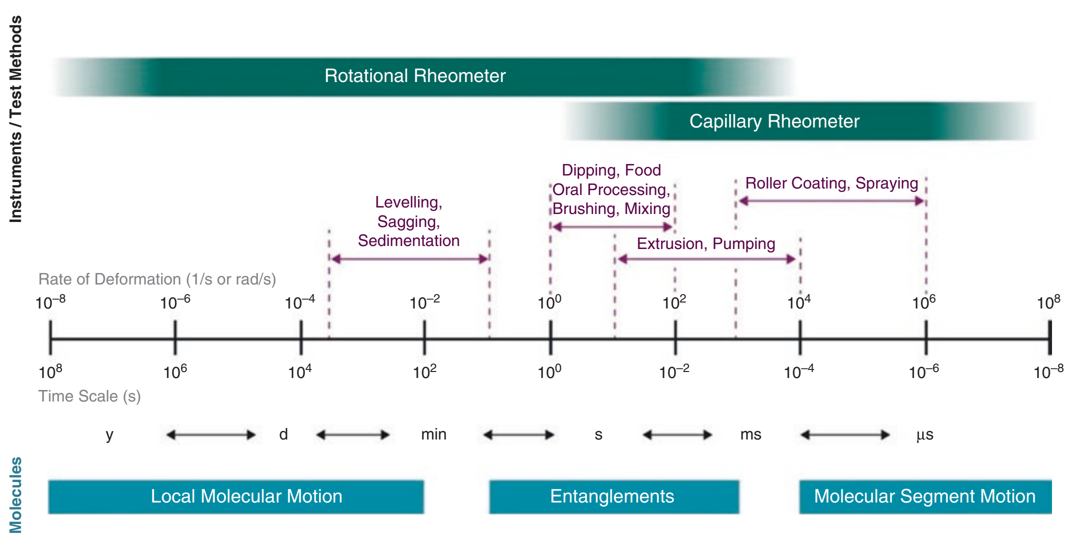

Fig. 1 Comparison of rheometry instrumentation and different measurable processes

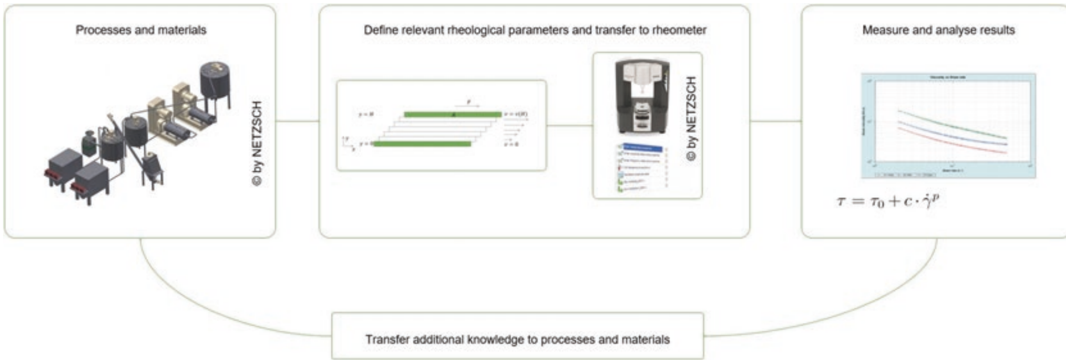

Fig. 2 Applying rheological measurements and models to processes

2 Rheometry Principles and Technologies

Overview on Rheometry

The range of rheometry instrumentation is diverse: from simple viscometers, inline rheometers to rotational and capillary rheometers. In this chapter, we provide an overview of different rheometer setups with the focus being on rotational rheometry as it is the most commonly utilised instrumentation in the field of food characterisation.

Flow Cups

Flow cups are a relatively cost-effective option for rheological analysis of fluids and are typically used in the paints and coatings industry. A flow cup consists of a funnel-shaped cup with an outlet at the lower end. In order to determine the viscosity of a fluid, the time it takes for the sample to flow out from the cup is measured. The higher the viscosity, the longer the sample takes to flow out from the cup. A flow cup is typically operated at room temperature. The shear rate to which the sample is subjected depends on the filling level which changes during the measurement. This makes the setup suitable for Newtonian fluids but causes limitations when non-Newtonian samples are studied. There are several standards available for flow cups such as ISO 2431, ASTM D 1200 (Ford Viscosity Cup) (Meichsner et al., 2016). Since this method does not allow for control or measurement of shear rates or shear stresses, it is considered a relative viscometer (Weipert et al., 1993).

Falling-Ball Viscometers

Another type of relative viscometers are called falling-ball, such as the Höppler falling-ball viscometer (Weipert et al., 1993), which consists of a tube of known diameter inclined by 10°. During the measurement a ball falls down the tube and depending on the sample viscosity, the required time to pass through the pipe changes. Since the flow field of the falling-ball is complex, it requires specific correction factors which is obtained from certified calibration oils (Weipert et al., 1993). Viscosity measurements with falling-ball viscometers are density dependent and suitable for Newtonian fluids (Meichsner et al., 2016).

Capillary Rheometers

Capillary rheometers utilise the relationship between the pressure drop of a sample flowing through the capillary and the sample flow rate (Dealy & Saucier, 2000). Calculations of rheological properties are based on the Hagen-Poiseulle equation (Tadros, 2010; Meichsner et al., 2016). Glass capillary viscometers such as the Ostwald capillary viscometer use hydrostatic pressure caused by gravity. Typical samples for glass capillary rheometers are low viscosity Newtonian liquids (Dealy & Saucier, 2000). A high-pressure capillary rheometer is capable of measuring both low- and high-viscosity materials with the ability to define shear rates or shear stresses within a measurement (Dealy & Saucier, 2000). A high-pressure capillary rheometer typically consists of a barrel with one or two bores (2 in Fig. 3) set to a defined temperature (4). The

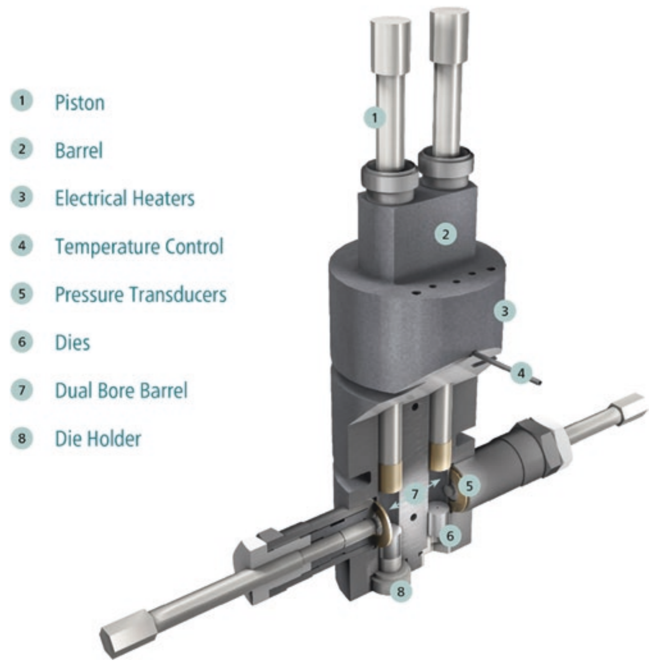

Fig. 3 An illustration on the inner components of a high-pressure capillary rheometer. Electrical heater band not shown

Table 1 Corresponding instrument raw data, mechanical data and rheological data for high-pressure capillary rheometers

Instrument raw data	Mechanical data	Rheological data
Drive speed	Piston speed [m.s^{-1}]	Shear rate [s^{-1}]
Pressure	Pressure difference [Pa]	Shear stress [Pa]

barrel is filled with sample material and a piston (1) is used to push this through a die (6) with known dimensions (diameter, length). The pressure at the die is measured with pressure transducers (5) and used for calculation of the shear stress (see Table 1). Using a second die of 'zero length' in parallel enables corrections to be applied and calculation of absolute shear viscosity and extensional viscosity.

High-pressure capillary rheometers allow us to perform rheological measurements at high shear rates, making them ideal instruments for studying material behaviour under processing conditions (see also Fig. 1).

Rotational Rheometers

The first rotational rheometer instruments were launched in the twentieth century. They provide characterisation of absolute physical properties of a broad range of materials. These versatile instruments can be equipped with a variety of different accessories or geometry configurations and perform measurements under varying and precise conditions.

A rotational rheometer is an instrument enabling analysis of specific types of sample flow or deformation. Typically, a rheometer and the accompanying software are used as a problem-solving tool to establish properties such as consistency, tackiness, stability or processability of a material. These properties in the field of rheology often fall under terms such as viscosity and viscoelasticity and can be measured by rotation or oscillation, respectively. The theory behind such measurements is detailed in the following section. Tack and axial measurements are described in the section 'Texture, Tackiness and Mouthfeel' in this chapter.

2.1 Principles of Rotational Rheometry

In order to understand the principles of rheometry, an initial introduction should be made to the basic concepts of shear rheology. The two-plate model consists of layers of fluid between two plates with surface area A, as shown in Fig. 4.

When a force (F) in x-direction is applied to the upper plate, the layers will move in a laminar flow in x-direction where the velocity in x-direction depends on the y-position. At the bottom plate (y = 0), the velocity will be 0 and at the upper plate (y = H) the velocity is highest (assuming the upper fluid layer adheres to the top plate and the lowest layer adheres to the bottom plate, see Fig. 5).

In the two-plate model, the shear stress (σ) is defined as

$$\sigma = \frac{F}{A} \quad (1)$$

The shear rate $(\dot{\gamma})$ is defined as

$$\dot{\gamma} = \frac{dv}{dy} \quad (2)$$

The shear viscosity (η) of a material is defined as

$$\eta = \frac{\sigma}{\dot{\gamma}} \quad (3)$$

The above-mentioned behaviour is applicable for ideal, viscous materials such as completely melted fats or oils (Weipert et al., 1993).

The two-plate model is also suitable for defining elastic properties of a material. An elastic material with the area A as is deformed by a force F in x-direction, yielding a deformation D in x-direction (see Fig. 6).

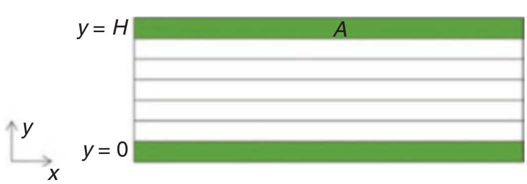

Fig. 4 Two-plate model: fluid layers between two plates at rest

The shear strain γ is defined as

$$\gamma = \frac{D}{H} \quad (4)$$

whereas the shear modulus G is defined as

$$G = \frac{\sigma}{\gamma} \quad (5)$$

An ideally elastic material will deform providing the force F is applied and will return to its initial form once force F is no longer applied. Most materials do not possess completely viscous or elastic behaviour but are actually a mixture of both. In order to describe this material behaviour, the complex shear modulus G^* is defined as

$$G^* = \frac{\sigma(t)}{\gamma(t)} \quad (6)$$

with t representing time.

G^* is the vector sum of the storage modulus G' (also known as the elastic modulus) and the loss modulus G'' (also known as the viscous modulus) of the material where the following relationship exists

$$|G^*| = \sqrt{(G')^2 + (G'')^2} \quad (7)$$

and the loss factor tan δ is defined as

$$\tan\delta = \frac{G''}{G'} \quad (8)$$

When an oscillatory movement is applied to a sample, the loss factor represents the phase shift between the shear stress and shear strain (possible sample behaviour see Fig. 7).

2.2 How Do Rheometers Work?

Rheometers must have the capability to apply and measure certain stresses or deformations to a sample. The inner workings of a rheometer are finely tuned and balanced in order to measure 'at rest' stationary conditions. The important components enabling such sensitive measurements are highlighted in Fig. 8, an inductive motor (1 in

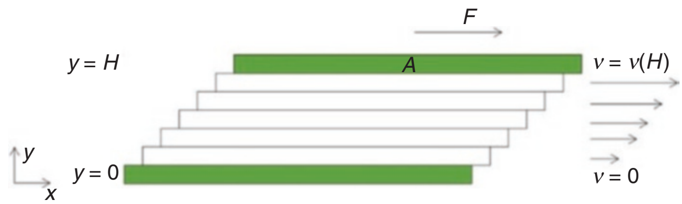

Fig. 5 Two-plate model: sheared fluid layers between two plates

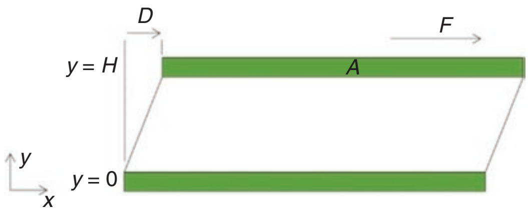

Fig. 6 Two-plate model: deformation of an elastic material

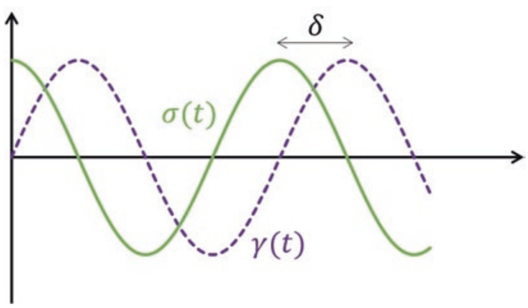

Fig. 7 Phase shift and phase angle between applied shear stress and resulting shear strain

Fig. 8) enables the precise control of the instrument torque and angular position. An air bearing (3) allows the lowest residual friction between the motor stator and rotor (2). This low friction is how the most sensitive measurements are conducted. When characterising sample behaviour under 'at rest' conditions, extremely low deformations are applied. The position of the rotor is monitored by a position sensor (4). The torque applied from the motor to the rotor must be transmitted directly to the upper measuring geometry (6) which requires a secure connection between rotor and geometry. In order to achieve this, a precision chuck mechanism (5) secures the connection between these components. Sample is applied to the lower measuring geometry (8). Once lowered to the measuring gap from the loading gap, the upper measuring geometry is in direct contact with the sample. The upper measuring geometry applies a torque (shear stress) or a speed (shear rate) to the sample. A sample may exhibit expansion or shrinkage during a measurement, e.g. due to temperature changes or normal stresses, measured by a strain gauge (7). Normal force control also enables tack tests or texture analysis as described in the section on Texture, Tackiness and Mouthfeel of this chapter.

The raw data from the instrument can be used to calculate mechanical or rheological data. In order to calculate rheological data, conversion factors and corrections are needed. In order to calculate the shear rate in a sample, properties of the geometry such as thermal expansion, inertia and dimensions must be known. A non-exhaustive overview of the interrelationship between different levels of data is provided in Table 2.

Rheological properties can be influenced by temperature, shear, pressure, time or further external parameters such as UV light. For many foods, processing, storage and consumption temperatures are in the range of 0 and 100 °C and are in a liquid state. However, for other food materials, lower or higher temperatures are used, e.g. extrusion of ice cream, where temperatures are in the sub-zero range (Eisner, 2006). Rheometers can apply specific heating and cooling rates, for measurements requiring low temperature gradients and high temperature precision. Typical configurations in rotational rheometers use Peltier modules for heating and cooling or electrical heaters for heating and chilled gas for cooling.

The measuring geometry selection for a rheometer is deliberately extensive. This is to ensure an appropriate measuring tool for both test type and the nature of the sample. For example, the sample may contain particulates, it might be viscous and sticky or exist as an emulsion. The categories of

Fig. 8 An illustration of the inner components of a rotational rheometer

Table 2 Corresponding instrument raw data, mechanical data and rheological data for rotational rheometers

Instrument raw data [W]	Mechanical data	Rheological data
Motor power	Torque [Nm]	Shear stress [Pa]
Encoder position	Angular displacement [rad] Angular velocity [rad s^{-1}]	Shear strain [%] Shear rate [s^{-1}]
Strain gauge electrical resistance	Normal force [N]	1st normal stress difference [Pa]
Stepper motor position	Vertical position [mm]	Gap [mm]

typical standard geometries are: plate systems (parallel plates, cone and plates) and cylinder systems (cup and bobs). These geometries are discussed in further detail in the next section of this chapter.

2.3 Measuring Geometries for Rotational Rheometers

Absolute measurement geometries enable calculation of the flow profile and absolute rheological properties for the entire sample, regardless of its flow properties (ISO 3219-2:2021, 2021). The following conditions must be fulfilled in order to calculate absolute rheological properties (ISO 3219-2:2021, 2021):

- Laminar flow
- No wall slip
- No slip between flow layers
- Correct loading of the sample

Laminar flow can be verified by calculating the Reynolds number in the respective flow field. In order to exclude wall slip, measurements at different gap sizes are carried out, when no wall slip occurs the results do not change as a function of gap size. The assessment of possible slip between flow layers requires insights into the rheological data and rheological behaviour of the respective sample. The correct sample loading is described in the 'Sample Handling' section of this chapter.

Cone-plate and concentric cylinders are considered absolute geometries. Relative geometries are not able to provide a measurement of the exact flow profile and rheological properties.

However, by implementing certain corrections for parallel plates, a very accurate representation of rheological properties can be obtained (ISO 3219-2:2021, 2021). Corrections can also be applied to more complex geometries in order to estimate viscosity values (Duffy et al., 2015). Common examples of non-absolute measurement geometries are parallel plates.

2.3.1 Parallel Plate Geometries

Parallel plate geometries consist of an upper plate with a radius (R) that rotates or oscillates with a certain angular velocity and torque, against a lower plate. The distance between the upper plate and the lower plate (H) is the measuring gap (see Fig. 9). The shear rate, along with the upper plate radius, is not constant since the sample is sheared with a higher velocity at the edge compared to the centre.

The simple combination of flat upper and lower plates is available in various materials, diameters and surface finishes.

- **Size** – typically ranging from 4 to 60 mm in diameter. This extensive range is available in order to accommodate different sample viscosities. The smaller geometries (<25 mm) are suited to highly viscous (>10 Pa s) samples and the larger geometries (>50 mm) for low viscosity (<0.1 Pa s) materials.
- **Measuring gap** – can be changed with parallel plates. Gaps can be tailored to match the sample's viscosity (i.e. smaller gaps for lower viscosity samples) and to achieve different shear rates. Smaller gaps subject samples to higher shear rates (for the same angular velocity), whilst larger gaps will only achieve lower shear rates. As a compromise of a modifiable gap with these measuring systems, an average shear rate is applied to the sample and is not absolute (as with cones and plates). As general guidance for all measuring geometries, if particles are present, a measuring gap of 10 times larger than the largest particle should be selected. This is to prevent particles from jamming during the measurement which will cause artefacts in the results.
- **Surface finish** – can be smooth, roughened (sandblasted) or serrated. Different surface finishes are available to accommodate more challenging samples. Emulsions, for example, may be prone to slippage. This manifests itself as a lowering/drop in viscosity during a shear rate measurement. In order to encourage the material to flow, it is recommended to use a modified surface interface which provides extra grip (see Fig. 10).
- **Materials** – standard geometries are typically made from stainless steel (SS316), suitable for most laboratory environments as they are compatible with a wide range of sample types and easily cleaned with solvents. In some circumstances, when working with acidic samples, such as gastric acid, a polymeric geometry may be more suitable. For example, PEEK and acrylic geometries (see Fig. 11) can be selected. The added advantage is that they are lighter; therefore, they are useful for high frequency oscillation measurements on low viscosity samples. In addition, titanium, aluminium and hastelloy steel geometries are also available.

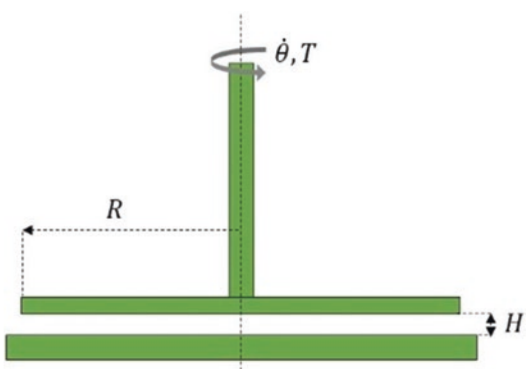

Fig. 9 Schematic of a parallel plate geometry

2.3.2 Cone and Plate Geometries

Cone and plate geometries consist of a flat lower plate with an upper cone-shaped geometry available in a variety of materials and surface finishes, e.g. roughened to prevent sample slippage. The tip of the cone is truncated and any measurements with these geometries are performed at a set gap (see Fig. 12). This enables absolute viscosity measurements; irrespective of the location of the sample within the measuring gap, it will be

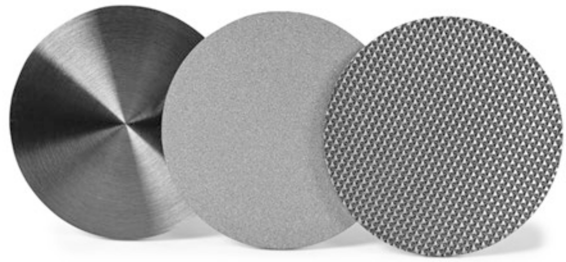

Fig. 10 Different surface finishes of upper plate geometries: smooth, roughened and serrated

Fig. 11 Alternative material upper plate geometries: PEEK and acrylic

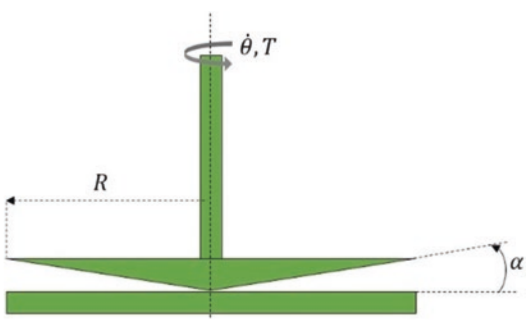

Fig. 12 Schematic of a cone and plate geometry

subjected to the same shear rate providing a significant advantage over parallel plate geometries. The cone angle (such as 1°, 2° or 4°) α and the radius (such as 10, 40 or 60 mm) R of the cone must be chosen according to the sample and proposed measurement. Compared to parallel plate geometries, the gap cannot be changed. This limits the applicability for samples comprising of particles.

Figure 13 provides a very simple guide to selecting a plate geometry according to the nature of the sample. Important considerations are highlighted, such as if particles are present (and their size), including if the material is rapidly drying (as many food products often are). If samples are prone to slippage, then a modified surface interface should be considered (see more detail in the 'Surface Finish' section of this chapter).

2.3.3 Cup and Bob Geometries

Cup and bob geometries consist of a lower cup with a radius R_a to hold the sample and an upper bob with a radius R_i to measure it (see Fig. 14). Like other measuring systems, these can be selected with different surface finishes and mate-

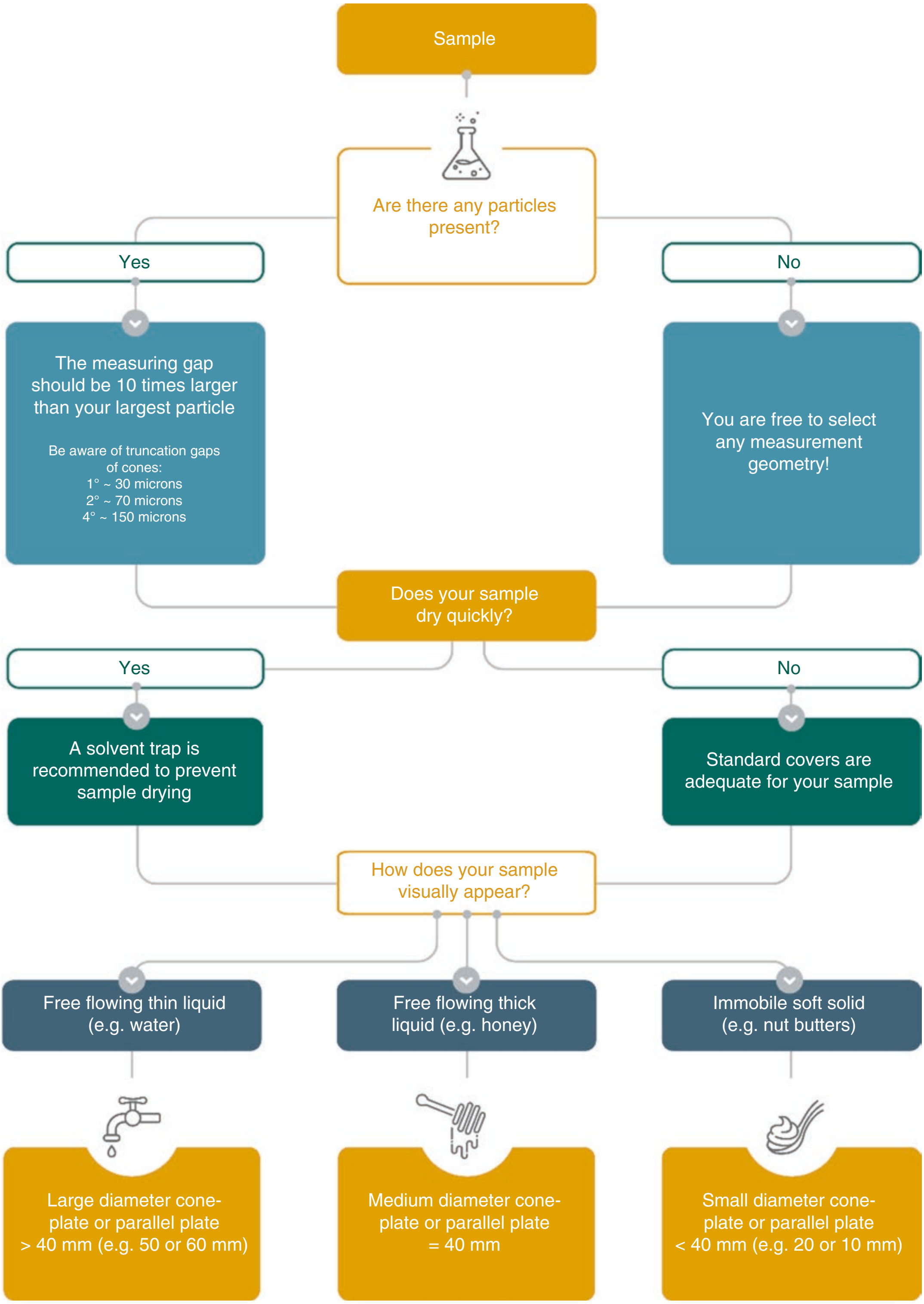

Fig. 13 Flowchart guidance on measurement plate geometry selection according to the nature of the sample

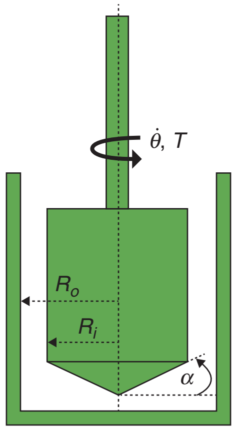

Fig. 14 Schematic of a cup and bob geometry

rials. Cup and bob geometries are suitable for measuring low viscosity systems due to the increased surface area, making them more sensitive. The relatively large gap between the upper bob and the wall of the lower cup makes them suitable for samples containing larger particulates. However, for low viscosity materials being measured with any larger gap, caution must be given to the onset of 'Taylor flow' (non-laminar flow) affecting the results. This can be detected by an erroneous increase in viscosity at higher shear rates. Calculating Taylor and Reynolds numbers ensures that the cup and bob geometry is still operated at a level without flow instabilities or Taylor vortexes.

- **Surface finish** – for samples prone to slippage, a roughened or splined (see Fig. 15) cup and bob can be selected. If sedimentation readily occurs in a suspension, a spiralled bob may help to slow/prevent the dispersion from settling during the measurement. If the dispersion is particularly unstable, then using a paddle will be more effective (see Fig. 22).
- **Vane tools** – are relative geometries and are useful for measuring samples with particularly delicate structures such as foams or soft solids with a yield stress like yoghurt. The shape of the vane (see far left geometry in Fig. 15) lends itself to slicing into the sample without disturbing or destroying too much of the sample structure prior to measurement (in comparison to a solid bob). Vane tools possess different vane lengths and radiuses.
- **Double gap** – is recommended for measuring extremely low viscosity samples/solvents. As seen in Fig. 16, the upper bob is hollow, providing an extra measuring surface area and, consequently, sensitivity. The relatively large sample volume requirements make them suitable for measuring relatively volatile samples at elevated temperatures.

3 Application Examples and Sample Handling

A rotational rheometer is an incredibly powerful and versatile tool with the ability to generate a wide range of rheological and textural information, such as viscosity, yield stress, thixotropy, viscoelasticity, tackiness and mouthfeel. Some examples are discussed in this section, with emphasis on how a rheometer may provide insight into different properties of foods.

A rough guide to testing an unknown sample for the first time can be seen in Fig. 17. By performing an initial table of shear rates on the sample, insightful information can be determined about the rheological behaviour and whether further modifications need to be made to optimise the testing conditions. For example, if a sample is found to be thixotropic (when viscosity is time dependent and rebuilds after shearing) considerations can be made on how the sample is handled, loaded and appropriate equilibrium times after loading can be applied. Similarly, if a sample is prone to drying, then a solvent trap cover (see Fig. 33) recommended to be used so that an accurate rheological representation of the sample can be made without drying influencing the results.

3.1 Yield Stress

If a product possesses a yield stress, it requires a certain amount of force (or stress) in order to encourage flow. Under rest conditions these products will remain rheologically stable and hold their form or shape. Food samples with a

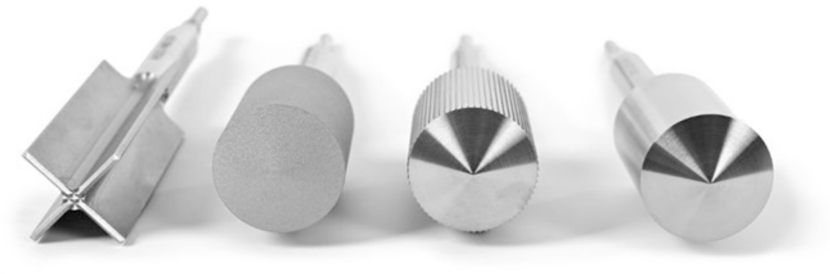

Fig. 15 Selection of upper bob geometries. Left to right: vane, roughened, splined and smooth

Fig. 16 Double gap upper bob and lower cup

certain structure (such as many sauces) possess a yield stress which have been finely 'tuned' to provide the consumer with satisfactory pouring, spreading or dipping, thereby introducing the perception of a quality and luxurious product before tasting. Measuring yield stress can be undertaken via a variety of rheological tests; stress ramp, stress growth, oscillation amplitude sweep, multiple creep testing, tangent analysis and model fitting (Sun & Gunasekaran, 2009; Larsson & Duffy, 2013).

In order to obtain relevant, robust and reproducible yield stress data, it is essential to assess the different test types and have a consistent approach. Yield stress is not a material property per se and it depends on the chosen approach as how it has been measured.

Examples of yield stress results, on different ketchups, determined using the stress ramp method with a rotational rheometer are shown in Fig. 18. During this measurement, an increasing stress is applied to the sample during a user-defined amount of time. The sample's structure will start to stretch and resist until it is no longer able to withstand the applied stress (the yield point), defined as the peak in the curve. After this yield point, the material will flow.

Observations of ingredients will indicate whether a product contains a 'rheological modifier' or thickener. In this instance, the premium ketchup contained a significantly higher percentage of tomatoes than the value brand ketchup, which had been thickened or 'bulked out' with corn flour. However, the results still indicate that the premium ketchup has a higher yield stress (~22 Pa compared to ~12 Pa for the value ketchup).

3.2 Viscosity

There are two basic types of flow: shear flow and extensional flow. In shear flow, the fluid components shear past each other (see Fig. 5), whilst in extensional flow, the components flow away or towards one another. The most common flow behaviour, and one that is most routinely measured on a viscometer or rheometer is shear viscosity.

Viscosity is the resistance of a material to flow and a commonly used term to describe consistency of a product. A material that decreases or increases in viscosity (with increasing shear rate or stress) is termed non-Newtonian (shear thinning or shear thickening, respectively, see Fig. 19). Non-Newtonian materials include sauces and ketchups (as seen in Fig. 18), melted chocolates and yoghurts. A Newtonian fluid is one where the shear stress is linearly related to the shear rate, therefore the

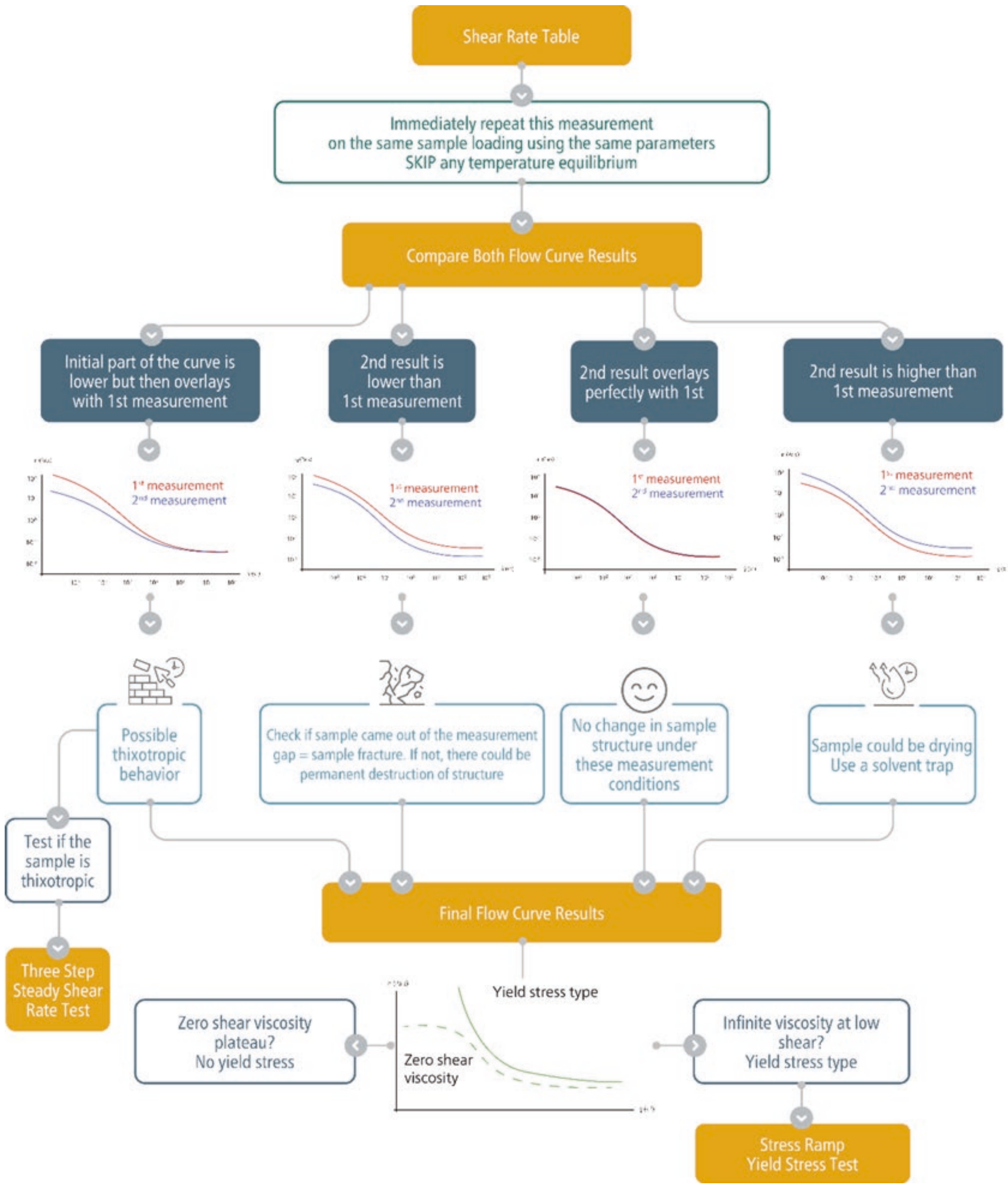

Fig. 17 Guidance for flow curve measurements of an unknown sample

viscosity is invariable with shear rate or shear stress (see Fig. 19). Newtonian fluids include water, low concentration colloidal dispersions and some oils.

As mentioned previously, viscosity modifiers are commonly used in foods in order to improve consistency, mouthfeel or even stability by introducing a yield stress (see chapters 'Starch, Modified Starch and Extruded Foods' and 'Hydrocolloids as Texture Modifiers'). Products need to perform in manufacture; handle stresses of transportation, behave correctly through application (squeezing, pouring, spreading) prior to consumption and remain stable over time.

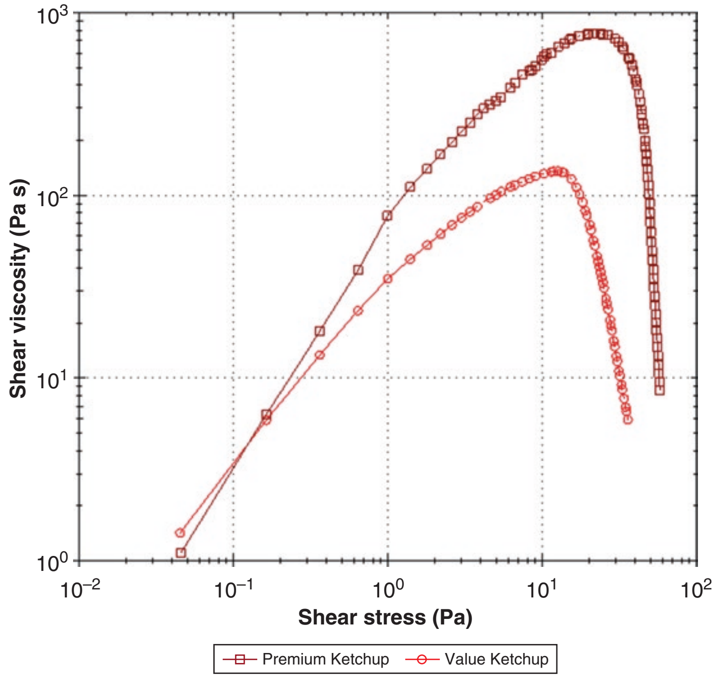

Fig. 18 Yield stress comparison of a premium and a value ketchup measured by a stress ramp test on a rotational rheometer at 25 °C

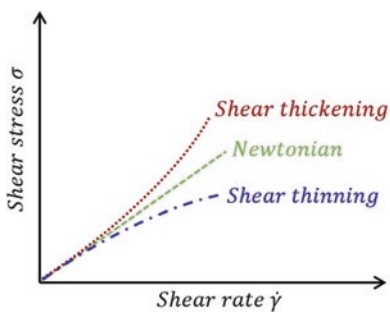

Fig. 19 Schematic representation of flow curves of materials with different shear-rate dependent flow behaviour

Viscosity can be measured on a rotational rheometer, capillary rheometer or viscometer. A rheometer is a more versatile and sensitive instrument, the combination of both rotational and capillary rheometry covers an extremely wide range of shear rates and applications (see Fig. 1). A viscometer typically employs a mechanical bearing that limits the speed and torque capabilities of the instrument, resulting in a relatively narrow measuring window. This can be suitable for certain relevant applications, or for Newtonian materials. However, a rotational rheometer is used to study a much wider range of shear rates because it possesses an ultra-low friction air bearing.

A comparison of white, milk and dark chocolate using a standardised chocolate test method is shown in Fig. 20. Particle size of the cocoa solids, sugar and milk in addition to the flow properties of the fat phase (cocoa butter) influence how the chocolate melts and feels in the mouth. A reduction in particle size increases viscosity which may have subsequent issues for manufacturing and pumping chocolate within the factory.

Dark chocolate exhibits the lowest viscosity across the measured shear rate range and will be easiest to process and manufacture. White chocolate possesses the highest viscosity which is commonly reported throughout the confectionary industry as being the most challenging.

In addition to measurements of viscosity, as a consequence of shear rate, shear viscosity can also be obtained as a function of time or temperature. In the example of chocolate, a temperature ramp can indicate how it will flow in the mouth or during processing temperatures.

A rheometer can also be used to simulate processes, such as starch pasting. Figure 21 shows the starch pasting viscosity profile as a function

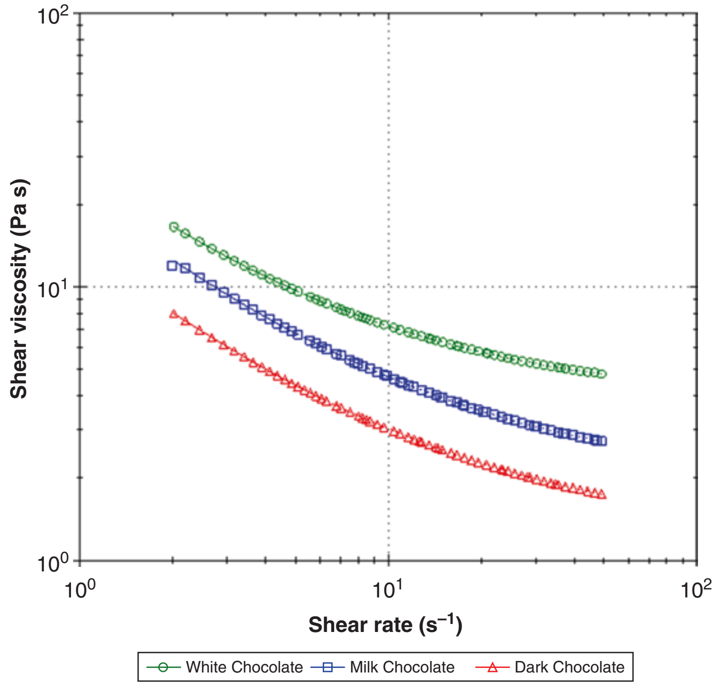

Fig. 20 A shear viscosity comparison of white, milk and dark chocolate at 40 °C

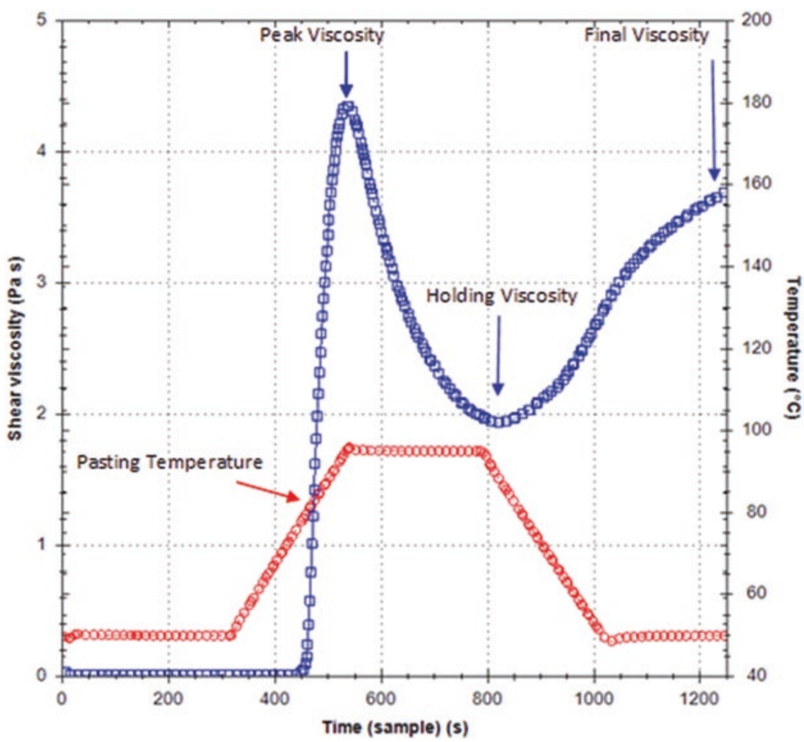

Fig. 21 The viscosity profile during a starch pasting measurement

Fig. 22 Starch pasting paddle

of temperature. These measurements are conducted using a starch pasting paddle, as shown in Fig. 22 (see chapter 'Starch, Modified Starch and Extruded Foods').

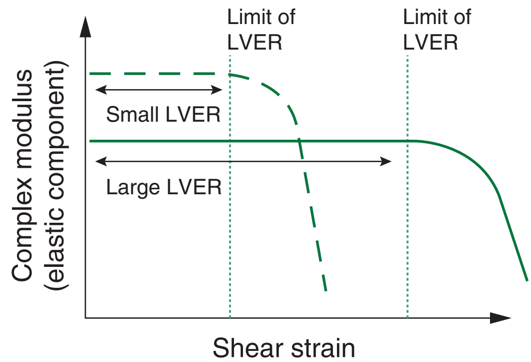

Fig. 23 Illustration of the LVER of different materials, comparing the elastic component (G') as a function of applied shear strain

3.3 Viscoelasticity

Using a rotational rheometer to provide information on the viscoelasticity of a material can be a very valuable insight into how the product will behave over different timescales. The most common method is small amplitude oscillatory shear (SAOS) testing. The precursor to any oscillatory measurement requires the establishment of the material's linear viscoelastic region (LVER). The linear viscoelastic region of a material is where the stress and strain are proportional and is obtained by an amplitude sweep, which applies an increasing oscillatory strain (or stress). Representative of structure within a material, the elastic component (G') of the complex modulus is plotted as a function of, in this example, shear strain (see Fig. 23). Within the LVER, applied strains are insufficient to cause structural breakdown (yielding) and thereby microstructural properties are being measured. The point at which the LVER deviates from linearity is the limit of the LVER, shear strains applied outside of this region will be destructive to the sample and therefore will no longer be representative of the microstructural properties. Once the LVER of the material has been established, a strain (or stress) should be selected within this region enabling any subsequent oscillatory measurements to be non-destructive and representative of the material's properties.

There are various oscillatory measurements that can be performed on a material to obtain information regarding behaviour over time, temperature or time scale (frequency). The elastic modulus (G'), viscous modulus (G") and phase angle (δ) are representative of the material's viscoelastic behaviour. Viscoelastic materials exhibit time dependency, which can be evaluated by varying the frequency of the applied stress or strain. High frequencies correspond to short time scales and low frequencies correspond to longer time scales. Typically, a material's viscoelasticity is classified by how it behaves under rest conditions, such as low frequencies. At low frequencies, a viscoelastic solid material will exhibit a G' that is higher than G" indicating solid behaviour is dominant ($\delta < 45°$) (see Fig. 24). For a gel-like material, G' and G" are parallel and δ is constant with a value between 0° and 45° (Chambon & Winter, 1987). A viscoelastic liquid will, however, exhibit a G" that is higher than G' at low frequencies, indicative that liquid behaviour is dominant ($\delta > 45°$). The viscoelastic spectrum may vary greatly depending on the material under test. Some materials may transition to exhibit the reverse behaviour at high frequencies than they did under rest conditions. This is particularly important to understand when designing new formulations to determine behaviour under different conditions. Something that appears very liquid-like at rest, may not repli-

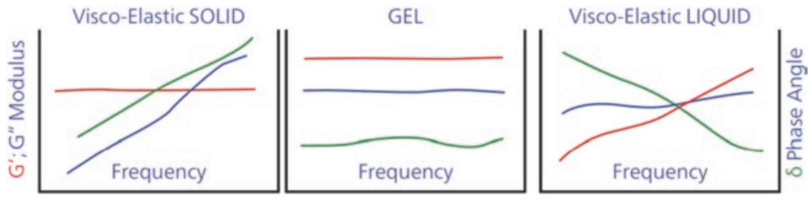

Fig. 24 Illustration of different viscoelastic behaviours (viscoelastic solid, gel and viscoelastic liquid) as a function of frequency

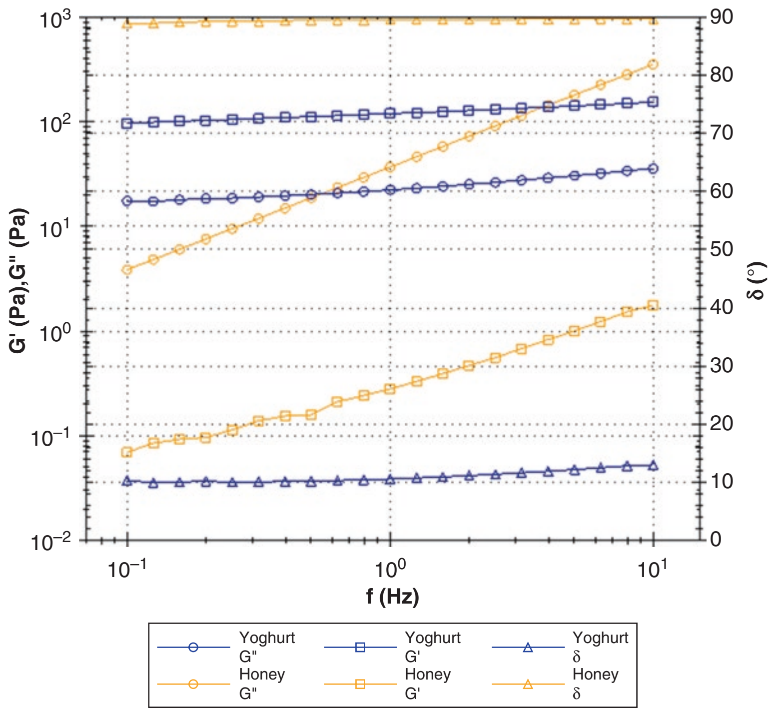

Fig. 25 An oscillatory frequency sweep measurement of honey and yoghurt at 25 °C

cate this characteristic under faster time scales such as during processing or in application.

Fig. 25 shows a comparison of yoghurt and honey plotted as a function of frequency. It can be seen that honey behaves as a viscoelastic liquid. The phase angle remains high throughout all applied frequencies, indicating that honey will flow. In contrast, yoghurt exhibits a low phase angle throughout the measurement, with a slight increase towards higher frequencies, indicating a solid-like behaviour is dominating. This type of solid-like response is desirable when considering the rheological stability of a product. When requiring a suspension to remain stable, a viscoelastic solid-like behaviour should be observed during an oscillatory frequency sweep.

3.4 Texture, Tackiness and Mouthfeel

Recent advances in rheometry design enable rheometers to gain insight on both texture and mouthfeel of a product. From studying the force required to snap a biscuit or to probe and spread cream cheese, there are non-standard measuring geometries that can utilise the axial capabilities of a rheometer to provide textural information. Fig. 26 shows some examples of texture analysis probes for measuring soft solids, pastes, gels etc.

Fig. 28 shows the comparison of force required to snap a milk chocolate coated biscuit at room temperature to one that had been stored in the refrigerator. The upper texture analysis geometry (see Fig. 27) was programmed to move down at

Fig. 26 Texture analysis probes for investigating the characteristics of soft solids

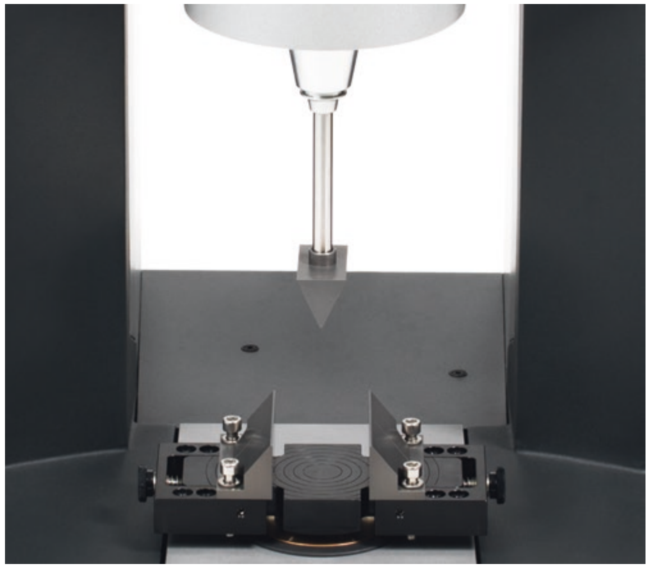

Fig. 27 Texture analysis example set-up for characterising brittle solids such as biscuits

50 mm/s to a gap of 0 mm and the normal force response was captured. The force required to snap the biscuit stored in the refrigerator is almost double of that stored at room temperature (Fig. 28).

In addition to single axial measurements on a sample, the axial capabilities can be utilised to mimic mastication. Fig. 29 shows an example of three axial cycles performed on a sample of jam using a 20 mm parallel plate geometry. The rheometer can be programmed to perform several cyclic axial measurements in combination with shear. The squeeze flow element simulates the tongue against the palate whilst rotational shear mimics mastication. The analysis of both positive and negative normal force peaks can be interpreted into; consistency, yield stress, adhesiveness and stickiness of the foods (Campanella & Peleg, 2002; Chung et al., 2012). Comparisons in the literature have been made with and without shear, in addition to with and without saliva, to study the influence of chewing and saliva on the breakdown of structure (Chung et al., 2012).

In addition to texture analysis and tack measurements, a tribology attachment can also be used to understand the mouthfeel of a material by incorporating soft surfaces to replicate the relatively soft palette and tongue within the mouth.

3.5 Sample Handling

Sample handling is an important aspect to consider when obtaining accurate rheological data.

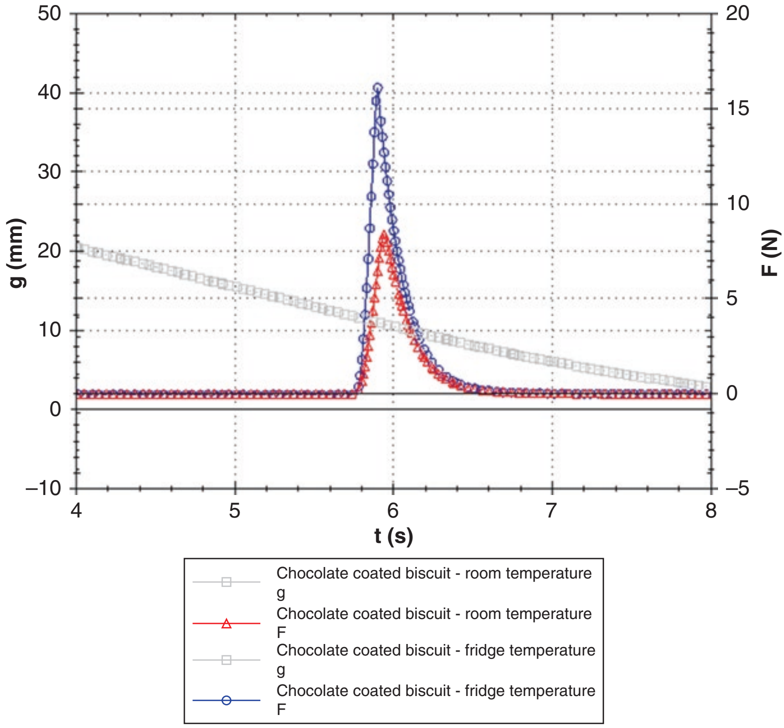

Fig. 28 Texture analysis measurement of a chocolate coated biscuit at room temperature in comparison to one taken directly from the refrigerator

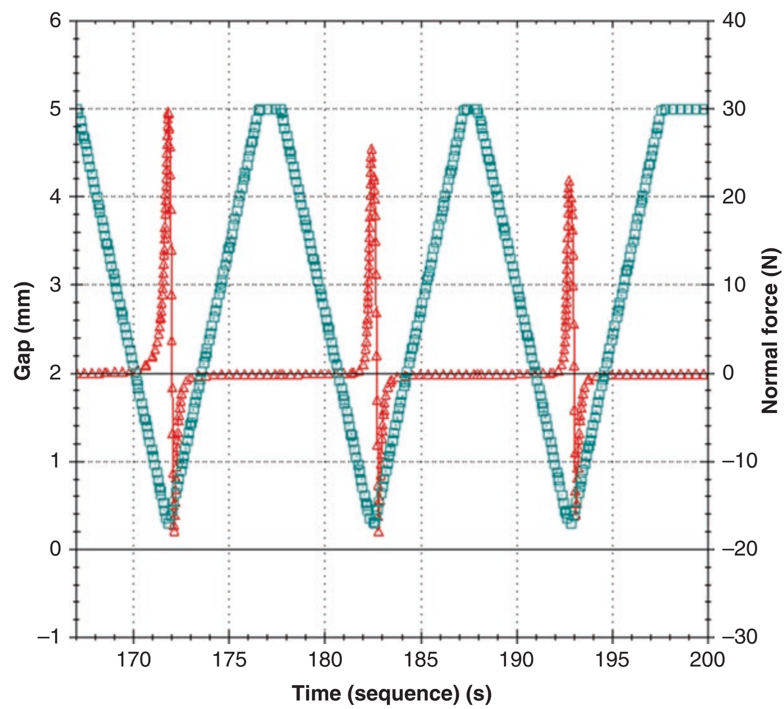

Fig. 29 Example of tackiness of a jam measured at 25 °C. Green squares represent the cyclic change of the measurement gap over time. The red triangles represent the measured normal force response of the jam. With each cycle the structure is broken down, indicated by a decrease in peak normal force

Fig. 30 Sample loading for cone and plate geometries

Fig. 31 Sample loading for parallel plate geometries

For a plate configuration, in order to follow a correct loading procedure (as mentioned previously), an approximate volume of sample should be poured or applied onto the lower plate. It is desirable to initially slightly overfill, and any excess sample removed after the rheometer lowers the upper plate to a trimming gap (see Figs. 30 and 31). If the measurement gap remains overfilled, then the excess sample will provide greater resistance to flow, and an incorrect elevated viscosity will result. Likewise, if the measurement gap is underfilled, a lower viscosity will be reported. It is essential that this procedure is followed in order to provide a consistent and accurate measurement of the rheological properties.

For a cylinder lower geometry, the cup should be filled to the bottom of the leading edge as shown in Fig. 32. The filling level is indicated by the dotted line.

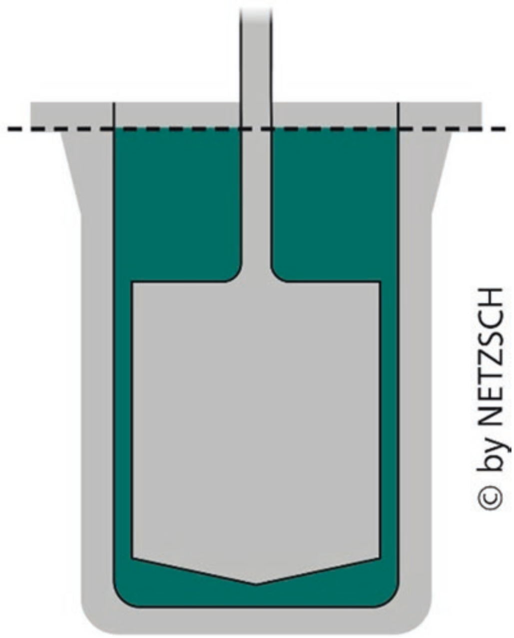

Fig. 32 Cup and bob geometry filled with sample

Ideally, the sample should be as homogeneous as possible in order to generate representative data. The presence of air bubbles within a sample (if not a foam) should be removed before testing, if possible. Air bubbles add to sample volume and once dissipated during testing the sample volume may be dramatically reduced, thereby resulting in a lower viscosity value.

Consistency is key when handling samples prior to testing. Whether a sample is poured, spooned, syringed or squeezed onto the lower measuring plate can have an influence on the final results of the measurement. These different loading procedures all subject the sample to very different shear rates, depending on how delicate the sample is, permanent destruction of structure could occur prior to measuring. If many users are operating the instrument, it is recommended that a standard operating procedure (SOP) is designed in order to create a consistent sample handling procedure. When loading extremely viscous samples, a greater normal force may be needed to distribute the sample throughout the measurement gap. For particularly volatile samples or to prevent samples drying during the measurement, a dedicated solvent trap accessory can be employed. Fig. 33 shows an example of a solvent trap accessory, used to prevent moisture or solvent loss throughout the measurement. Water or an appropriate fluid should be added to the reser-

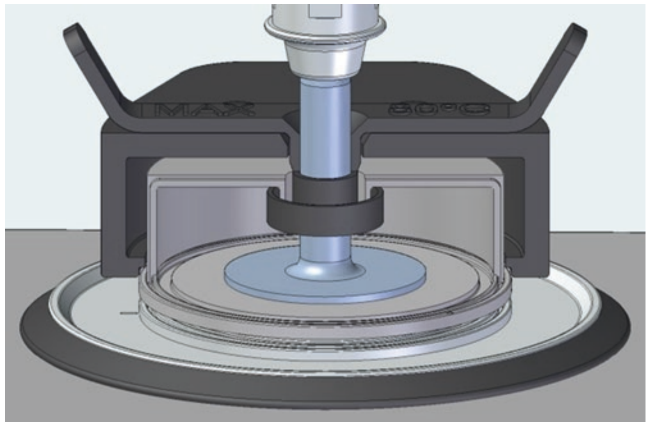

Fig. 33 Solvent trap accessory designed to prevent moisture loss from the sample during a measurement

voirs on both the lower plate and upper ring on the geometry shaft. Once the covers are closed, it provides a saturated environment around the sample, preventing sample drying and inaccurate rheological results.

4 Beyond Rotational Rheometry and Measurements

In this chapter, the focus has been on shear rheological characterisation of food samples using laboratory instrumentation. Rotational rheometers are versatile instruments, and they can also be used for material characterisation beyond shear rheology. It should be noted that rotational rheometers are also widely utilised for the tribological (see chapter 'Tribometers for Studies of Oral Lubrication and Sensory Perception') characterisation of food and food/saliva mixtures in order to study mouthfeel, enabling a quantitative description of mouthfeel. Rotational rheometers are also used for rheological characterisation of powders with a wide range of applications in the food sector such as dairy powders. The focus in this chapter was mainly on practical aspects. However, it should be pointed out that modelling and model fitting also play important roles in interpretation of rheological data as indicated in Fig. 2. Other rheometer types also have their place when studying aspects of food development and manufacture. In-line rheometers can provide real-time information on performance during processing. High-pressure capillary rheometers can be used to gain insight into both extensional and shear flow behaviour of foods under processing conditions.

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Tribometers for Studies of Oral Lubrication and Sensory Perception

Qi Wang, Yang Zhu, and Jianshe Chen

1 Introduction

1.1 Tribology

The term tribology originates from the Greek word *tribos*, meaning 'the science of rubbing', or the science of friction, wear and lubrication. The interdisciplinary nature of tribology brings together researchers from a wide range of scientific backgrounds, including chemists, engineers, materials scientists and physicists (Bhushan, 2013). The application of friction science in human activities can be traced back to the ancient world. The use of drills fitted with bearings made from bones and antlers to create fire and the use of stone discs for grinding cereals are good examples of effective friction. According to an Egyptian colossus, using the medium for effective lubricating has been commonly applied in building pyramids (Halling, 1976; Bhushan, 2013). For example, the transportation of large stone blocks and statues involved the use of rollers and sledges for friction reduction. The wheel bearings taken from Egyptian tombs were covered with a mixture of animal fat, quartz sand and iron scrap.

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Friction in many mechanical designs means an unnecessary energy consumption and, to some extent, a shortened lifespan of the device. Thus, the priority of tribology research has always been on the minimization and elimination of losses resulting from friction and wear at all levels of technology where the rubbing of surfaces is involved, including, for example, internal combustion, aircraft engines, gears, cams, bearings and seals (Stokes, 2012). However, there are also plenty of cases where friction and wear are favoured. The automobile is a typical example of utilizing tribology in two extreme ways. Brakes, clutches and driving wheels are examples that require effective friction to prevent gears from slipping and provide traction. On the other hand, the friction or wear in the gearbox and piston rings in a reciprocating internal combustion engine needs to be minimized in order to prevent surface wear (Halling, 1976; Bhushan, 2013). Tribology is also a part of our daily life. Blinking eyes, gripping or holding things and walking are routine actions that require well balanced friction regulation.

1.2 Principles of Tribology

Friction in nature is a mechanism of energy dissipation. The causes of the energy dissipation between two sliding solids have multiple possibilities, including the plastic deformation and the

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fracture of the local asperities. While surface wear is a well-known phenomenon for surface friction, elastic deformation is little investigated. As the deformation during the elastic cycle process would partially recover, the so-called 'elastic hysteresis' loss can be fairly small for most metals and rubbers (Halling, 1976; Bhushan, 2013). The friction coefficient is the most valid parameter for the characterization of a lubrication system. The term was first introduced by Leonardo Da Vinci as 'Law of friction' and is defined as the ratio of the friction force to the normal load, as shown in Eq. 1, where μ_0 is the coefficient of friction,

$$F = \mu_0 F_{l.} \quad (1)$$

French physicist Guillaume Amontons rediscovered friction law after he studied dry sliding between two flat surfaces and Amonton's friction law became widely accepted (Amontons, 1699). According to Amonton's theory, the friction force is independent of the shape and size of the contacting area but is directly proportional to the normal load. The friction force is also independent of the velocity once motion starts. While these are true for dry surfaces in relative motion, the situation becomes much more complicated once the surfaces are presented in between with a thin layer of lubricant. In this case, a lifting force (F') acting opposite to the normal load causes an effective reduction of friction as shown in Eq. 2:

$$F = \mu\left(F_l - F'\right). \quad (2)$$

Much-reduced energy dissipation within the contact asperity is another cause for the lowered friction under a lubricated condition. More importantly, the friction coefficient is no longer a constant, but a variable dependent not only on the inherent properties of the substrate surface but also on the sliding speeds (mm s^{-1}), normal force (N) and lubricant viscosity (Pa s) (Bongaerts et al., 2007a). The combination of these three factors gives an indication of the thickness of the lubricating film.

When the friction coefficient is plotted against the combined factor of the normal load (W), the lubricant viscosity (Ƞ) and the sliding speeds (U), the so-called Stribeck curve can be obtained. A typical Stribeck curve can be divided into three lubrication regimes, i.e. boundary, mixed and hydrodynamic regimes (see Fig. 1).

Increased surface load, decreased sliding speed and reduced viscosity often lead to a physical contact of two surfaces due to much reduced film thickness and therefore a high friction coefficient. This is termed the boundary regime when the two surfaces are in close contact, and the friction is dominated by microstructural and chemical properties of substrates. As the surface load decreases, sliding speed increases, or the fluid viscosity increases and lubrication enters a mixed regime when a lubricating film is partially formed between the two surfaces and effectively supports the load. Within the mixed regime, the friction coefficient shows a fast decrease with increasing film thickness and quickly reaches a minimum. Once the two surfaces are fully separated by a thick layer of lubricant, hydrodynamic lubrication is expected, and the friction behaviour is dominantly influenced by the fluid viscosity and the sliding speed of relative motion (de Vicente et al., 2006b). In addition, as the lubrication behaviour occurs between elastic substrates, elasto-hydrodynamic lubrication (EHL) can be expected (Selway & Stokes, 2014; Selway et al., 2017; Sarkar et al., 2021). In this regime, the friction coefficient not only changes with the Stribeck parameters but is also influenced by the elastic deformation of the interacting materials. In this

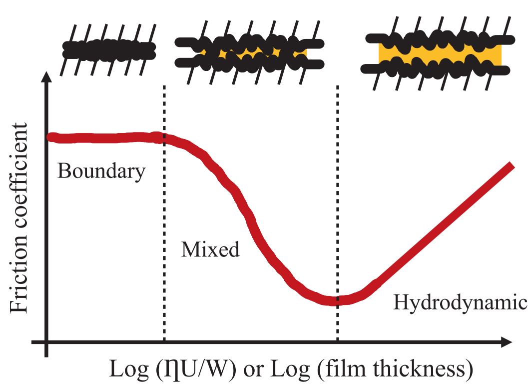

Fig. 1 Typical Stribeck curve as a function of film thickness or combined factor of viscosity, sliding speed and surface load

situation, a significant elastic deformation of the substrate results in an altered lubricant thickness and contact. There is no doubt that friction between two contacting surfaces can be adjusted by many systematic parameters, such as the properties of the lubricating film, the surface roughness and the structural rigidity of the substrate and the adhesion between the two contacting surfaces (Selway et al., 2017; Rudge et al., 2019).

1.3 The Design and Operation Principle of a Tribometer

The tribometer is specifically designed to simulate the friction behaviour that is not necessarily possible to be measured in real situations. A typical tribometer usually contains a paired contact medium, also known as tribopairs (normally a probe against a substrate), which is attached to various ancillary components providing motion, imposing loading, controlling temperature and simulating surface contacts.

The design of a tribometer would need to follow certain principles. Firstly, a controllable motion between two interacting surfaces is essential. By 'controllable' we refer to the sliding speed, direction, contact area, etc. Secondly, the system must have a precise control of the normal load during surface movement. An acceleration or change of direction would alter the frictional force. A sudden entrainment and accumulation of lubricant may cause the probe to vibrate or bounce over the substrate. Thirdly, a tribometer should also have a mechanism for correct recording of the friction force. A load cell of appropriate capacity is usually used for this purpose (Chen, 2007).

A tribometer can be operated in different modes such as rolling (specific for ball apparatus, obviously), sliding or their combination, and each has its own underlying physical principles of operation. For instance, a ball-on-plate design is suitable for a pure sliding or a combined sliding and rolling test protocol. In addition, oscillatory mode, a special operation protocol that takes the form of a sliding test, is usually used in a tribological device equipped with a ball or plate-on-plate tribopairs. However, despite the different operating modes, the calculation of the friction coefficient remains the same. Once two surfaces are in relative motion at a steady speed (U), the friction force (F_R) can be expressed as $F_R = \mu \times F_L$, where μ is the friction coefficient and F_L is the normal force or the surface load (in *N*) (see Fig. 2).

1.4 Experimental Techniques for Industrial Tribology Research

In the twentieth century, a number of experimental techniques were developed for tribology study. These were either commercially available for general applications or laboratory-modified/built for specific purposes. Many commercially available techniques adopt a pre-selected operating speed and the test is often conducted at successively higher loads. For instance, studies of wear or melting usually adopt the four balls configurations and Falex tester (Fig. 3), which adopts a pure sliding motion and can operate under an extreme contact load and a sliding speed of about 100 m s^{-1} (Stachowiak et al., 2004; ASTM D 3233-93, 2014; ASTM D 2783-88, 2017).

Pin-on-Disc and Pin or Ball-on-Slab apparatus adopts a sliding and usually operates under mild conditions, with a reciprocating velocity below 40 mm s^{-1}. A Pin-on-Disc apparatus consists of a fixed pin and a rotating flat disc, allowing friction measurements under a controlled sliding speed and contact area. A Pin-on-Slab

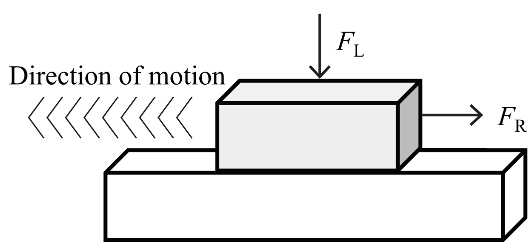

Fig. 2 An illustration represents the friction between interacting surfaces. Arrows indicate directions and magnitudes of forces. F_L is the normal force, *V* is the sliding speed and F_R is the force of friction. (Redrawn from Prakash et al., 2013)

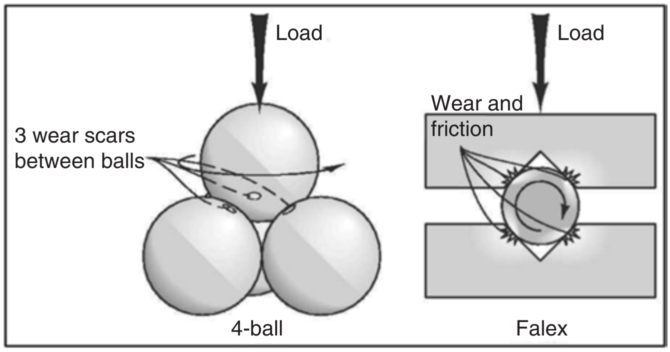

Fig. 3 Schematic representation of basic sample configurations used in simulations of dry or partially lubricated sliding contacts. (Reproduced from Stachowiak et al., 2004)

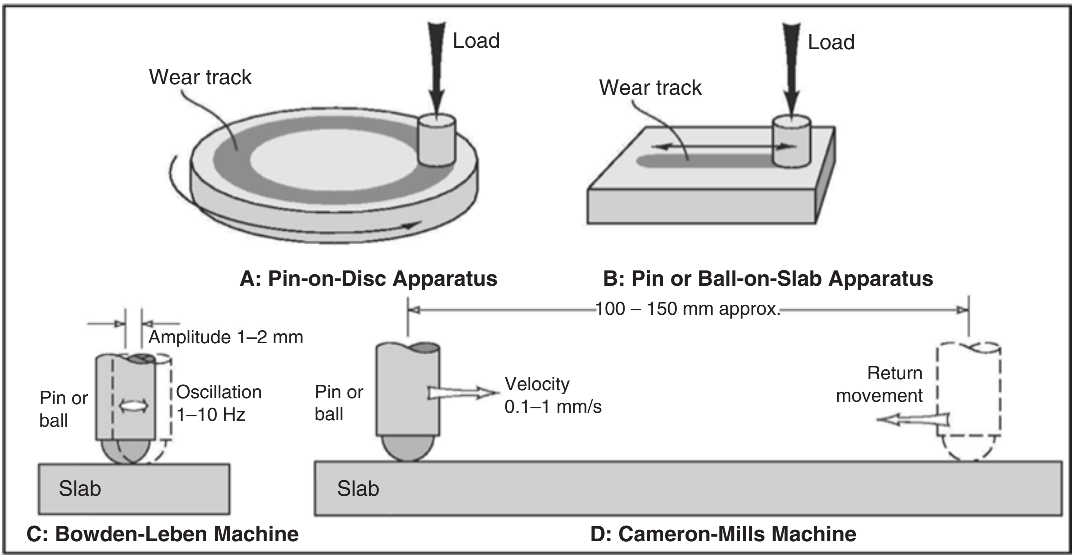

Fig. 4 Schematic representation of Pin-on-Disc and Pin-on-Slab design. (Reproduced from Stachowiak et al., 2004)

apparatus usually refers to the Bowden-Leben instrument and the Cameron-Mills machine (Bowden & Tabor, 1954; Mills & Cameron, 1982), both operating based on reciprocating sliding as opposed to unidirectional sliding (see Fig. 4). These are typical examples designed for engineering tasks and could be perceived as the prototypes for the instruments used for food application in the near future.

2 'Oral Tribology'

Oral processing of food involves a series of sequential or simultaneous oral actions, including ingestion and biting, transporting food to the molars for chewing, mixing food with saliva to form a bolus and transporting bolus to the posterior pharynx for swallowing (Chen, 2009). During this process, food changes its physical, chemical and microstructural properties and becomes completely different from the food before ingestion. Thus, the underlying physical principles of texture sensation during food oral processing may vary, most likely a transition from rheology to tribology, as illustrated in Fig. 5 The use of traditional techniques such as texture analyser, viscometer and rheometer to investigate the texture properties at the early stage of oral processing has gained great success (Cutler et al., 1983; Dickie & Kokini, 1983; Stanley & Taylor, 1993). However, as food is broken down into

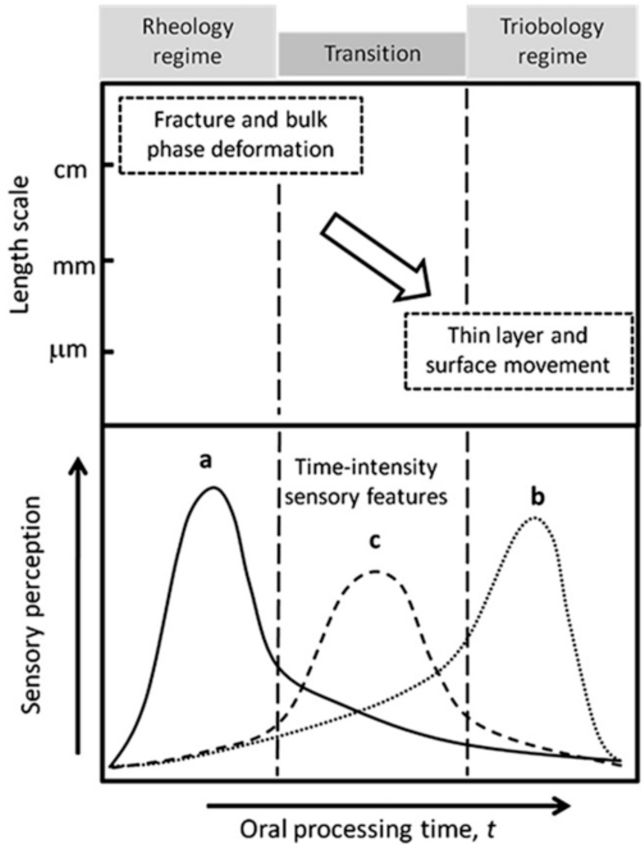

Fig. 5 Rheology-tribology transition of food oral processing: (top) showing a length-scale change of food bolus with the oral processing time; (bottom) showing the perceived intensity of sensory feature reaches its maximum at different stages of an eating process, letters a and b representing texture property that most intensively sensed at the early and later stage of food fragment, respectively; letter c represents attributes sensed dependent on both rheology and tribology mechanisms, at the middle stage of oral processing. (Adapted from Chen and Stokes 2012)

smaller particles, the surface resistance sensed by the tongue and other oral mucosa becomes an important factor in influencing a series of thin-layer related texture attributes, such as smoothness, creaminess and greasiness (Stokes et al., 2013; Sarkar & Krop, 2019). Towards the end of oral processing, bulk phase deformation of food is no longer relevant, but the shear movement of the tongue in a close contact manner dominates the sensation. Thus, the dynamic process of eating and sensory perception is considered a transition from initially rheology-dominating to tribology-dominating (Chen & Stokes, 2012).

The oral cavity is a complex system consisting of moving surfaces and bio-lubricants (the saliva). An oral tribological system is a rather complicated system, in which a combination of soft-soft, soft-hard and hard-hard interacting surfaces are in relative motion. Oral lubrication could be influenced by many factors including saliva secretion and composition, oral temperature, tongue topography and food composition. Individual oral behaviour such as jaw and tongue movement also plays a role in influencing oral lubrication. The presence of a 'saliva conditioning film' makes oral tribology even more complicated because of its subtle influences on oral lubrication (Sarkar et al., 2019a; Sarkar & Krop, 2019). It has been well reported that the composition, component distribution, film thickness and structure of the saliva film could change significantly during food oral processing (Bongaerts et al., 2007b; Chen, 2009; Mosca & Chen, 2017; Sarkar et al., 2019b; Boehm et al., 2020). However, *in situ* measurement of oral lubrication is challenging, partly due to ethical restrictions and also due to the lack of feasible techniques (Mo et al., 2019). Therefore, designing a friction configuration that resembles actual oral conditions for in vitro oral lubrication studies has been a favoured approach for food oral processing research.

3 Instruments for 'Oral' Tribology Studies

A wide range of instruments and methods have been used or developed for in vitro analysis of oral lubrication investigation. The core concern of these instrumental approaches is the reliable mimic of the oral conditions. Tribometers designed for food applications usually adopt a varied sliding range between 0.001 and 1 m s^{-1} (range of extremes for the operational velocity of commercially available instruments) and a normal load of up to 5 N. Even though this may lead to a good Stribeck curve, experimental conditions are still a bit exaggerated from the real oral conditions, where a gentle tongue movement typically around 100 mm s^{-1} and contact stresses reported to be between 30 and 70 kPa (Alsanei & Chen, 2014; Laguna et al., 2016). The selection of a proper substrate is another technical challenge in the design of a tribometer for food applications. Appropriate mechanical strength, hydrophobicity and most importantly the surface microstructure are core requirements for a substrate in order to mimic oral lubrication. The following sections give a brief description of the various tribometers reported in the literature for food applications.

3.1 Friction Tester

The friction tester was one of the many early attempts for the measurement of friction, consisting of simply a surface and a rotating shaft. The prototype of this device was first developed as a 'kinetic friction tester' (Fig. 6), in which two spring balances are attached to the ends of a rubber band looped against a rotating shaft. The shaft is driven by a motor and rotates at a controlled speed. Once the shaft starts rotating, first clockwise and then reversed, the resistant force impeding the rotation of the cylinder and the rubber band can be measured through the attached two spring balances, T_1 and T_2. The coefficient of friction can then be calculated using the formula shown by Halling (4-3).

$$\mu = (1/\pi)\log_e(T_1/T_2) \tag{3}$$

However, this prototype was not suitable for food applications, and modifications of the above design have been made to study the role of saliva during food oral processing (de Wijk & Prinz, 2005). The new design is shown in Fig. 7, where a rubber band is looped around the metal cylinder protruding from an electric motor, while the end of the rubber band is attached to a load cell. A drip tray underneath the metal cylinder is required in order to collect food residues. Once started, the motor first rotates clockwise at a certain speed and the friction between the cylinder and the rubber band is recorded by the load cell as F_1, then the motor rotates in a counterclockwise direction and F_2 is recorded. F_1 and F_2 are then converted into the friction coefficient based on the same Eq. 3.

Despite its simplicity, the device offers a reliable friction measurement of fluid and soft solid foods, providing a good interpretation of surface-related sensory attributes (de Wijk et al., 2006; de Wijk & Prinz, 2006). It has been reported that the rough/astringent sensation correlates well with a high friction and creamy/fatty sensations with a low friction (de Wijk & Prinz, 2007). The reduced lubrication and increased friction sensation are most likely caused by saliva-induced particle flocculation (de Wijk & Prinz, 2007). However, some drawbacks of the friction tester are clearly evident. Most notably, the contact mechanism of the design is restricted to certain materials, typically rubber and metal, which do not resemble oral conditions. The device also lacks a well-defined and controlled sliding speed, and the rubber band needs to be replaced after every measurement. Furthermore, the open test chamber makes it difficult to control the test environment, e.g. temperature and humidity.

3.2 Soft Texture Analyser Tribometer (STAT)

Another simple tribometer has recently been developed for oral lubrication research (Chen et al., 2014). The design consists of a texture

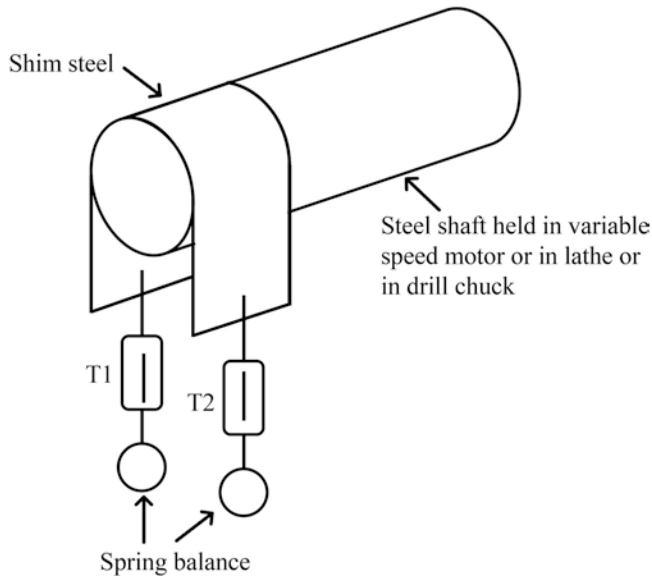

Fig. 6 A kinetic friction tester. (Redrawn from Halling, 1976)

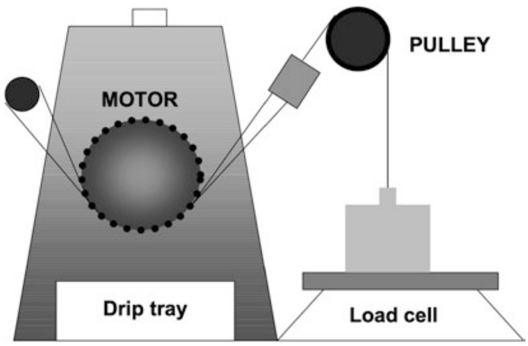

Fig. 7 A schematic diagram of friction tester. (Adapted from de Wijk and Prinz, 2005)

analyser TA. XTplus (Stable Micro Systems, Surrey, UK) laid on its side. Custom-made accessories were used to assist with friction measurements. A stainless steel locking base is screwed to the base of texture analyser. A temperature-controlled platform (0–100 °C) was used (see Fig. 8a, b). A metal disc fitted with three stainless steel balls slides over the platform to create friction movement. Different weights can be placed on the top of the disc for a proper control of surface load. An adapting clamp connects the ball probe to the load cell of the texture analyser so that the friction force can be precisely recorded (Fig. 8c).

This design adopts a ball-on-disc arrangement and a pure sliding mode. The speed of the ball disc sliding against the static lower surface can be set from as low as 0.01 mm s^{-1} to as high as 40 mm s^{-1}, the maximum speed range of the employed texture analyser. The versatility of the texture analyser allows test speed and distances to be accurately controlled by the stepper motor and accordingly the force, distance and time can be recorded. The reliability of the design is tested by using syrup solutions as near-Newtonian fluids. Reproducible friction data can be obtained and partial Stribeck curves can be measured, with clearly defined boundaries and mixed regimes (Wang et al., 2021a).

The main drawback of this instrument is its upper operational speed limit (40 mms^{-1}), which is much lower than the reported tongue movement against the hard palate (60–100 mm s^{-1}) (Alsanei & Chen, 2014; Laguna et al., 2016; Pondicherry et al., 2018). The relatively low sliding speed limits the construction of an entire Stribeck curve and hinders the understanding of the lubrication behaviour of food oral processing. Another weakness of the design is the metal ball used as the upper surface which is nowhere close to the mechanical strength or the chemical property of the human tongue or the hard palate. Moreover, manual adjustments of the position of

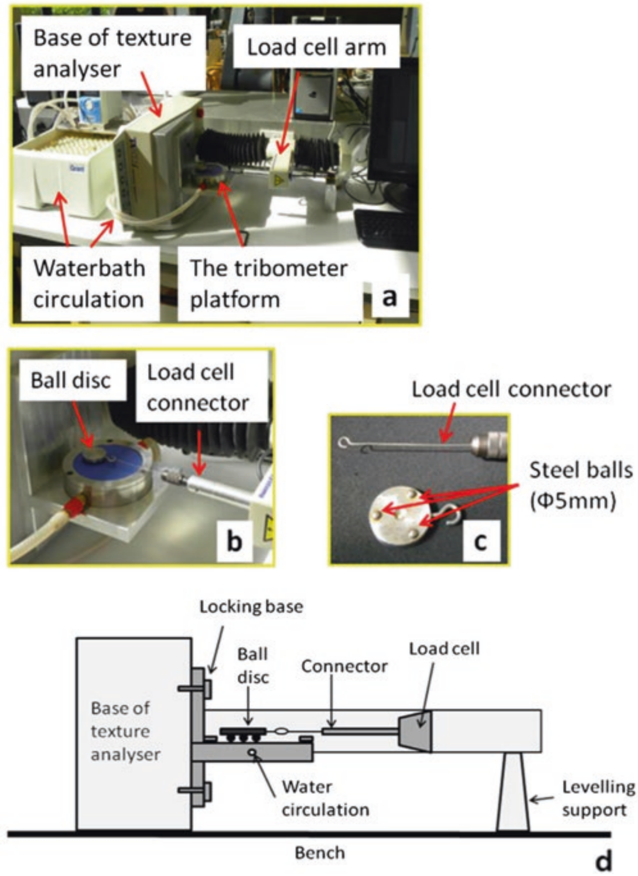

Fig. 8 A tribometer based on a texture analyser, adapted from Chen et al. (2014). (**a**) The layout of the experimental setup; (**b**) the ball disc and the load cell connector connected to the load cell; (**c**) the ball disc shown in its turnover position and the load cell connector; and (**d**) an illustration of the experimental set-up

the probe and the hook may lead to experimental error.

A new version of the soft texture analyser tribometer (STAT) has been developed, in which a stainless steel probe was replaced by a soft material (polydimethylsiloxane, i.e. PDMS). Additionally, an improved mechanism for automatic, precise control of probe movement was introduced (Wang et al., 2021c) (Fig. 9). The disc base and linkage mechanism were redesigned and fabricated through 3D printing. The new design has a closed chamber which offers a much better control of the temperature and relative humidity.

This instrumental set-up has been applied to a number of in vitro studies of oral lubrication and sensory perception, either with the original design or the new version of STAT (Morell et al., 2016; Cai et al., 2017; Brossard et al., 2021). For instance, Upadhyay and Chen (2019) used this device to confirm that the emulsifier type and saliva play an important role in the 'smoothness' sensation of oil-in-water emulsion. In the mixed regime, Pearson's correlation showed that the 'smoothness' sensation was negatively correlated with the friction coefficient within sliding speed between 5 and 30 mm s^{-1} ($p < 0.05$). Moreover, the addition of artificial saliva strengthens the correlation, reinforcing the importance of saliva in in vitro lubrication studies.

Functional and sensory properties of O/W emulsions were assessed by Wang et al. (2021c), in which the instrument and sensory analysis showed that droplet size played an important role in the friction and sensory characteristic of o/w emulsion systems. The reduced fat droplet size depressed the perceived 'smoothness' but enhanced the 'thickness' sensation of reconstituted milk samples containing the same mass fraction of fat. In another study, the in vitro

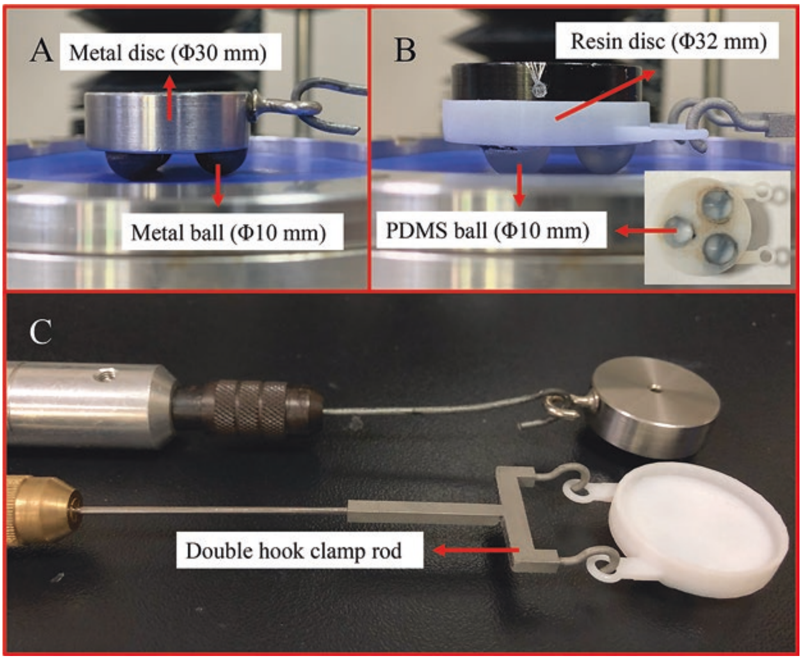

Fig. 9 The main components and set-up of the soft TA-tribometer, adapted from Wang et al. (2021a). (**a**) The stainless steel disc base; (**b**) the disc was made of photosensitive resin and the linkage was made of stainless steel; (**c**) an illustration of the disc base and a double hooked linkage rod for load cell linking

friction behaviour and sensory responses of red wine and human saliva mixtures were investigated by Brossard et al. (2016). A good correlation between astringency score and friction coefficient was found at a sliding speed of 0.075 mm s^{-1} ($R^2 = 0.93$), and for higher velocity, relatively lower correlations were observed ($R^2 < 0.7$), suggesting that astringency sensation most likely happens when tongue and palate are at a close contact and low movement speed, at a typical boundary regime in the Stribeck curve.

3.3 Optical Tribological Configuration (OTC)

Dresselhuis et al. (2007) developed an oral-mimicking tribometer. In their design, two well-established instruments were nicely synchronized for a simultaneous friction test and visual observation under a simulated oral lubrication condition was undertaken (Fig. 10). A probe with a pig's tongue secured to the upper surface was used.

During the test, the upper probe was held stationary while the lower glass plate oscillated at a given speed between 0 and 80 mms^{-1} and over a distance of 16 mm. The vertical normal load (F_z) was controlled at 0.5 N. The friction force (F_x) in the horizontal direction was measured simultaneously by the attached load cell. With the help of CSLM (i.e. confocal scanning laser microscope) attached underneath the glass substrate, the microstructure of emulsion lubricant can be observed at four stages: (1) before applying a load, (2) after applying a load, (3) after shearing and still under the load and (4) after the removal of the load (Dresselhuis et al., 2008b).

The use of a pig's tongue as a substrate is a good attempt to improve *in vitro* tribological measurement in the context of oral lubrication. However, the frequent replacement of the pig's tongue is a main drawback of this design. Inevitable variation of surface roughness among tongue tissues means that reproducibility will be another practical issue. The pig's tongue has been recommended as a suitable substitute for the human tongue with respect to the papillae structure. However, the utilization of glass material as a lower surface is also not ideal for oral mimicking. Carpenter et al. tried utilizing a compliant disc specimen, the synthesized PDMS, on a glass platform to provide a soft as well as transparent contact (Carpenter et al., 2019).

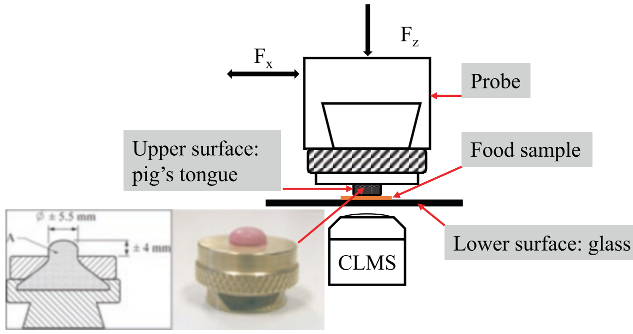

Fig. 10 The set-up of an optical tribological configuration (OTC). (Reproduced from Dresselhuis et al., 2008a)

Applying OTC for oral tribology study allows visualization of the microstructure change during tribo-shearing. The technique has been applied successfully to study the tribological properties of food emulsions (Dresselhuis et al., 2007, 2008a, b), emulsion-filled gels (Devezeaux de Lavergne et al., 2016; Liu et al., 2016a, b) and microbubbles solution (Rovers et al., 2016). Take WPI (whey protein isolates) stabilized emulsion as an example; OTC technique gives a clear indication of how emulsion droplets behave under mimicking oral conditions. Emulsions with a lower amount of WPI tend to coalesce, most likely due to the increased hydrophobic interaction, resulting in a lower friction coefficient (Dresselhuis et al., 2007, 2008c). However, the surface-induced coalescence does not necessarily happen to a well stabilized emulsion system as revealed by CSLM observation.

3.4 Rheometer-Based Tribometer

Rheometers are commonly available in many food research laboratories for studying stress-strain relationships of food materials. Modern rheometers are designed with a precise control of the rotation of the probe, the torque, as well as the applied normal force, the same parameters for tribological analysis. Therefore, adapting a rheometer with a specifically designed attachment can convert it for tribological measurements.

3.4.1 Tribo-Rheometer

A tribo-rheometer is one of the early attempts at converting a commercially available rheometer into a tribometer. A traditional torsional rheometer attached with a tribo-rheometric fixture is used for this purpose. A stainless steel plate separated from a temperature-controlled Peltier plate achieves a suitable geometry. An annular fixture or a circular disc may be installed on the lower surface protecting the Peltier plate damage (see Fig. 11) (Kavehpour & McKinley, 2004). The tribological test can be performed at a temperature ranging from 0 to 95 °C and a normal force between 1 and 50 N can be achieved (Kavehpour & McKinley, 2004). Varied angular velocity can be achieved by running a velocity sweep under constant normal force. Measured torque can be converted into a friction force and the friction coefficient can then be calculated.

Various tests have been performed using synthetic oils with various known viscosities and friction data then summarized in the form of a classical Stribeck curve. It was found that an increased surface load and surface roughness lead to an early shift of the friction curve from mixed to hydrodynamic regime and that the effect of viscosity was more pronounced for a lubrication system with a rougher surface (Kavehpour & McKinley, 2004).

Another tribo-rheometer setup which uses a ring geometry attached to a rheometer (Discovery Hybrid Rheometer, TA Instrument, USA) has been reported (See Fig. 12). The ring geometry is connected to the rheometer head through a coupling adapter and a beam coupling to perform rotation movement. The beam coupling is self-aligned to ensure uniform solid–solid contact and axial force distribution between the surfaces (Nguyen et al., 2016; Godoi et al., 2017). This instrument is able

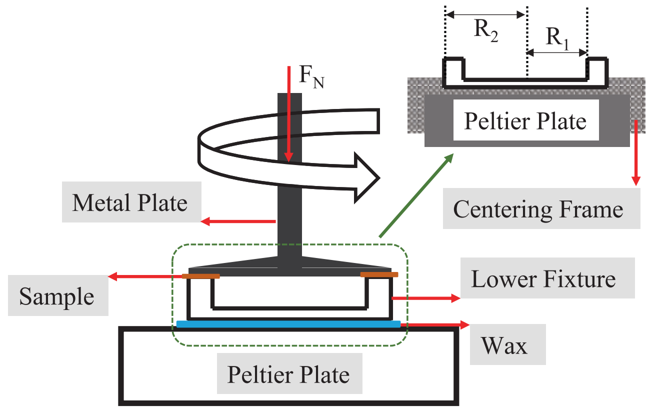

Fig. 11 A schematic diagram of the tribo-rheometer and the ring fixture with radius R_1 and R_2. (Redrawn from Kavehpour and McKinley, 2004)

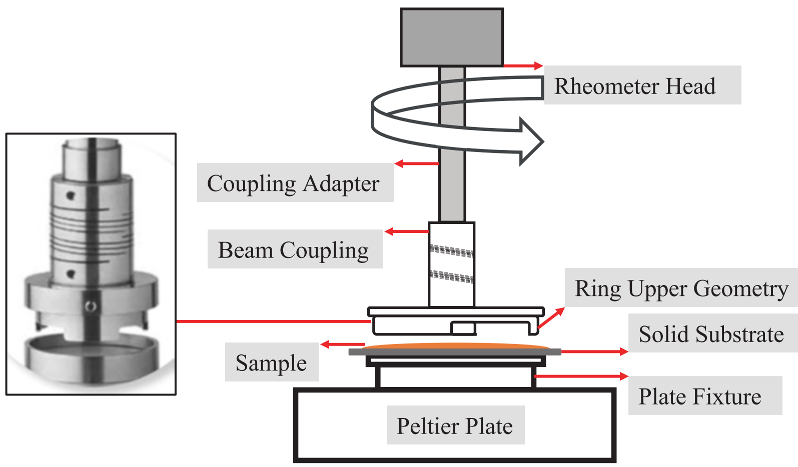

Fig. 12 A schematic diagram of the tribo-rheometer set-up and the half-ring fixture. (Redrawn from Nguyen et al., 2016)

to provide a maximum normal force of 50 N with a fine adjustment of 0.005 N. The Peltier plate provides rapid, precise and stable temperature control over a range from –40 to 200 °C. The rheometer is capable of providing an angular velocity in the range of 0–300 rad s^{-1} (TA-Instruments, 2021). The friction force (F_F) can be calculated using Eq. 4 in which r_1 and r_2 are the inner and outer radii of the ring (mm), respectively (Nguyen et al., 2016). Here, F_N is the normal force (N) and M is torque (N m).

$$F_F = M\left(r_1 + r_2\right) / \left(r_1^2 + r_2^2\right) \quad (4)$$

This design has been used to assess the lubrication behaviour of pasteurized milk and cream cheeses with different fat contents. The friction coefficient measured at a low entrainment speed (less than 100 mms^{-1} which is close to the shear rate in the mouth) was significantly different between samples of different fat levels (Nguyen et al., 2016).

3.4.2 Tribo-Rheo Cell

There are two versions of the tribo-rheo cell, each employing a ball-on-plate tribology attachment, consisting of a rotating upper geometry and a stationary plate/disc. The difference between the two lies in the number of stainless steel hemispheres that the upper geometry holds. The original tribo-rheo design was developed and validated by Goh et al. (2010) (Fig. 13) and used a double-ball-on-plate to achieve a point contact. The upper geometry consisted of two hemispheres mounted on a disc that was rigidly fixed to the rheometer shaft. The lower contact surface consisted of a polymethylmethacrylate testing chamber with a mechanically fastened soft sili-

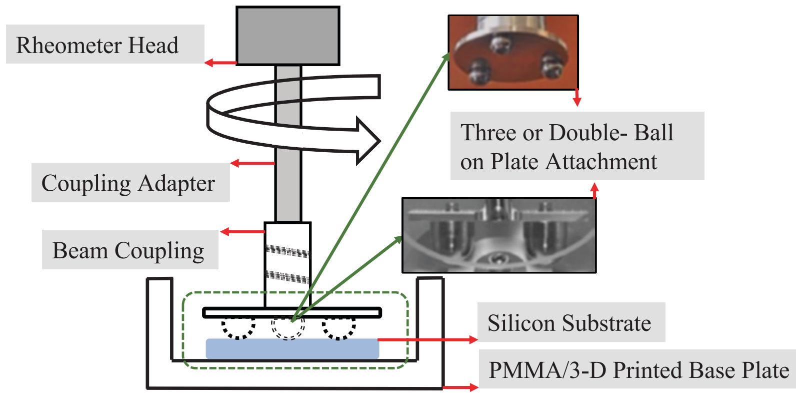

Fig. 13 A schematic diagram of the tribo-rheo cell with a two-ball-on-plate fixture. (Redrawn from Taylor & Mills, 2020; Goh et al., 2010)

con sheet serving as the lower contacting substrate.

The three-ball-on-plate configuration developed by Taylor and Mills (2020) utilizes three hemispheres as the upper substrate and a soft PDMS lower surface. The three stainless steel hemispheres are fixed to a flat plate in an equilateral triangular arrangement and enable a balanced normal force over three contact points. A 3D printed base plate is used to secure the PDMS substrate and to serve as a test chamber.

Both types of tribo-rheo cell allow the calculation of the friction coefficient based on the torque (M), applied normal force (F_N) and the distance between the contact point and the centre of the rheometer shaft (L), as in Eq. 5:

$$\mu = M / LF_N. \tag{5}$$

3.4.3 Mounted Tribological Device

The mounted tribological device is another laboratory-modified instrument which utilizes the motion and temperature control facilities of a rheometer, adapting a ball-on-three-plates (ball-on-pyramid) principle and a point-contact mechanism (Fig. 14) (Baier et al., 2009; Heyer & Läuger, 2009). This set-up consists of an upper driven sphere and three plated lower fixtures fastened to a universal stage. As the lower plates were positioned at an incline, an uneven distribution of the normal load may occur, resulting in an incorrect friction calculation. This can be corrected by allowing movement of the bottom stage to ensure a balanced normal load on three contacting points (Heyer & Läuger, 2008). The upper rotating sphere may also be adjusted to ensure the forces are evenly distributed. A Peltier-controlled element is connected to the rheometer for temperature control over a range from –40 to 200 °C (Läuger & Heyer, 2010).

The calculation of friction force (F_F) and friction coefficient (μ) can be made based on the values of the inclined angle (α) of the plate, the axial force (F_N), the normal force rectangular to the plates F_L and the torque (M) in the following equations (Heyer & Läuger, 2008):

$$F_L = 2\cos(\alpha) F_N; \tag{6}$$

$$F_F = M / r_{\text{ball}} \sin(\alpha); \tag{7}$$

$$\mu = F_F / F_L. \tag{8}$$

Rheometer-based tribometers have gained popularity among food scientists because of their favourable capability to provide a much wider range of normal force, operational speed and temperature for lubrication analysis. Modern rheometers are capable of readily adjusting the speed, gap and load dimensions. The operating gap and normal force can be smoothly adjusted with a resolution of 0.1 μm and 0.005 N, allowing the construction of a full Stribeck curve. Versatile attachment accessories are available, including ring-on-plate, double ball-on-plate, three ball-on-plate and ball-on-three plate geometries. The material and surface properties of the substrate may be varied, including PDMS, polypropylene, high-density polyethylene and other soft materials (Baier et al., 2009; Joyner et al., 2014a, b; He et al., 2018; Kieserling et al., 2018), include

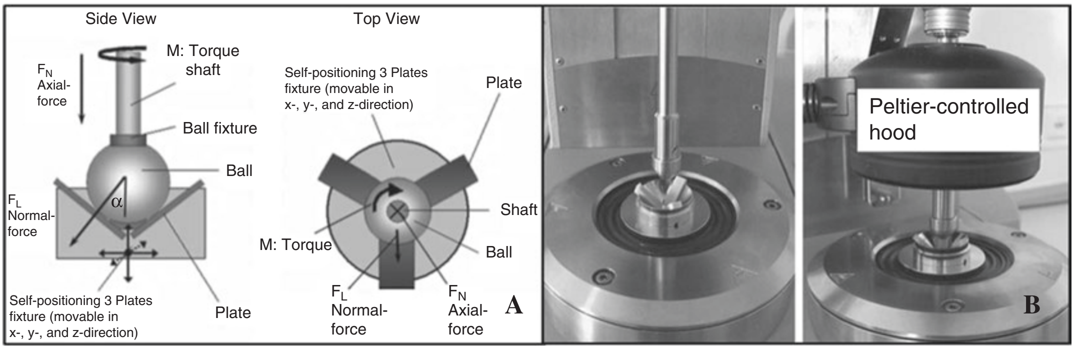

Fig. 14 A schematic diagram of the mounted tribological device (**a**) and the tribology accessory with and without Peltier hood (**b**). (Adapted from Heyer & Läuger, 2009)

evaporation and backflow of the lubricant which are difficult to control. For a mounted tribological device, precise positioning of the three-plate fixture is technically challenging. Any slight displacement of the plate will result in large friction variation (Heyer & Läuger, 2008).

3.5 Mini-Traction Machine (MTM)

The mini-traction machine (PCS Instruments) is probably one of the most commonly used tribometers in food applications. The instrument was developed to simulate grease lubrication found in mechanical machine components such as roller bearings and gears in an engine (Cassin et al., 2001; de Vicente et al., 2006a), but its application quickly expanded beyond its initial purposes. The MTM employs a ball-on-plate geometry, equipped with a polished steel or ceramic ball and a steel disc. The ball is mounted at the end of an angled pivoting shaft and the disc is mounted on a vertical shaft. The temperature of both the disc and the vertical shaft is controlled by a recirculating fluid (0–150 °C) (see Fig. 15) (Cassin et al., 2001). The normal load and friction force are measured by a load sensor and a force transducer, respectively, attached to the ball motor. A servomotor attached to the vertical shaft gives a precise control of the rotating disc (de Vicente et al., 2006a).

MTM is capable of offering a very wide range of surface loads up to 75 N and entrainment speeds ranging from 10^{-4} to 4 ms^{-1}. The steel-on-steel conjunction can provide a maximum contact pressure of 3.1 GPa (PCS-Instruments, 2017). However, in order to simulate the viscoelastic properties of the tongue and oral palate, the conventional steel geometry is replaced by compliant elastomers, e.g. silicone rubber or PDMS, in recent food science literature (Malone et al., 2003; Bongaerts et al., 2007a).

During each test, both the ball and disc are independently driven and can achieve relative movement from a pure sliding to a pure rolling motion or sliding–rolling combinations (0–200% slide-to-roll ratio). For each entrainment speed, paired measurements with the same slide-to-roll ratio are taken and averaged, with one taken with $V_{ball} > V_{disc}$ and another with $V_{ball} < V_{disc}$ (de Vicente et al., 2005).

3.6 Other Tribometers

3.6.1 High Frequency Reciprocating Rig

Tsui et al. (2016) used a sliding reciprocating testing device (high frequency reciprocating rig, HFRR) (PCS Instrument UK) for lubrication analysis. The device is based on a ball-on-plate, the upper specimen being a PDMS ball and the lower plate a glass microscope slide held on a temperature controller (Fig. 16a). During the test, the PDMS ball slides back and forth over the stationary lower substrate, while a force transducer measures friction force.

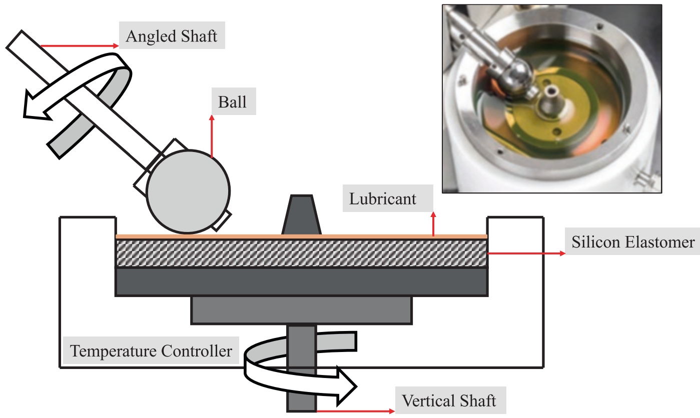

Fig. 15 Schematic diagram of the mini-traction machine (MTM)

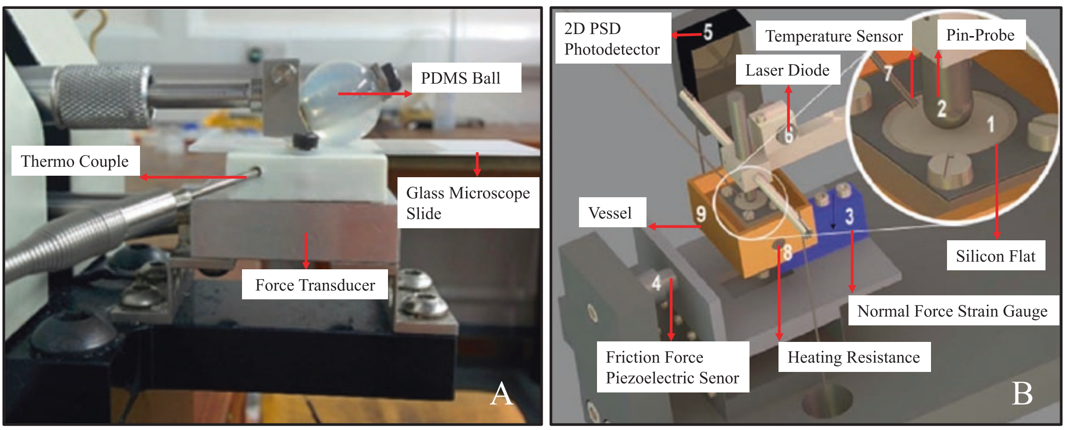

Fig. 16 (**a**) High frequency reciprocating rig, reproduced from Tsui et al. (2016); (**b**) a schematic diagram of reciprocating motion sliding tribometer, reproduced from Ranc et al., 2006

With this design, the Hertzian contact diameter is larger than the stroke length and this simple reciprocating, sliding test does not entrain a significant amount of fresh fluid into the contact zone. Thus, the local shear and film loss was found to be relevant in explaining the time-dependent friction behaviour (Tsui et al., 2016). On the other hand, rather than shear-induced flow, Tsui et al. (2016) suggest that periodic fluid replenishment should be considered as one of the main factors contributing to the dynamic lubrication occurred in food oral processing.

3.6.2 Reciprocating Motion Sliding Tribometer

Another highly sophisticated pin-on-plate reciprocating sliding tribometer was adopted by Ranc et al. (2006). The device consists of a relatively hard hemispherical body (steel or polychlorotrifluoroethylene) and a structured flat soft silicone base (see Fig. 16b), arranged inside a temperature-controlled chamber mounted to the lower test platform. During the test, the hard pin-probe oscillates against the flat silicone substrate. The pin-probe is driven by a linear motor and its displacement is measured by a stationary photodetector. The normal force and friction force can be measured by a strain gauge and a piezoelectric sensor, respectively (Ranc et al., 2006).

This set-up contains a large amount of custom designed fittings and accessories. Ranc et al. conducted a pioneer work by utilizing moulding technique to assess the influence of surface microstructure on friction behaviour by simulating the tongue roughness (density, diameter and height of papillae). The friction coefficient was critically affected by the papillae's density and height. The friction coefficient was found to decrease significantly with increased mode papillae density under a dry condition. However, it was found that, once surfaces were lubricated, a high papillae density yielded a higher coefficient of friction, probably due to the disrupted homogeneity of the lubricant film.

3.6.3 Tribolab

A universal mechanical tester 'Tribolab' (UMT, Bruker, Billerica USA) is available to characterize the friction and lubrication under a simulated oral condition. The device consists of a rough cylindrical PDMS probe that contacts a smooth PDMS substrate mounted on a high-torque motor accommodating the full range of speeds and torques (Fig. 17) (Fuhrmann et al., 2020). This mounted platform is able to provide oscillation of up to 60 Hz and stroke length between 0.1 and 25 mm and enables a flexible adjustment of normal load from 1 mN to 2 kN. The lubrication behaviour of sausages and gelatine gels has been explored using the instrument and results show a great dependence of lubrication on the particle size of sausage fragments, and for gelatine gels, the friction was affected by its composition; for instance, gels containing emulsions showed a low friction force, the release of oil droplets is responsible for this observation, and a higher friction force was obtained for starch-filled gelatin gels, most likely due to the altered surface property of contacts, released starch granules may provide a rough and sticky surface.

4 Applications of Tribology for Sensation Predictions During Oral Processing of Food

4.1 Creaminess

Creaminess is one of the most frequently referred to and liked sensory attributes for fat-containing foods. The perception of creaminess is without doubt related to fat presence, and creamy intensity is often reduced in fat-free or low-fat version foods. Detection of fat could involve multiple mechanisms (Weenen et al., 2003; Dickinson, 2018) and the perception of creaminess is even more complex in terms of its sensory mechanisms, involving possibly olfactory, gustatory and tactile cues (Di Cicco et al., 2019).

Fat is predominantly made up of triacylglycerols (TAG), a major form of lipid in the human diet. Free fatty acid (FFA) could also be present in small amounts such as in dairy products and can also be obtained through oral hydrolysis of TAGs by the lingual lipase (Voigt et al., 2014). Factors of genetic, neuro and sensory physiology will all contribute to human appreciation of fat (Heinze et al., 2015). In terms of genetic influence, fat perception was found affected by the

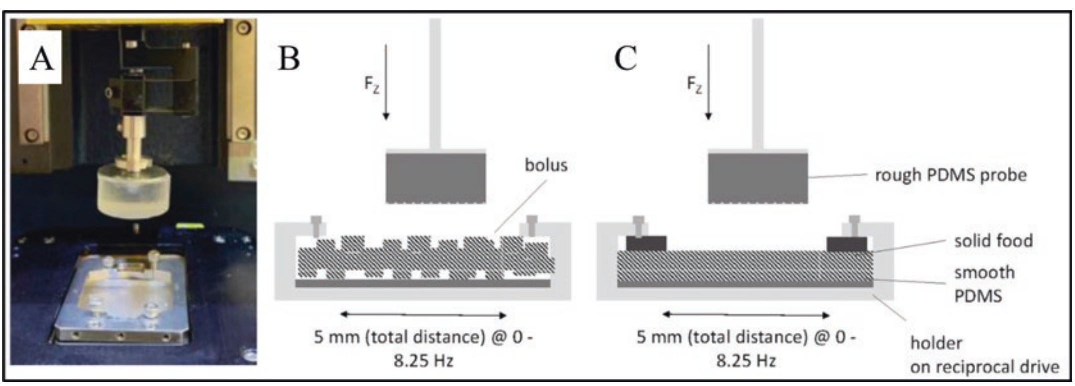

Fig. 17 Overview of the tribological set-up. (**a**) Measurement set-up with intact soft solid food gel, (**b**) PDMS probe with broken down food bolus particles and (**c**) PDMS probe with intact soft solid food. (Adapted from Fuhrmann et al., 2020)

variations of several single nucleotide polymorphisms (SNPs) within the genes of the so-called fat receptors. For example, the difference in CD36 alters the detection threshold of oleic acid and the transduction of the signal of long-chain fatty acids was affected by GPR120 (Ichimura et al., 2012; Pepino et al., 2012). At a neuro level, neuroimaging revealed varied brain activity in response to high-caloric food exposure, including homeostatic, reward, gustatory and somatosensory regions (Schwartz et al., 2000). After oral exposure to high-fat dairy products, an immediate increase in hypothalamic (hypothalamus) and amygdala (reward regions) activity was observed (Grabenhorst et al., 2009). Similarly, significant positive correlations were revealed between fat concentration in emulsions and neuro activity in hypothalamic, gustatory and somatosensory regions, which involve the anterior insula, frontal operculum and secondary somatosensory cortex (SII), anterior cingulate cortex and amygdala responses (Eldeghaidy et al., 2011). With respect to sensory physiology, varied somatosensory capabilities among individuals would also generate a great impact on fat perception. Saliva composition, age, sex, body mass index (BMI), diet and sensitivity for the bitter component 6-n-propylthiouracil (PROP) could all contribute to fat sensation (Bartoshuk, 1979; Tepper & Nurse, 1997; Kamphuis et al., 2001; Mattes, 2011). Saliva composition, in particular the concentration and activity of lingual lipase, might play a critical role in influencing oral perception of the TAG and FFA. However, since the activity of lingual lipase in human saliva has been found extremely low, whether FFA can be taken as an indicator of fat presence remains debatable.

Recent studies have also proved that saliva could act as an emulsifier during oral processing of oil/fat and effectively converts oil/fat from bulk status to a dispersed status (Ma et al., 2022). Based on this finding, one may speculate that varied fat sensation could be caused by the varied emulsifying capability among individuals (Glumac et al., 2019). For example, it has become evident that the capability of oral emulsification determines one's sensation threshold of greasiness. It is therefore believed that the sensation of greasiness is due to the presence of free oil/fat inside the oral cavity (Ma & Chen, 2022). There is no doubt that oral emulsification of oil/fat has a profound effect on the oral behaviour of oil/fat and its impacts on fatty and creamy sensations require further exploration.

Kokini was the first who introduce the concept of lubrication to oral texture sensation (Fig. 18). It was suggested that sensory perception of smoothness, slipperiness and some other tactile sensory features were dominantly lubrication dependent. By also incorporating thickness, Kokini et al developed a plausible model of creaminess sensation, based on the thickness and smoothness (Kokini & Cussler, 1983; Kokini, 1987).

The relationship between lubrication and creaminess perception has been explored by conducting friction analysis for a series of dairy products, including milk, yoghurt and cheeses. Model emulsions have also been studied extensively due to their easily modifiable physicochemical properties. Mayonnaise is one of the many earlier examples. Results from the Surface Forces Apparatus showed a negative relationship between friction force and fat content (Giasson et al., 1997). Results obtained by de Wijk et al. also showed that increased fat content would lead to reduced friction but a higher sensation of creaminess in custard samples (de Wijk & Prinz, 2005). A similar trend was also observed by Malone et al. (2003), who demonstrated that the fattiness perception showed a great dependence on lubrication behaviour. They observed that emulsions that have an overlapping trend in boundary and mixed lubrication regimes exhibited comparable perceived fattiness (Malone et al., 2003).

Chojnicka-Paszun et al. (2012) studied the fat sensation of homogenized milk containing different amounts of fat content and found that the difference of the perceived sensory attributes was only observed for systems containing 1% fat and above. The score of creaminess intensity was found to correlate positively with a fat content of milk, but negatively with the friction coefficient. The increased creaminess and thus decreased

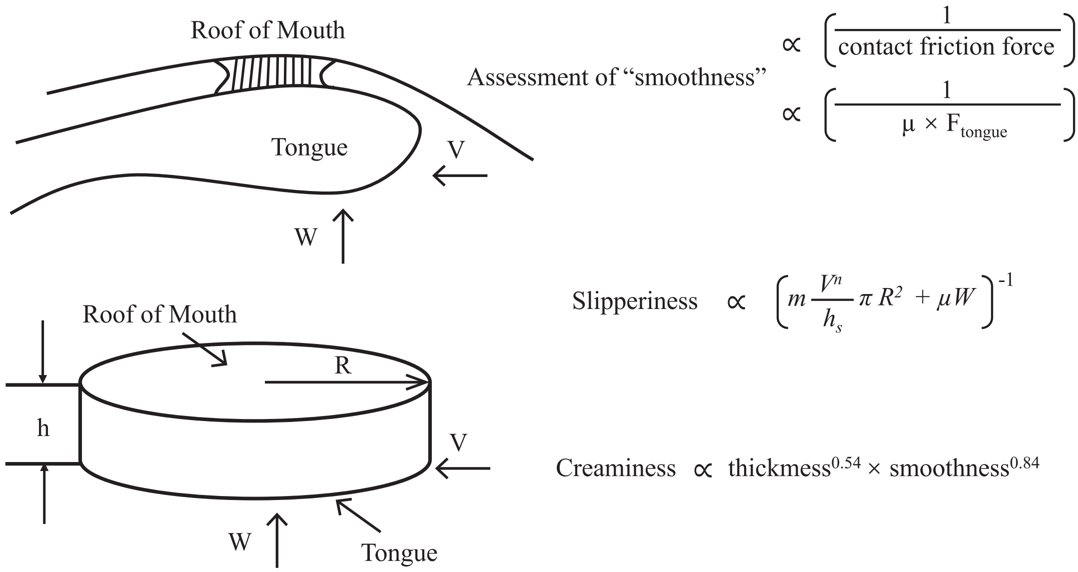

Fig. 18 Kokini's model of oral lubrication. (Redrawn from Kokini et al., 1977)

friction were attributed to the surface-induced coalescence of fat droplets, as observed by CSLM images (Chojnicka-Paszun et al., 2012). The effect of local coalescence on friction and creamy mouth feel was also observed by Dresselhuis et al. They found that emulsions that were more sensitive towards coalescence gave rise to a lower perceived and experimentally measured friction and most probably a stronger creamy mouth feel (Dresselhuis et al., 2008a).

In addition to fat content, the effective size of dispersed fat/oil droplets also played a critical role in perceived creaminess. Fuhrmann et al. (2019) revealed that the clustering of protein-stabilized emulsion also affected the friction and perceived creaminess. An increasing degree of clustering of oil droplets would lead to decreased friction coefficients and increased creaminess sensation. However, it is worth mentioning that along with clustering the viscosity also increased by three orders of magnitude (Fuhrmann et al., 2019). The potential contribution of viscosity to creaminess has been examined by Sonne et al. (2014). Using yogurt as a sample, they identified that the in-mouth creaminess sensation could be better predicted by combined factors of rheological, particle size and tribological characteristics ($r^2 = 0.97$).

4.2 Astringency

Astringency is often described as a feeling of dryness, puckering and roughness inside the oral cavity. It is usually accompanied by sensations of bitterness and/or sourness, in particular during the consumption of phenol or metal salts-enriched beverages. However, the perceptual mechanism of astringency has not yet been fully elucidated. Currently, there are three plausible theories about astringent sensation. The first one assumes astringency is a gustatory sensation (Schiffman et al., 1992; Simon et al., 1992; Iiyama et al., 1995; Critchley & Rolls, 1996), perceived by the interactions between 'free' stimuli or soluble stimuli and the exposed receptors and potentially activates the trigeminal or taste nerves (Gibbins & Carpenter, 2013). The second theory is based on the precipitation of specific salivary proteins, for example, proline-rich proteins and histatins, by polyphenols and/or altered salivary lubrication (Lu & Bennick, 1998; Naurato et al., 1999). Some others believe that astringency sensation is a pure tactile phenomenon, triggered by the relative motion between mucosal pellicles (Breslin et al., 1993). Polyphenol/protein aggregates or free polyphenols might disrupt the salivary film, which could lead to a weakened pellicle with a reduced capability of epithelium protection and ultimately trigger strong responses from the mechanoreceptors (Moayedi et al., 2021). Moreover, tactile-led astringency would be much stronger when the oral surfaces are in relative motion but with reduced lubrication (Breslin et al., 1993; Green, 1993; Gibbins & Carpenter, 2013; Ma et al., 2016). The theory of lubrication loss seems to be well accepted. For example, it has been reported that the astringent sensation could be perceived on oral surfaces that do not contain gustatory receptors, such as the inside surface of the upper lip (Green, 1993). Brossard et al. (2016) indicated that astringency sensations for red wine with varied concentrations of tannic acid were well correlated with the measured friction coefficient. A higher fiction was most likely due to more extensive precipitation and aggregate formation. Another study by Lei et al. (2022) claims that astringent sensation is caused by friction from rough surfaces. The exposure of salivary pellicles on the oral surface as a consequence of protein dehydration and protein-polyphenol aggregation causes increased roughness and higher friction (Lei et al., 2022). Ma et al. (2016) further confirmed that the friction-induced astringency arose from the temporary failure of the boundary/mixed lubrication. However, this temporary failure would soon recover with continuous saliva secretion.

While the above-mentioned mechanisms of lubrication failure sound plausible, evidence supporting a counterargument is also available. For instance, Rossetti et al. (2009) suggested that the precipitation of salivary protein was not necessary for astringent perception. They examined the lubrication property of two typical tea catechins (epigallocatechin gallate, EGCG; epicatechin, EC) and found that EGCG increased friction and was perceived as astringent mainly due to the depletion and aggregation of the saliva proteins, but EC solution was also perceived to be astringent, although it did not alter the lubricating properties of the salivary film and no aggregation was formed. Besides, the increase in friction coefficient is not always equivalent to the enhancement of astringent perception and vice versa. Milk, to some extent, could mitigate the perceived astringency induced by EGCG, probably due to the formation of milk protein/EGCG mixture which protects the salivary lubricating film, but this large aggregation increases the friction considerably as compared with water (Rossetti et al., 2009).

Contradictory to the role of friction on astringency perception has also been reported by Rudge et al. They convinced that lubrication depended critically on the structure and function of adsorbed salivary film, especially in the presence of proline-rich proteins (PRPs), but with regard to astringency, the loss of lubrication was not necessary (Rudge et al., 2021). Even though polyphenols with different molecular weights were all described as astringent (Ferrer-Gallego et al., 2014), small polyphenols (e.g. EC; caffeic acid, CA) aggregate only with negatively charged salivary mucins and hardly cause a lubrication loss. The same is also for metal salts, which precipitate salivary mucins but do not harm salivary lubricity. On the other hand, large polyphenols allow for precipitation of both mucins and gPRPs, causing an aggregation-induced lubrication loss (Rudge et al., 2021). Therefore, one may suggest that lubrication losses-induced astringent sensation is mainly caused by the removal of the specific salivary gPRP layer as a result of aggregation usually induced by large polyphenols, such as EGCG tannic acid (TA) (Rudge et al., 2021). With respect to small polyphenols, astringency is mainly induced by small molecules binding to receptors, direct interaction with oral mucosa pellicle or the altered structure of salivary film (Bradway et al., 1992; Yao et al., 2000; Bajec & Pickering, 2008; Schöbel et al., 2014).

While oral tribology provides a different approach to astringency research, one should be aware that the perception of different astringent compounds could be through different mechanisms. For a multi-composition beverage (e.g. wine), the existence of a stimulus such as ethanol makes it even more difficult to reveal its perception mechanism. Wang built a model utilizing partial least squares regression on sensory and physicochemical parameters and found that the main sub-qualities dryness and pucker were well aligned with the boundary friction formed by the salivary pellicle and model wine in the Stribeck curve, while smoothness and fullness were to be governed by viscoelasticity and viscosity of the saliva film (Wang et al., 2020, 2021d). Therefore, one may suspect that astringency is not a single sensory quality but may involve several sub-qualities.

5 Challenges and Future Developments

The measurement of the lubrication behaviour of food systems can now be feasibly conducted by various kinds of commercially available or laboratory-built devices. Considering the fact that tribological results reflect the friction response of an entire system, lubricant and substrate surfaces included, a small difference of an *in vitro* lubrication design from that of the real oral conditions, including contact medium/geometry, motion type and endogenous lubricant, could generate unexpected results. Thus, in establishing a viable and reliable tribometer for *in vitro* oral lubrication study, the following concerns need to be addressed.

5.1 Tribopairs

The human tongue and hard palate constitute a tribo-system. The human tongue is a special organ consisting of eight muscles fully flexible in three dimensions. It has an elastic modulus ranging from 10 to 120 kPa as a result of relaxation and contraction of tongue muscles (Alsanei et al., 2015). The hard palate has a rigid structure (modulus between 14 and 23 MPa) with multiple bony parts and an 'attached' thin mucosal tissue (Choi et al., 2020). Moreover, both the tongue and hard palate feature an irregular surface structure for individuals. For instance, it was found that tongue surface roughness differed significantly among young adults, probably due to the varied density and size of fungiform and filiform papillae, as suggested by Wang et al. (2021b).

The unique topographic structure of the human tongue and hard palate is well poised for feeding and speech (Moayedi et al., 2021). However, the influence of such structure on friction behaviour was not fully understood. Great endeavours have been made to emulate oral contact *in vitro*. Initially, tribopairs were fabricated by hard materials (such as steel and glass). Obviously, these contacts are unlikely to reflect the real soft contact inside the mouth. Thus, alternatives such as rubber, 3M surgical tape and PDMS have latterly been adopted (Bongaerts et al., 2007a). However, limitations still exist for these substrates. Firstly, tribopairs in most tribometers do not resemble the topographic characteristics of the human tongue and the morphological features of papillae. Although a few attempts have been made to achieve real tongue topography through the moulding technique, thorough verification is still required for its application in food and sensory studies (Ranc et al., 2006; Andablo-Reyes et al., 2020; Wang et al., 2021b). The modulus difference of the tribopairs is another issue that has been largely overlooked. Even though tribological contacts in the mouth involve soft tissues, the modulus of the tongue and palate differed by a factor of about 100. Thus, it is more about 'soft-hard' contact and the application of engineering biopolymers with tailored moduli is encouraged to enable tribopairs to be representative of the oral condition.

5.1.1 Mode of Surface Movement

Today's tribometers are properly equipped with load cells and other accessories which are more than sufficient to cover the speed range of tongue movement and its contacting pressure. However, it is well known that tongue manipulation in real situations differs greatly from case to case and from person to person. It is extremely difficult for one instrument to constantly mimic the changing conditions of oral lubrication. Therefore, caution must be taken when interpreting tribological results for sensory implications.

A primary consideration is the difference in surface movement between an instrument and the actual oral case. The majority of *in vitro* techniques adopt a ball-on-disc sliding or mixed sliding/rolling design with a relatively restricted contact area (Bongaerts et al., 2007a), while others favour a plate-plate contact in oscillation mode (Fuhrmann et al., 2020). A point-contact design makes it easy to reach a high velocity during sliding/rolling surface movement (up to 1 m s^{-1}), with a substantial amount of lubricant entrained into local contact, thus altering the friction. However, with respect to food oral processing, during food bolus transportation and oral clearance, soft oral tissues are constantly pressed and tested with a large contact by the tongue. Thus, point contact combined with a wide operating speed range might only reveal a limited aspect of oral tribological phenomena.

5.1.2 Morphological Dynamics of Human Tongue

Food oral processing involves a series of sequential or simultaneous oral actions, including chewing, transporting and swallowing (Chen, 2009). Processing of liquid and/or soft solid foods usually involves squeezing between the tongue and the palate. For solid foods, the tongue is responsible for both bolus squeezing and transportation to the molars for mastication (Fuhrmann & Diedrich, 1994; Murakami et al., 2020). High flexibility is essential for the tongue to perform these tasks. Combinations of contraction and relaxation of the tongue muscles alter its shape, size and strength instantaneously and therefore its contact with the hard palate or food particles. Thus, it is reasonable to speculate that oral friction may have a dynamic pattern varying significantly at different stages of food oral processing. However, present tribology techniques usually perform with a defined procedure, by simply running a speed ramp or oscillation test under a constant surface load. How these reflect the dynamic morphological variation of the tongue in *in vitro* tests hasn't attracted enough attention.

5.1.3 Saliva

Human saliva plays a vital role in the oral processing of food. Digestion starts the moment food is ingested due to the presence of two major saliva enzymes: α-amylase and lingual lipase. Food changes its physical, chemical and biochemical properties and becomes completely different from that before ingestion (Chen, 2009). Another major contribution of saliva is its superior lubricating effect as an endogenous lubricant, smoothing tongue movement and bolus transportation (Choi et al., 2020). In vitro friction test has confirmed that the friction coefficient was reduced by more than two orders of magnitude for a saliva lubricated PDMS contact (Bongaerts et al., 2007b). Saliva also acts as a very efficient surfactant. The tongue surface is hydrophobic in nature, but becomes hydrophilic upon wetting by saliva.

Currently, there are two approaches to introduce saliva in friction tests. One approach is simply to pre-mix food with saliva before adding it to the test chamber. Alternatively, by first pre-adsorption of a thin salivary film on the substrate surface and then conducting the friction measurement after the food sample is added. Both approaches have been successfully adopted in mapping the sensory and lubrication properties of red wines (Brossard et al., 2016; Wang et al., 2021d). Generally speaking, the first approach is applicable for investigating the dynamic changes of the overall textural properties of liquid foods or the bolus of solid and soft solid food, while the disruption mechanisms of an adsorbed lubricating film (resulting from saliva-food interaction) can be conducted using the second approach.

Another very important issue is the choice of saliva. Ethical restriction means that a large-scale collection of human saliva is not encouraged. Another practical problem in using human saliva is its variability among human individuals and its instability once it leaves the oral cavity. The use of artificial saliva could be a possible solution in this case. However, the highly complex composition and property of human saliva means that it is practically impossible to develop an artificial saliva with identical compositions/properties to real human saliva. Some simple versions of artificial saliva have been reported in the literature, but no consensus has been reached among food researchers.

6 Conclusions

A wide range of viable tribometers have been developed for the study of *in vitro* oral tribology, and some of these instruments are for general purposes while others are for a specific application. Endeavours have been made to provide a simulation of the friction occurring during the oral processing of food. However, it must be noted that current tribometers differ in many ways from the actual oral tribological environment, either in the contact conditions or in the motion of the oral surfaces. One should also bear in mind that, rather than a material property of food, tribology is a system property. The softness of the oral surface, tongue geometry and topography are highly irregular and vary considerably among individuals. The tongue strength could also change hugely during the dynamic process of food oral processing. The use of saliva (human or artificial) is another important fact that requires careful consideration during the experimental design of oral lubrication research. These disparities appear to be overlooked in the design of tribology apparatus. Further improvement of the current techniques is still needed in order to make breakthroughs in the understanding of oral texture sensation and perception.

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New In Vitro and In Situ Instrumental Approaches for Food Texture Research

Miodrag Glumac

1 Introduction

Food texture is fundamentally a sensory attribute of food products when experienced by consumers. Despite numerous literature reports and an abundance of experimental reports, food texture is still hard to define. It primarily represents all the attributes of food that provide various types of mechanical, tactile, visual, and auditory stimuli to the human sensory system. Previous literature reports have extensively described concepts and advances in food texture research covering a broad range of topics (Bourne, 2002). Many advances in food texture research have previously been comprehensively described (Chen & Rosenthal, 2015a, b).

Food texture represents the qualities of food that are detected by the tongue, palate, and teeth when present in the mouth. It greatly impacts the consumer's preferences and expectations that are based on their previous life experience. Texture impacts the choices of consumers, their food intake, food acceptance, food preference, and food expectations. It includes all the rheological and tribological characteristics of food that are derived from their shape, aggregate state, mechanical, and chemical properties. It is also very important to highlight that food texture and food structure are not the same, the first being a sensory experience with the latter being related to material properties. Food structure can be measured when food is in its native state, as well as after it has experienced major deformations and changes during oral processing in the mouth, during the formation of the bolus. Food can come in various physical states such as liquid, semi-solid, soft solid, and solid. Different types of food will have their texture perceived based upon the numerous ways it is manipulated in the mouth. Food texture is influenced by the presence and ratios of all major food constituents such as water, salts, oil, protein, and sugars in their various concentrations, and the structural organization that provides the shape and consistency of various food things.

One important issue that needs addressing is the difference between human-derived sensory and machine-derived instrumental attempts to characterize and describe food texture. Food texture is assessed by human participants when they come in touch with foodstuff present in their mouths. Instrumental food texture measurements are derived from various measuring procedures and instruments that try to investigate food properties such as their rheological and mechanical characteristics. This issue has been recently highlighted (Chen, 2020) as a common misconception. Obviously, one can measure food texture properties with a mechanical instrument, but this should not be confused with sensory properties

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experienced by a human. Extreme caution must be applied when claiming to successfully correlate instrumentally derived texture properties with a sensory experience. This was done with some success for a single parameter such as viscosity in relation to the sensorial thickness score (Sala & Scholten, 2015). It is important to stress that this chapter focuses on novel ways of instrumental food texture measurement as opposed to human sensory experiments.

In order to establish how the literature reports on the topic of food texture fair against the three major parts of this book chapter, a systematic analysis was done with the help of available online libraries. Clear trends were established when analyzing the literature overview spanning the last 40 years (1982–2022) with this information shown in Fig. 1. The databases research aimed to compare how the food texture investigations fare against ultrasound data used in food oral processing, the oral tribological data, and various instrumental machines that simulate the mastication (chewing) of oral masticators. This data was obtained from the database libraries that were the Web of Science (accessed on 12.2.2023) and Science Direct - Scopus (accessed on 12.2.2023). The exact keywords were “food” AND “texture” data which was compared with the data for keywords “oral” AND “tribology,” “food” AND “oral” AND “processing” AND “ultrasound,” and a combined set of data for two separate searched phrases “mastication” AND “simulator,” “chewing,” AND “devices.”

The index and criteria for searching were the food science and technology research area, citation type, research topic, and category for the Web of Science database with articles in the English language selected. For the Scopus database, the subject area was the Agricultural and Biological Sciences with articles published in journals and written in English. Duplicates were removed and a Python 3 code for crossreferencing the same journals based on the DOI number was employed to have a clear picture of the exact number of manuscripts. The main finding from the data analysis shown in Fig. 1 is that the ultrasound used for food oral processing, oral tribology, and oral masticators manuscripts has a very limited number of overall publications, their yearly publishing frequency is still fairly low, and the number of publications is orders of magnitude smaller when compared to manuscripts for food texture. This goes to show that although these reports are very important, they belong to

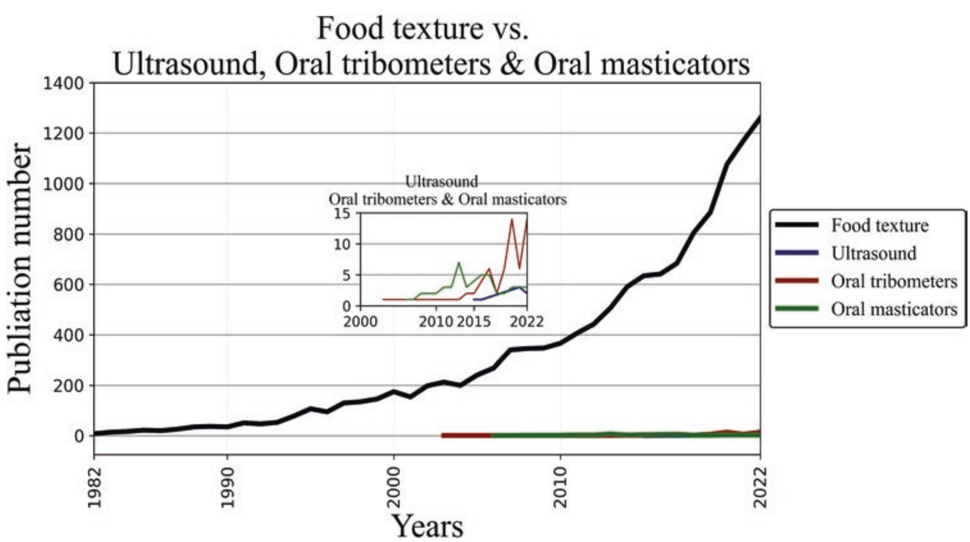

Fig. 1 Overview of the publication history of food texture compared with ultrasound, oral tribology, and oral masticators. Food texture publications (black), ultrasound (blue), oral tribometer publications (red), and oral masticators (green). Data were taken from Web of Science and Science Direct (Scopus) databases (digital libraries). Inset shows publications from 2000 to 2022 for the three areas

fairly new and emerging branches of general food texture research. The inset (smaller time-frame window) in Fig. 1 emphasizes that most manuscripts were published relatively recently in the period between 2010 and 2022 and in lower numbers (<20 per year) further demonstrating the novel nature of these three sub-areas of instrumental food texture research. This goes to show that novel approaches and techniques for texture research are crucially important to address the complex and multidisciplinary nature of these investigations.

This book chapter aims to summarize a comprehensive explanation of various progress and novel approaches to instrumental measurements of food texture where ultrasound, oral tribometers, and oral masticators are highlighted. Because the reports dealing with these instruments are not numerous as stated above, and they deal with a different way of characterizing food texture, they are discussed on a case basis. Recently there has been a shift towards doing food texture research by using instruments that can be designated as oral biomimetic instruments. These instruments are manufactured to closely mimic one or multiple parameters of the anatomical structures of the human oral cavity (size, volume, surface area) and processes (movements, food breakdown) found during human food consumption. Novel techniques such as using ultrasound for charachterising food texture will also be elaborated upon. Future aspects will give some comments on how to further improve instrumental setups and literature gaps present to improve the future of food texture research.

2 Instrumental Approaches in Food Texture Research

The main body of work presented here deals with firstly addressing the overall state of various instruments in food texture research. Several segments regarding (i) classical approaches to food texture research and (ii) novel approaches to food texture research are elaborated upon. Then modifications to the texture analyzer in food texture research are addressed. Finally, the ultrasound techniques utilized for real-time texture monitoring of solid food models concerning artificial human tongue models, biomimetic approaches to oral tribology, oral tribometer setups, and oral masticator devices are explained.

2.1 Classical Approaches to Food Texture Research

The three most common (classical) instrumental food texture research instruments are traction compression machines (of which the most common is the texture analyzers (TA)), rheometers, and tribometers. Their usage depends on which physical state, type, and origin of the target food product is measured but also mechanical properties of the food are researched. When measuring the mechanical properties of food, it is common to use a texture analyzer when the structure of food is mostly solid and soft solid (Chen & Opara, 2013), while rheometers are mainly used for food boluses, soft solids, and viscous liquid food types (Fischer & Windhab, 2011), and tribometers are used for liquid foods and liquid boluses where interaction between foods and various surfaces dominate (Stokes et al., 2013). Tribometers are employed to probe how various food stuff compressed against two surfaces behave during the course of relative shearing motions. The analysis is often presented in the form of Stribeck curves, depicting the evolution of friction coefficient as a function of food viscosity, imposed normal load, and shearing velocity. The multitude of scientific manuscripts usually employs some or a combination of these instruments.

The procedures regarding the usage of these techniques have been well established. All these instruments try to emulate the deformations occurring inside the human mouth, requiring to cover the wide range of food products that make up our diets (with all the diversity of their mechanical and structural properties). Despite the long and thorough scope of data, these techniques provided they were still not able to fully take into account the complex structure of the human oral cavity. Therefore, in the next segment, the need for novel (biomimetic) approaches will be elaborated.

2.2 Novel Approaches to Food Texture Research

In recent decades, there has been a growing number of scientific reports that approach food texture research by incorporating novel methodologies and techniques. These complementary techniques help to enhance the experimental possibilities of the existing techniques or represent a new way of investigating food texture. These can be various new custom-made parts or electronic sensors that are coupled with them. Custom-made instruments that were designed and manufactured from scratch were recently reported and are mostly utilized as proof of concept works in academic research groups. Biomimetic approaches are incorporated into the machines to make them more in line with complex biological tissue and surfaces, volumes, sizes, motions, sequence of eating events, and saliva incorporation among many others. These instruments can be collectively classified as oral biomimetic, which aims to tackle a specific set of events of the broader process that is food oral processing in a physiologically relevant manner. They can cover one, two, or more specific parameters of food oral processing and one or more movements such as crushing, shearing, or other types of mechanical deformations.

For example, modified TA can be adapted to better emulate the crushing and biting during the first bite or squeezing of foodstuff at the beginning of soft food deformation. Texture analyzers utilizing ultrasound techniques have been explored recently. They utilize mono-element transducers to detect changes during the compression of food gels, such as the bending of artificial tongue models, and the contact area between the food and the tongue. However, the TA is limited to foods and tests that are mostly in solid form or cannot measure other parameters when the food is already crushed.

When food is in a semisolid state or the food bolus has been already made, it is subjected to more shearing behavior between the tongue and the palate. To research these events, a multitude of oral tribometers that were either custom-made or adapted to oral conditions have been manufactured (Paul et al., 2022; Sarkar et al., 2021). Oral tribometers can be limited by the state of food for example more solid and very viscous.

Novel instruments such as masticators can mimic both compression and shearing motions of food oral processing. They tackle mastication and bolus formation investigations and are very useful for food texture characterizations. Several chewing machines were designed and used in experiments as they were able to mimic the conditions of food crushing and derive the same type of boluses found after oral processing in the human mouth. Although they cover a wide range of motions, the oral masticators present in literature are not standardized, and at times one machine for example can incorporate saliva while a different one cannot. This all makes the comparison between setups hard and limited to basic measurements such as particle size after mastication or the number of chewing cycles. All the instruments described here incorporate other sensors, techniques, and additional sources of data acquisition.

3 Modifications to the Texture Analyzer in Food Texture Research

Modifications to texture analyzers are mostly represented by additional custom-made parts and or other instruments with sensors as additions to the main instrument are the focus. Note that the multitude of various texture analyzers from different companies with their different probes, software, or different models that are commercially available won't be discussed. Several interesting reports deal with how the texture analyzer was modified and used to research food texture. A specialized part that acted as a syringe holder was mounted on the texture analyzer and used for controlling the flow of fluid to test its cohesiveness in researching fluids for swallowing difficulties (Hadde & Chen, 2021). The texture analyzer setup was coupled with a high-speed camera to capture and analyze the breakage of the fluid as it transitions to droplets. This setup was effective in determining the characteristics of the fluids which is important in future food formulations. One report explained how a custom-made part made from metal that could hold cutlery items (forks) was mounted on the texture analyzer to test soft foods models (Pematilleke et al., 2022). The experiments were aimed at testing for pressure tests but in much more controlled conditions using the texture analyzer. The results showed that the custom-made texture analyzer setup correlated well with human tests and thus was able to produce reliable data. The texture analyzer was mounted with an Iowa Oral Performance Instrument (IOPI) device attached to a custom-made pully and an air bulb detector that was either tested by a human subject in their mouth or with an artificial oral system made from polydimethylsiloxane (PDMS) and a pig's tongue (Mo et al., 2019). These investigations were aimed at recording friction coefficient and investigating oral lubrication in the presence of various fat and non-fat foods with the influence of saliva as well. The modified texture analyzer used in ultrasound investigations is explained in detail elsewhere (segment 3), and the one used for oral tribological investigation (segment 4) as well, and they won't be explained in detail here. It is clear that texture analyzers have a good reputation in food texture research; however, the potential of mounting various sensors and utilizing them is still enormous. More customization such as adding sensors to the texture analyzer and novel approaches to measuring different food texture properties should be the aim of future investigations.

4 Ultrasound in Food Texture Research: Tongue-Food Interaction

Ultrasound represents a unique way to investigate food texture in real-time and how various food stuff interacts with oral surfaces under different conditions. Ultrasonic waves can propagate through materials and depending upon their acoustic properties various phenomena can be observed and followed. Studies can utilize mono-element piezoelectric transducers (longitudinal waves) or multielement transducers that can provide images based upon the Doppler effect (B-Mode imaging). Changes in the wave that propagate through the system and its properties can thus provide information about these changes. The main usage of mono-element transducers was to investigate the tongue-food interface in vitro under various conditions. Depending on the main purpose of the investigation, the corresponding echos of the ultrasound wave can give the following information:

(i) Observe interactions between the tongue model texturized surface and food models
(ii) Measure deformations of the tongue and food models during compressions
(iii) Determine how tongues that were non-deformable and deformable influence the tongue-food-palate system during compressions
(iv) Investigate both simple and complex food models during compressions

These investigations were done on a custom-modified texture analyzer that was able to have mounted artificial tongues and ultrasound probes beneath them. A total of four cases of systematic research on the relationship between tongue properties, food properties, and breakdown behavior are described.

4.1 Tongue-Food Interaction

4.1.1 Case I: Impact of Surface Roughness and Lubrication

Introduction: Food oral processing is a dynamic process and there is an urgent need to investigate what happens inside when food is deposited and masticated in real-time. The ultrasound technique can be thus a very useful tool employed to tackle these questions.

Goal: The goal of the first study was to use a ultrasound transducer that produced waves of 1 MHz frequency to analyze the evolution of the acoustic signal between the dorsal surface of artificial tongues (tongue mimicking surfaces) under lubrication and gel food models (Mantelet et al., 2020a) For this purpose, a reflection coefficient (R*) was envisioned that can register these changes in the acoustic impedance at the interface.

Methods: The study used artificial (biomimetic) tongues made from PVC that were made to have three different levels of asperity height and their distribution density was in line with values found in humans. Food systems represented gels made of either just from agar or just gelatin or a mixture of both agar and gelain in the same gel with one gelating gel made with the addition of a Tween 20 emulsifier to regulate the gels wettability properties.

Main findings: One of the main discoveries was that the apparent reflection coefficient evolved based on the changes in the tongue-food system. It increased when the asperities on the tongue were higher and denser, levels of lubrication were lower, and the rigidity of the food gels was lower. Smooth surfaces with a lubricating layer had similar values of the reflection coefficient (~33.6%). This coefficient measured how the food gels were able to mold themselves to the asperities and form a film on the tongue-food interface.

Short conclusion: The experiments demonstrated that the ultrasound technique was very useful for the changes in food deposition on rigid artificial tongues. It was able to capture the difference between food type and tongue roughness type in real-time.

4.1.2 Case II: Impact of Tongue Roughness During Compression

Introduction: In a follow-up second study, the ultrasound technique was further utilized in a similar setup to follow what happens with food gels during uniaxial compression under a controlled setting. By compressing food models, one can follow the changes that are happening between the artificial tongue and food that is derived from the first echo signal, and food and the artificial palate (represented by a flat circular TA probe) that is derived from the second echo signal (Mantelet et al., 2020b). These changes were represented as a variation—the evolution of the reflection coefficient (ΔR*) depending on the various properties such as rigidity, fracture properties, or adhesives when compressed against the tongue surface.

Goal: The main aim of this study was to see how the evolution of the reflection factor evolves during a compression sequence that is mimicking the first moments of food oral processing of these types of foods. Under mechanical stress, the gels can display different behaviors according to the (i) polymer concentration, (ii) polymer type, (iii) properties of the artificial tongue surface, and (iv) lubrication condition.

Methods: The modified bottom part of a texture analyzer was used for holding the ultrasound transducer and the artificial tongue in the same way as in the previous study with the probe acting as an artificial palate. Food models were the same eight types made with agar or gelatine (or both polymers) described in the previous section.

Main findings: Based on the experimental data, several interesting trends were noticed. The asperities and their properties led to high variations of the reflection coefficient due to the different molding capabilities of the food gels. Food gel mechanical properties impacted the contact area between their surface and the artificial tongue one. Agar displayed very different behavior compared to gelatin. Agar systematically released more water than gelatin followed by the ultrasound due to the fact a water film formed between the tongue surface and the gel which decreased the ultrasound reflectivity.

Short conclusion: The changes in the evolution of the reflection coefficient (ΔR*) are very valuable sources of information that could help bridge the gap to better understand how food can mold itself on the tongue surface and what is the contact area of such interactions. This could be useful in monitoring texture perception in real-time.

4.1.3 Case III: Impact of Deformable Tongue Roughness and Rigidity During Compression with Food Gels

Introduction: Further improvements were made to more closely resemble the mechanical properties of a human tongue, the usage of polyvinyl alcohol (PVA) for their manufacturing (Srivastava et al., 2021b). By freezing and thawing the PVA one can control and modify the rigidity and by having a specific number of cycles can achieve desired mechanical properties. Likewise, using different sandpaper can provide a certain roughness on these tongues which is an important factor to take into account concerning human tongue asperity height and distribution. Besides the apparent reflection coefficient, the changes in the thickness of both tongues and food models are followed by the time of flight value which measures the changes and behavior of the ultrasound signal of the two interfaces tongue-food and food-palate during compression.

Goal: The objective of this investigation was to see how compression influences tongue thickness and food deformation and follow the changes by ultrasound parameter time of flight and reflection coefficient.

Methods: Four types of artificial tongues were made with varying mechanical properties and the roughness of their surface (asperity height and distribution) with the main division being soft and hard and smooth and rough. Food gels were made from agar and gelatine polymers. Time of flight was also able to capture fracture of the softest food gels and follow the deformation of the tongue in this case.

Main findings: Food properties had a big impact on the time of flight values where the soft gels could deform the tongue less, and more rigid gels deformed much higher. The rigidity of the tongues influenced how the tongues can be deformed during compression, where the softer tongues systematically had bigger deformations measured in millimeters than the hard tongues. Food properties such as syneresis and the ability of the gels to mold themselves on the tongue surface played the biggest part in the reflection coefficient values. Different rigidity, tongue asperity height, and asperity correlation length influenced the reflection coefficient for gelatin-type gels.

Short conclusion: By using the PVA polymer, artificial tongues were brought closer to values found in human tongues for rigidity, asperity height, and distribution. Time of flight values and reflection coefficient were proven to be useful to analyze the tongue-food dynamics. Changes of the time of flight were induced by different properties of food gels Young's modulus, water release capacity but also tongue parameters such as rigidity and roughness. It was possible to measure the apparent reflection of acoustic echoes at a small scale even when the tongues and food models had relatively similar acoustic impedance.

4.1.4 Case IV: Behavior of Stacked Gels Composition and Arrangement During Compression on the Deformable Artificial Tongue

Introduction: Because many food types that can be consumed often don't have a simple structure and consistency, the need for testing more complex models is very important. One model type of food is a two-component systems where two gel types (Santagiuliana et al., 2018) are stacked on top of each other and it is then possible to test their texture contrast in experimental setups. The deformation of cylindrical stacked gels and deformable artificial tongues was followed by ultrasound during compression (Srivastava et al., 2021c). These experiments recorded and followed three echoes, the first one between the artificial tongue and the bottom food gel, then between two gels and the top layer gel and the artificial palate (probe of the texture analyzer).

Goal: The main aim of this study was to first see is the characterization of more complex heterogeneous food with a stacked gel model. Secondly, how deformation of the whole tongue food system behaves between gels and their different mechanical properties, and the position of a specific layer on the tongue.

Methods: This study used a higher frequency transducer that had 5 MHz frequency and was able to achieve the good spatial and temporal resolution necessary to measure the behavior of interfaces between the two gels. This allowed characterizing the fluctuations derived from mechanical phenomena in this system. The experimental protocol consisted of three steps: rest, compression, and relaxation during which the tongue and the gels were followed by ultrasound. A total of 14 different agar and gelatin-based gels were made with increasing concentrations of agar and gelatin that were a maximum of 2.5 w/w and 12.2 w/w in total, respectively.

Main findings: Deformations were mostly influenced by the polymer type, mechanical properties of elasticity and brittleness, and the position of the gel layers' bottom and top. During experiments, agar was more influenced by changes in polymer concentration because it was more brittle than gelation which had no impact due to high elasticity.

Short conclusion: Ultrasound was able to provide a deeper understanding of stacked gel food model behavior during compressions on a deformable tongue that surpasses the capability of conventional techniques. These progressive investigations of the relationship between the type of artificial tongue used, food model structure and composition, the propagation of ultrasound waves, reflection indexes—echos, and crushing by the probe of the texture analyzer are summarized in Fig. 2.

4.2 Ultrasound Imaging

Besides, mono-element transducer research is possible with ultrasound multielement probes that can provide two-dimensional images of the oral cavity. This is captured by the B- mode image that can be transformed into an M-Mode image of an ultrasound apparatus and recorded as pictures and/or videos that depict motion as a function of time. These can be useful as they can monitor in real-time how food is positioned and behaving during oral processing with the technique being non-invasive and doesn't induce any changes in the monitored oral cavity-food system. Images can provide various parameters such as size, shape, movements, contours, speed, and duration of eating events. Reports dealing with such kinds of investigations are quite rare and limited, which highlight the knowledge gap pres-

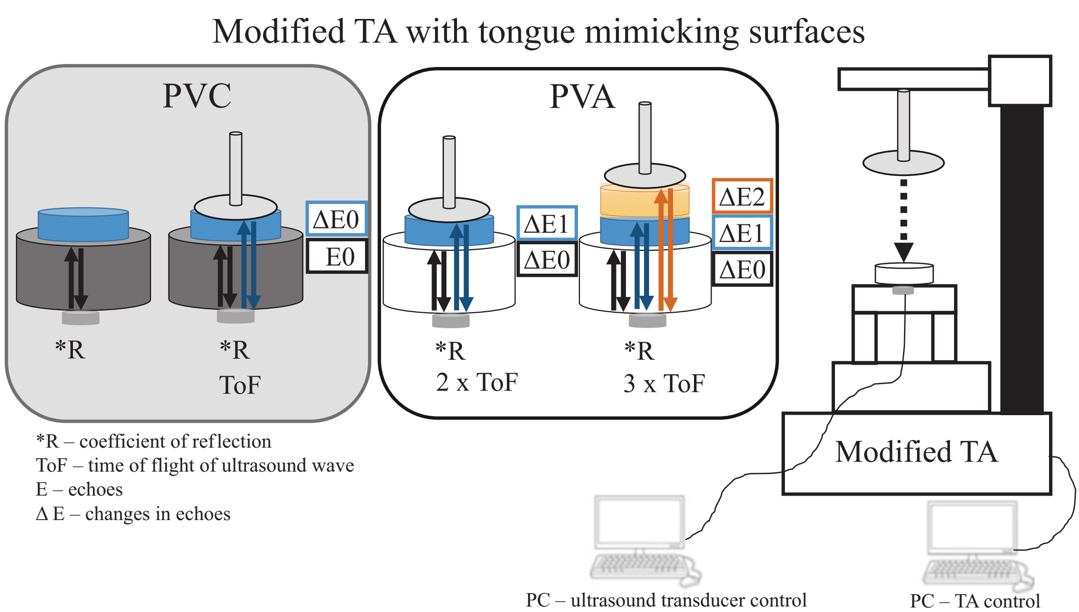

Fig. 2 Modified texture analyzer with artificial tongues and ultrasound transducer with deposited food gels. In gray shade is the solid non-deformable PVC tongues and in white deformable PVA tongues with arrows showing the propagation of ultrasound waves through the system. On the right is the layout of the experimental setup with PC controllers for both the TA and the ultrasound sensors. Arrows show the propagation of ultrasound waves with an increasing number of reflections with one reflection in black, two in blue, and three in orange color

ent in the literature. Several interesting studies shall be elaborated upon where the main idea of utilizing ultrasound imaging to follow food oral processing will be explained.

4.2.1 Ultrasound Imaging for Investigating Semi-Solid Food

Introduction: In one report, de Wijk and co-workers (2006) investigated oral movements during food oral processing using imaging to quantify them. The food was assessed by a human panel for the sensory attributes (sweet, bitter, thick, and creamy) with food having either low or high viscosity values.

Goal: Main objectives of the study were to investigate how oral movements of the tongue can be quantified with ultrasound during the consumption of semi-solid food types. To achieve this oral movement is investigated by using food with high and low intensity of sweetness or high and low viscosity (de Wijk et al., 2006).

Methods: The study used a Picus ultrasound imaging system with a 5 MHz probe using the B mode imaging. The data was stored as video images and was later subjected to image processing by using a two-step algorithm in MATLAB.

Main findings: Oral movements were influenced by food properties such as viscosity and sweetness as well as the sensory parameter that was being rated. During manipulation when food was in the bulk phase, higher sweetness food needed more movements than lower sweetness one during judgment. A reversed trend was noticed when judging thickness where lower sweetness food needed more movements than high sweet food type. Swallowing induced specific movements to the middle, posterior, and horizontal parts of the tongue. When rating sweetness, there was an increase in oral movements based on the viscosity of the food. Finally, during the clearance phase movements of the tongue's middle and posterior area increased as the viscosity of food increased, as viscous food was more difficult to manipulate in the mouth.

Short conclusion: This innovative but preliminary study highlighted the differences in oral movements as followed in the ultrasound images from several locations in the mouth. It didn't show the development of the movements over time or their nature but showed promise of using ultrasound in food oral processing studies.

4.2.2 Ultrasound for Investigating Tongue Movements and Food Bolus

Introduction: Another report by Blisset and colleagues (2007) investigated food oral processing followed by both 3D articulography and ultrasonography to discover the effect of chewing swallowing, oral tissues, and tongue movements on bolus size.

Goal: The main aims of the study were to see the relationship between jaw and tongue movements, how bolus size influences the index of tongue movements, and to see how bolus size is affected by chewing, swallowing, and oral tissue movements.

Methods: The confectionery chew food model was used as the food model that six healthy oral physiology participants had to chew. Participants would take 1, 2, or 4 units and chew them while being recorded with 3D articulography with electromagnetic articulography and ultrasonic echo sonography using M-Mode images captured from the B-Mode recordings.

Main findings: Ultrasound data showed that a lower number of confectionery units were consumed the fastest; however, tongue movement index differences correlation with the number of units was more difficult to establish. A significant correlation between tongue movements captured by ultrasound and jaw gape captured with articulography was observed when participants masticated four confectionary food models. The index of tongue movements increased to an early peak after with it started to decrease for a longer period, while the gape jaw data linearly decreased as the number of chews increased.

Short conclusion: By modifying the food model unit count, mastication parameters were influenced and they had a varying effect at the beginning of chewing because of various choices for particle selection. In the middle stage of chewing, the distance and range of jaw and chin movements were noticed (Blissett et al., 2007).

4.2.3 Investigating Food Oral Processing by Ultrasound Imaging

Introduction: In another interesting study looked into food bolus volume and tongue movements during food oral processing followed by ultrasound (Gao et al., 2013). Ultrasonography in the M-Mode is very useful for visualization of the dorsal surface of the tongue and also bolus formation and its commute from the tongue to the pharynx. Variations of tongue movements can be characterized by different food types, bolus types and volume, mechanical properties, and individual variability as well.

Goal: The experiments were designed to investigate the processing and swallowing behavior of hard and soft gels, sol, and water followed by ultrasound. Both M-Mode and B-Mode images were used to characterize these events.

Methods: The ultrasound imaging system was a Toshiba SSA-780A that used a convex probe with a 3.1-MHz (PVT382). Food gels were made from agar and sol was made from thickener for regulating dysphagia. Four healthy women were participants in this study which had the convex probe positioned under the chin.

Main findings: The tongue distance which represents the distance of a tongue at rest from the probe was different for different participants. Oral residence time increased for higher concentration agar gels and higher volume of the sample. Oral residence time in this study was reflected by the mechanical properties of food and food volume. Bolus and its mechanical properties were more dependent on the mechanical nature of the food that was consumed and not the volume.

Short conclusion: Ultrasonography was used to extract and measure movements of the tongue during food oral processing of gels several interesting trends. The increase of tongue curvature–grooving was influenced by the volume and mechanical properties of food gels, as it increased for the agar. However, velocity wasn't changed for the volume; it induced greater movement of the tongue.

5 Modified and Custom-Made Oral Tribometers

When food texture investigations are focused on the thin film lubrication between surfaces tribometers are employed as the main tool needed to properly capture these events. This is important for formulating novel food products and discovering the underlying principles that govern lubrication behavior. Very briefly an overview of tribometers and their categorization will be mentioned. A custom-made tribological setup will be explained and investigations that were carried out utilizing it will be mentioned.

5.1 Overview of Tribometers Aimed at Oral Tribology Investigations

It has been evident that to understand the tribological events that are happening in the mouth a broad specter of factors must be incorporated into the design of mechanical instruments used in experiments. These are wide-ranging and depending on their construction can have various approaches to which factor/aspects of oral condition they mimic. Recently several publications adressing tribology as a novel tool for food oral processing investigations (Paul et al., 2022), food oral tribology (Xu et al., 2022), soft tribology, and sensory perception of dairy products (Corvera-Paredes et al., 2022), food systems friction measurements with soft tribology experimental setups (Rudge et al., 2019), and oral tribology relationship to sensory perception (Sarkar & Krop, 2019) have been published that describe in detail oral tribological setups. For a full list of various tribological setups, one should refer to these publications, with only custom-made or heavily adapted commercial setups aimed at mimicking the conditions in the mouth will be mentioned (Table 1). Second part will focus on the custom-built tribometer from the authors labora-

Table 1 Overview of custom-made oral tribometers currently deployed in food oral processing investigations

No.	Oral tribometer type	Tribopair geometry and biomimetic characteristics	Tested food or food model	Speed (mm/s)	Load (mN)	Reference
1	Mini-traction-machine (MTM)	PDMS ball-on-PDMS disc setup	Dairy products	1–1000	2000	Laguna et al. (2017)
2	Modified rheometer	Elastomer surface 3D printed attached to the top plate of the stainless steel plate	Microgel Protein dispersions	0.001–2000	2000	Soltanahmadi et al. (2022)
3	Optical tribological configuration (OTC)	Hydrogel probe against hydrogel disk	Emulsions	80	500	Dresselhuis et al. (2008)
4	Lab-modified texture analyzer	Steel ball-on-PDMS disc setup PDMS ball on PDMS surface	Emulsions Wine Yogurt	0.1–40	570	Chen et al. (2014)
5	Custom pin-on-disk tribometers	Rotational disk with stationary hydrogel probe		0.01–100	0.1–20	Urueña et al. (2018)
6	Novel custom-made biomimetic tribometer	Aluminum hard palate and soft texturized artificial PVA tongue	Semi-solid cheese Newtonian solutions	5–30	5000–20000	Srivastava et al. (2021a)

tory and research group, with the main findings from the most recent investigations will be mentioned.

5.2 Custom-Made Oral Tribometer Investigations

Introduction: When looking at tribo-pair, the oral cavity represents a highly complex environment due to factors such as contact area, complex motions, surface roughness, roughness distribution, changes in rigidity, and lubrication by saliva or food-saliva mixtures. Linking the physical measurements of food like mechanical properties, rheological, and tribological to sensory-derived assessment is still rather difficult exactly because of the complexity found in the in vivo conditions. Moreover, linking some tribological-derived results to sensory-derived experiments is difficult as there is a wide range of geometry, surfaces, and setups available that don't often take oral conditions into account. Comparison between such kinds of studies is difficult as well due to these factors.

Due to the need to address these issues of imitating the oral cavity more closely, a custom-built tribological setup (Glumac et al., 2023) that utilizes many aspects of soft tribology was manufactured from scratch (Fig. 3). Having this in mind the first experiments on the tribometer were aimed at investigating various factors to test the feasibility of the setup. The main scientific goal was to investigate and enhance knowledge of friction forces and their changes over time during food oral processing. The tribometer addresses several aspects of mimicking the in vivo conditions. It has a high degree of motion that can do both sheer and compression movements. It has a high contact area between the artificial palate and the tongue akin to those found in the real mouth. A high range of forces can be implemented and a wide range of the shear velocities can be adjusted also making the setup highly adaptable. The other big factor of the tribo-system is the custom-manufactured and designed artificial tongue mimetic made from polyvinyl alcohol (PVA) hydrogel. The tongues can be modified in such a way that their roughness and rigidity are regulated and are comparable to those found in the human mouth. It is also hydrophilic which makes it more comparable to real oral conditions.

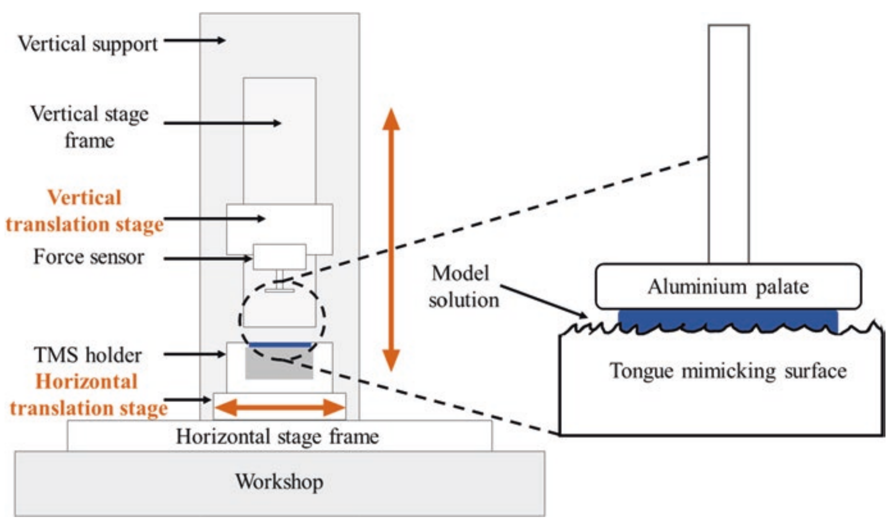

Fig. 3 Schematic representation of the custom-built tribometer setup. A hard palate made from aluminum is mounted on top of and connected with a force sensor. They are all attached to the vertically moving platform that is used to control the load. The bottom part holds the artificial tongue made from PVA and it is connected to the horizontally moving part. These two movements are controlled to create both load and shearing motions during the experiment

5.3 Variations in the Food Model, Operational Parameters, and Artificial Tongues

Goal: The main goal of these studies was to investigate how the tribometer is able to perform experiments under different operational conditions, artificial tongue properties, and several types of food models (Srivastava et al., 2021a). The friction coefficient calculated from these various conditions was the main parameter followed and directly correlated to the status of the tribo-pair. The operational conditions were loads ranging from 5 to 20 kPa, while the shear velocity that was tested ranged from 5 to 30 mm/s. The testing underwent four identical cycles of forward and backward motions of the horizontal stage during normal load. The artificial tongues were made to have their rigidity controlled by freeze and thaw cycles.

Methods: Two rigidities were made for the artificial tongue that equaled 50 and 100 kPa with two different roughness levels. The food models were Newtonian solutions of glucose and cottage cheese. The cheese was tested as undiluted (normal) and diluted with added 5% of either small or big cellulose particles.

Main findings: The friction behavior of the glucose solution didn't show a statistically significant difference, whereas the cheese displayed lower friction for samples without particles with higher friction for those with particles. The highest friction was for the undiluted cheese samples with large particles. Surface roughness had a profound impact on friction where systematically all food samples showed a higher friction coefficient during shear on a rough surface when compared to the smooth one. Operational parameters such as normal stress velocity didn't display a large influence on friction for samples with small or large particles. However, increased stress friction values tended to get smaller, and friction at the maximum and minimum values was significantly different. Shearing velocity had a far smaller impact on friction evolution with all samples displaying the same values. However, a statistically significant difference was found for 20 mm/s speed when comparing two samples of cheese with either small or large particles. Tongue rigidity in the absence of any food had a larger impact on friction, whereas softer tongues displayed higher friction when compared to hard ones. When food was introduced to the system, a reverse trend was observed where softer tongues produced lower friction values and harder tongues produced higher friction.

Conclusion: This systematic investigation of various physiological parameters such as rigidity, normal load, and shearing velocity on an in vitro setup is important in order to change food texture that in fact can improve the understanding of real-life scenarios of how a portion of food is manipulated in the mouth.

Future outlook: There has been a shift in the general understanding of the basic principles and approaches to adapting existing tribometers to mimic oral conditions. The process has been slow and gradual; however, there is a growing body of work and literature discussed here (see Fig. 1) that is exactly achieving this goal. The process has been until now focus on moving away from rigid structures toward soft deformable surfaces and trying to implement an increasing number of factors found in oral conditions (Fig. 4). In scientific reports, it is common to report just friction coefficient but friction derived from force ratio indeed has a far more complex evolution. This hasn't been investigated sufficiently for both simple or more complex food models. With increasing complexity, the instruments are approaching the parameters found in the mouth.

6 Oral Masticators

Masticators represent one of the innovative ways food texture can be researched by using instruments as they try to imitate the human mastication (chewing) process. These represent investigations mostly in academia that aim to bring further sophistication and possibilities of these custom-made instruments to make them closer to the real human condition, mimicking chewing cycles, saliva incorporation, and variation in force among other factors.

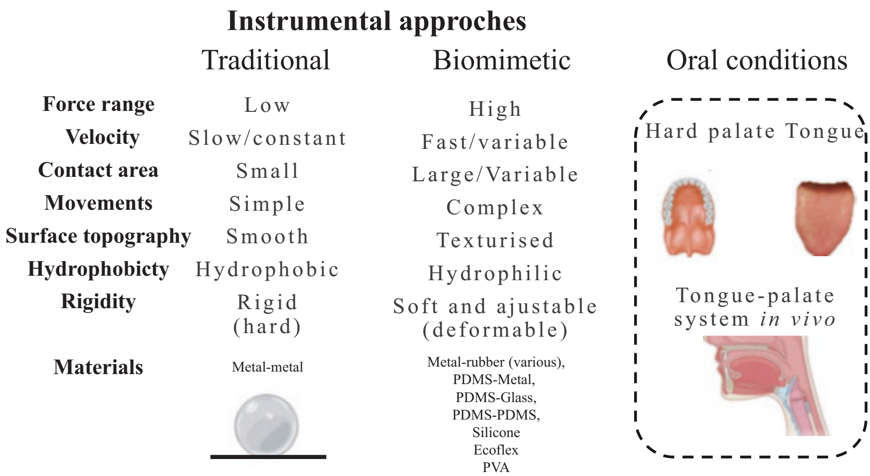

Fig. 4 Overview of parameters found in oral tribological investigations. The comparison between the traditional and a recent shift towards a biomimetic approach to oral tribology in integrating parts of instrumental machines. In the dashed box, the real human oral system is shown with a side profile of the tongue and hard palate structure

Oral mastication simulators (known as chewing devices or chewing machines) are used in food oral processing science to study the process of chewing and the mechanical and physical properties of food. They are designed to mimic the movements and forces (compressions and shearing) involved in chewing and can be used to evaluate the texture and acceptability of food products, as well as to understand the factors that influence food choice and intake. There are several types of chewing devices, including jaw simulators, which use a mechanical jaw to mimic the movements of the human jaw during chewing, and chewing robots, which use artificial teeth and a computer-controlled system to simulate chewing. These devices can be used to measure a range of parameters, including the number of chews, the force applied to the food, and the size and shape of the resulting particles (Panda et al., 2020). Chewing devices can also be used in the development of functional foods and therapeutic products, such as foods for people with swallowing difficulties or products designed to improve oral health. They can also be used to study the effects of aging on chewing and swallowing and to develop strategies for maintaining oral function in older adults. Two types of oral masticators are focused on researching food texture and other researching food flavor. Here, only the ones that are used in food texture research will be further discussed.

Oral masticators can incorporate factors that mimic various aspects of oral physiology such as the volume of the oral cavity, tongue characteristics, human saliva and food-saliva interactions, teeth, biomechanics of eating of the human mouth, dynamics of the chewing process, chewing, and bite forces among many others. Here, two reports dealing with oral masticator devices that were built to research food texture will be discussed (Fig. 5).

6.1 Overview of Oral Masticators

6.1.1 Oral Masticator for Investigating In Vitro Chewing of Cereal Bars

Introduction: To mimic human chewing a special device was made with a six-bar linkage mechanism that allowed for multiple degrees of freedom in regard to lateral and vertical chewing motions (Xu et al., 2008). This enabled the system to have an adjustable link that can generate a variety of chewing movements and trajectories (Fig. 5A).

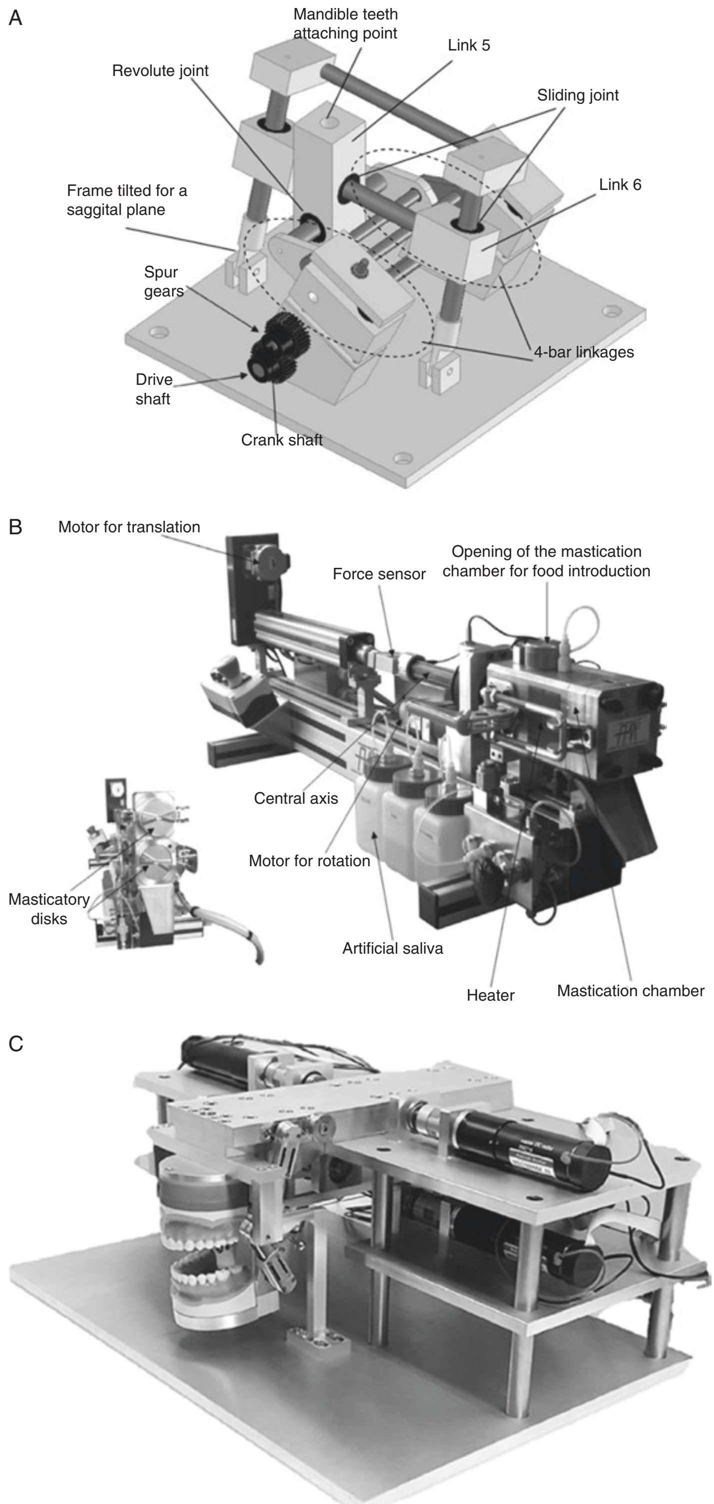

Fig. 5 Oral masticator devices are used to simulate food oral processing on an instrumental setup. (**a**) Instrument able to mimic human grinding and crunching oral movements (with permission Xu et al., 2008); (**b**) Oral masticator able to collect bolus at any stage of processing and can inject artificial saliva (with permission Mishellany-Dutour et al., 2011); (**c**) Masticator robot with human-like jaws that can detect forces for each tooth and mimic size, force, coordination of human jaw muscles (with permission Lee et al., 2018)

Goal: The study aimed to investigate how the device can masticate a cereal bar and compare these results to those obtained from human subjects.

Methods: The device was built in such a way that created to mimic the trajectory of the molar teeth during human chewing cycles. Mounted on it are anatomically correct tooth geometries with precise occlusion. The jaw trajectory may be changed to provide a variety of vertical and lateral motions, allowing different food samples to be masticated effectively.

Main findings: The machine was tested against human participants for its ability to chew food into small particles. This included mimicking the molar tooth during chewing and the trajectory and speed of the jaw comparable to those found in humans. Bolus particle sizes produced by the machine were compared with those of 11 human participants, where humans chew 2 and 4 g of cereal samples and the machine 1 g. The masticator did the first two cycles of chews with saliva after which food was repositioned for another five cycles and again for another five cycles numbering the cycles found in humans. Bolus was dried and underwent separation on 1.4 and 0.25 mm sieves, where the boluses from both the masticator and humans were compared. It was found that the masticator produced comparable size boluses to humans.

Short conclusion: In this study, the oral masticator was developed and compared for its ability to produce food bolus similar to humans. The parameters of the oral masticators were based upon those derived from human chewing studies with them being possible to mimic the chewing trajectory and movement and direction of molar teeth. The adjustability of the masticator was adapted so it could measure various food, although, in the present study, the food sample was limited. Further testing is needed to validate the masticator and is aimed at standardizing such kind of laboratory instruments.

6.1.2 Comparison of Food Particle Size Produced by Oral Masticator and Human Participants

Introduction: In another study, a masticator machine named Artificial Masticatory Advanced Machine (AM2) was made allowed for the simulation of various factors such as the number of chewing cycles, jaw movement, force, temperature, and saliva composition (Mishellany-Dutour et al., 2011; Woda et al., 2010). The machine was employed to study the process of breaking down food in the human mouth with shearing and compressive forces between the upper and lower teeth, as well as coordinated movements of the tongue, cheeks, and lips to gather and transport food particles. The machine has two surfaces with a similar active masticatory area where one disk is positioned to the opposing disk while applying compressive forces during the procedure (Fig. 5b).

Goal: Main aim of these investigations was to compare bolus formation between the masticator and human subject especially focusing on the particle size of the chewed food.

Methods: The study used two food models peanuts and carrots that were masticated either by machine or human participants for a set number of cycles.

Main findings: The masticator was able to replicate the sizes of the human participant test for both peanuts and carrots, but there was a difference between the two food models. No significant differences were observed between repeats of the bolus collection from the human subject.

Short conclusion: In conclusion, this masticator is a useful tool for studying the process of bolus formation during mastication. It allows for the study of food transformation in a controlled environment, overcoming some of the limitations that come with studying human-produced boluses. However, it does have its limitations and further research is needed to optimize its function to better mimic human masticatory behavior.

6.1.3 Oral Masticator Deployed for Food Texture Investigations

Introduction: Commercial texture analyzers can measure mechanical characteristics like hardness and viscosity, but this doesn't accurately reflect the human experience. Thus, a masticator (Fig. 5c) aimed at investigating food texture was made with the real-life scale of the upper and lower jaw with teeth was made (Lee et al., 2018). This had the aim of improving texture analysis, as it is necessary to replicate the human masticatory process in vitro conditions. This was done by measuring the interaction forces between human teeth and foods and developing a mastication robot that replicates human chewing behavior. Masticator is equipped with subminiature load cells at each artificial tooth of the upper jaw to measure the interaction forces between each tooth and food, analyzing which teeth are most active during chewing. Also implemented were linear actuators for human masticatory muscles that match the size, force, and coordination of muscle attachment. By coordinating these actuators, the resultant jaw motion can replicate human chewing and generate similar patterns of interaction forces between teeth and food.

Goal: The main goal of these investigations was validating and testing the oral masticator and analyzing food texture in the in vitro setup.

Methods: Two experiments were conducted using the developed mastication robot with the first experiment aimed at replicating the human masticatory motion by creating a desired trajectory of the lower jaw. The second experiment aimed to measure and analyze the interaction forces between each tooth and food, while the robot replicates the human masticatory motion.

Main findings: Two food types were tested in particular the brittleness of the cookie when they were bitten in a clenching motion at a low speed, but also the elasticity of the jelly when it was tested during measuring chewing force in a repeated grinding motion. The results show unique patterns of interaction forces among the incisor, cuspid, and molar teeth between the two different food types. Findings have the potential for further research on analyzing texture changes and force distribution during continuous chewing to further explore the potential of this masticator.

Short conclusion: The masticators were able to detect the brittleness of a cookie and the elasticity of jelly, and all tooth sensors were able to record different patterns and peak values. The results have the potential for further research in analyzing texture changes and force distribution during continuous chewing, but challenges remain in terms of developing a method for characterizing texture changes and upgrading the robot system to include an elastic container with a tongue for food manipulation and incorporating saliva distributor to the masticator.

7 Conclusions and Future Trends

Biomimetic instrumental approaches for in vitro and in situ food texture research were the subject of this work. Traditional approaches to instrumentally characterizing food texture can measure multiple texture attributes simultaneously and this is a rapidly growing field with these well-established techniques. These methods were able to study the texture of a wide range of food products, including liquids, semi-solids, and solids. The main advantage of them is their low cost, how reproducibility, the variety of foods they can test, and general standardization between various models and companies that provide these instruments. However, although these machines can measure physical texture properties such as young modulus or complex viscosity of foodstuff, there is a clear gap between this step and the next one that is trying to predict how these properties translate to the consumer experience. The traditional instruments should be coupled with additional sensors and elements in order to make them more multidimensional and have multiple streams of data acquisition.

Because the end goal of texture research is to make food desirable to consumers, there has been a recent trend in making new instruments, techniques, and approaches that incorporate various complex parameters such as anatomical, and physiological factors as well as the nature and complexity of biological tissues. They try to characterize not just physical characteristics but make an attempt in predicting already at the same time how these biomimetic factors (duration, speed, size, surface area, force, saliva incorporation) will influence the food when present in the oral cavity. They are collectively called oral biomimetic instruments and they were envisioned for bridging the gap between in vitro and in vivo conditions. The various techniques covered here, such as mono-element ultrasound, ultrasound imaging, oral tribology, and oral masticators, are showing great promise in the rapidly advancing field of biomimetic approaches to food texture investigations. They can capture a multitude of different data-acquiring channels usually complementary to one another and at any stage of the experiment. They can incorporate various biologically relevant parameters, features, and protocols that can provide data much more in line with realistic food oral processing.

However, there is still a lot of room for improving the existing techniques and developing new ones. These various challenges remain as implementing these techniques in practice still requires a lot of standardization between novel setups, many different steps in optimization, and a lot of caution when integrating a multitude of sensors and scanners into these instruments. The testing of some standard food models would also help to make the various new setups comparable before moving to more complex heterogenous foodstuffs. Future research will require more thinking and designing and deploying novel oral biomimetic instruments will inevitably become very important in the field of food texture characterization. They will be able to better provide more in-depth and complex characterization which will help formulate new foods with an increased sensory appeal to consumers.

In conclusion, the various traditional and novel instrumental approaches for both in vitro and in situ food texture research covered in this chapter offer a multitude of opportunities for advancing the key field in food science. Continued research and development in the instruments and their enhancements can undoubtedly lead to new insights and innovations in food texture characterization.

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Part IV

Food Texture, Food Products

Texture of Vegetables and Fruit

Marc Lahaye

1 Introduction

Texture of vegetables and fruit (V&F) represents an important quality criterion for both consumers and food processors. Its control all along the production, handling, storing, retailing/processing chain is determinant to make the most of productions and avoid losses that today amount to about one-third of the V&F world production (FAO, 2019). It is also key in offering consumer with fresh and transformed products that fit their desires and expectations. This is particularly important to promote the 400 g/day of V&F consumption recommended (WHO, 2020) to alleviate diseases related to western-type diets, such as obesity, cancer, diabetes by the intake of health promoting dietary fibers, antioxidant, and other phytocomponents (Vicente et al., 2022).

Food texture arises from physical properties of the food microstructures (Bourne, 2002). It is related to a group of mechanical or rheological properties sensed by touch, usually in the mouth but also any other senses perceiving sounds or pressure. These perceptions are described by consumers with different descriptors (Table 1). Along the chain of V&F production and processing, texture is critical with regard to handling, storage, and processing ability. Due to the diversity of edible fruit and vegetable organs and to the complexity of the texture determinants at different scales, reliable measurement of its contributing attributes remains a challenge.

V&F texture is usually assessed by measuring various mechanical stress response parameters, such as force, deformation, Young's modulus, and work (Abbott, 2004). Due to the heterogeneous and complex nature of V&F structures, mechanical response generally depends on time. These viscoelastic mechanical properties are characterized by a dynamic modulus with storage (E'), loss (E") moduli and damping factor (E"/E'). Furthermore, since many V&F are highly hydrated, the resistance of water flow in the porous structures under mechanical stress also contributes to their poroelastic properties (Bidhendi & Geitmann, 2019).

This chapter reviews texture determinants in V&F. It will not cover texture perception in relation with objective measurements, which can be found elsewhere (Aktar et al., 2019; Kohyama, 2020).

2 Organs, Tissues, and Texture Perceptions

Vegetables and fruit encompass several types of organs: fruit, root, tuber, leaves, flower, seeds, which, except for leguminous dry seeds, share a high-water content (up to 97%) in the

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Table 1 Texture descriptors by consumer

Descriptors	Characteristics
Crisp	Breaks apart in a single bite with sound
Fibrous	Readily separated filaments present
Firm/hard	Force required to compress or shear through flesh
Graininess	Presence of small particles felt during chewing
Grittiness	Presence of hard sharp particles during chewing
Juicy	Amount of liquid released when chewing
Mealy	Soft, dry, and granular flesh
Melting	Flesh disintegration in the mouth with little chewing
Skin toughness	Force required to bite through the skin

From (Harker et al., 1997; Bowen & Grygorczyk, 2022)

parenchymatous tissue that mostly composes them (Vicente et al., 2022). There are also other tissues and cell features leading to specific texture perceptions, such as stone-cells in pears (Cheng et al., 2019), which are perceived as gritty (Harker et al., 1997), vascular bundles (phloem and xylem) felt as fibrousness in peach and nectarine (Harker et al., 1997), sclerenchyma tissue with cellulose-rich cell walls leading to hardness and long fibers perception in asparagus (Harker et al., 1997). The epidermis of V&F is covered by a specific layer ("skin"), the cuticle, which is found under different forms at the surface of tubers and roots. In case of consumption of unpeeled organs, this cuticle can be perceived as "tough skin," such as in pit fruit (apple, pear, etc.) and berries (tomato, grape, etc.) (Bowen & Grygorczyk, 2022; Harker et al., 1997). Seeds can be part of the edible V&F tissues, such as in strawberry, tomato, and berries. In some cases, they may also contribute to grittiness perception (Harker et al., 1997).

V&F texture is subject to large variations related to genetic (species, varieties), physiological (developmental status) and environmental (biotic and abiotic stresses; storage) factors. This chapter focuses on V&F structural factors at different scales that determine texture.

V&F parenchyma tissue can be viewed as foams made of connected liquid-filled closed cells (Gibson, 2012), which physical characteristics and distribution in tissue affect texture and notably firmness. In apple, firmness depends on cell orientation (Abbott & Lu, 1996) and on cell cohesiveness seen through air space proportions and distribution (Winisdorffer et al., 2015). In tomato, an heterogeneous cell-size distribution in the pericarp was negatively related to firmness; the number of small cells under the cuticle was positively related to skin toughness, while mealiness was related to elongated cells in the pericarp tissue (Chaib et al., 2007).

In addition to histological features, V&F texture relies on cellular structural determinants at different scales.

3 Components of Texture

3.1 Water

One major actor of texture is water and its distribution in tissue (Fig. 1). Mainly compartmentalized in the cell vacuole, water builds-up turgor pressure with the contribution of the mechanical properties of the cell wall. Its implication in texture can be exemplified by the flaccid V&F resulting from freezing plasmolysis (Chassagne-Berces et al., 2009). A shift in the water distribution from the vacuole to the cell wall also contributes to lower turgor pressure and induces softening as in tomato (Saladie et al., 2007), grape (Castellarin et al., 2015) and apple (Tong et al., 1999). In fact, two groups of fruit are distinguished according to their ripening kinetics and cell wall swelling: fast ripening leads generally to swelled wall and "melting" fruit, while slow ripening goes along with limited or no wall swelling and firm to crisp perception (Bourne, 1979; Redgwell et al., 1997). Such water efflux and swelling associate changes in cell wall environment (pH) and chemistry and notably that of pectin (MacDougall et al., 2001). The increase in the apoplastic osmotic pressure following the switch of metabolites cell filling from the symplastic to the apoplastic route at the beginning of

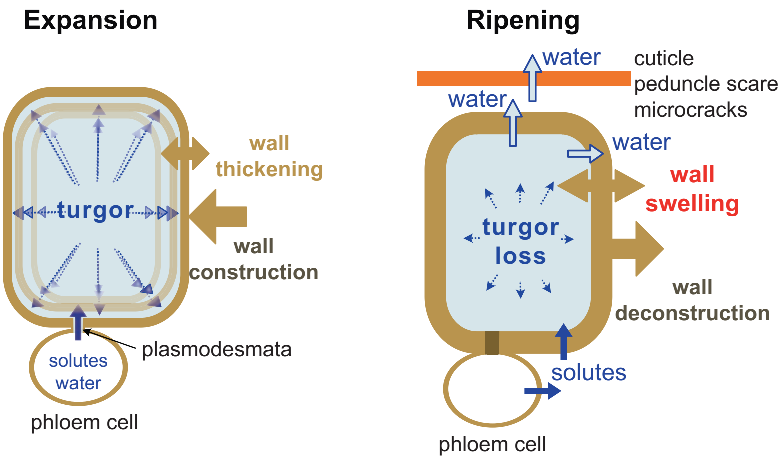

Fig. 1 Schematic representation of water and solutes pathway in expanding (left) and ripening (right) parenchyma cells of vegetables and fruit. During cell expansion, turgor driven enlargement involves cell wall construction and thickening. Water and solutes are transferred from vascular bundles (phloem) through the symplastic route via plasmodesmata. In the ripening tissue, cells no longer expand and lose turgor pressure due to cell wall relaxation (deconstruction), change in solutes concentration inside and outside the cell due to the apoplastic solutes downloading from phloem cells, and to cell metabolism with water losses through the cuticle, microcracks and calyx. Cell wall swelling will occur according to the extent of cell walls chemical changes

ripening likely contributes to cell wall swelling (Wada et al., 2008) as do leaky cell membranes notably due to cold storage alterations in the metabolism of lipids (Lu et al., 2020b).

Beside translocation, water loss also arises from organ metabolism, notably during postharvest storage. This loss that decreases turgor and thus, firmness, can occur through the calyx, lenticels, microcracks, and/or by diffusion through the cuticle (Khanal et al., 2020; Lufu et al., 2020). In that process, the cuticle structure and integrity are of prime importance for the control of water loss (Saladie et al., 2007).

Despite that water loss can be measured by weight difference during storage of vegetables and fruit, assessing water distribution in tissue and its contribution to turgor pressure is more complex. Water distribution can be obtained by measurements of the water status. This can be measured by thermocouple psychrometry, vapor pressure osmometry, and by use of a pressure chamber or a pressure probe (Boyer, 1995). Water vapor pressure measurements (psychrometry, osmometry) reflect water interactions with solutes or macromolecules in the sample. Such interactions limit water vapor diffusion in the environment. The pressure chamber and pressure probe report on the turgor pressure in tissue and individual cells, respectively. Following these methods, turgor was shown to decrease during tomato and grape berry along with the ripening-induced softening (Saladie et al., 2007; Wada et al., 2008).

Water environments can also be assessed by nuclear magnetic resonance spectroscopy (NMR) (Arendse et al., 2018). The transverse relaxation time of water (T_2) is affected by solutes, pH, and by constraint environments, such as in the cell vacuole and organelles or in pores through interactions with boundary molecules. Measurements can be realized by time-domain NMR spectroscopy on bulk V&F samples and non-destructively, by quantitative magnetic resonance imaging (MRI) on the whole organs. Analysis of water T_2 allows distinguishing populations and proportions reflecting different environments. In fresh V&F tissues, the longest T_2 usually corresponds to water in the vacuole, while lower ones are attributed according to a conceptual model of vacuolated cells to cytoplasm/organelles and apoplast (Snaar & Van As, 1992). Once membrane systems are destroyed by drying, cooking, freezing, and thawing, different T_2 will be obtained reflecting changes in water environments related to the matrix porous network, solutes, and water-macromolecules interactions (Hills & Nott, 1999). As a potential method for assessing V&F ripening process and internal disorders, NMR/MRI can be applied to monitor water relaxation studies in relation to V&F texture and successful cases have been reported on apple mealiness and tomato firmness (Barreiro et al., 2002; Li et al., 2020; Tu et al., 2007; Winisdorffer et al., 2015).

3.2 Storage Carbohydrates

Several V&F have substantial quantities of storage polymers distributed within their tissues. By far, the most important of these is starch, which in addition to cereals contributes substantially to texture of the edible portions of potato, yams, cassava, lentils, millets, plantains, sweet potato, and many other staple foods. Starch is discussed extensively in chapter "Starch, Modified Starch and Extruded Foods" of this book, but in the context of V&F it is worth recognizing that it occurs as highly structured crystalline granules, composed primarily of amylopectin, and amorphous amylose distributed within the cytoplasm.

During the ripening of starchy fruit, such as banana, starch metabolism represents an important event co-occurring with cell wall polysaccharide remodeling and degradation (Kojima et al., 1994). Later in this chapter (Sect. 5), we will discuss the development of texture through food processing operations whether undertaken on both an industrial scale and through domestic cooking. While starch is by far the most important storage carbohydrate from an economic and nutritional subsistence point of view, there are other storage carbohydrates such as inulin (a linear polyfructan) which occurs in a small number of plants such as the artichokes and chicory.

3.3 Cell Walls

Cell walls are the other major player in F&V texture (Fig. 2). They provide tissue cohesion by ensuring cell-cell adhesion at the middle lamella and tricellular junctions and their mechanical properties regulate turgor pressure. On consumption, V&F tissue disintegration in the mouth involves cell wall fracture and/or cell-cell debonding. The extent of cell separation without fracture is characteristic of textures, such as in soft olives, mealy apples, and peculiar desert banana texture perception (Rongkaumpan et al., 2019; Harker & Hallett, 1992; Lanza & Amoruso, 2018).

Cell walls of V&F are generally soft and hydrophilic, resembling the primary wall deposited in growing organs. They are composed of polysaccharides, namely pectin (about 30%) hemicelluloses (up to 35%), and cellulose (20–30%), together with minor amounts of proteins (about 10%), inorganic and organic ions and water (Albersheim et al., 2011). Specific cell walls are found in vascular bundles and in stone cells, which contain lignin. Aerial organs are covered by a cuticle made of waxes and polyesters of hydroxylated fatty acids. On the other hand, underground tuber and roots are covered by suberin. The interactions and/or covalent linkages between these different components regulate the mechanical and physicochemical properties underlying texture.

3.3.1 Polysaccharides

3.3.1.1 Pectins

Pectin is a well-known texturing polysaccharide used in diverse formulated food products (Lopes da Silva & Rao, 2006). This water-, chelator-, mild alkali-, and acid-soluble polysaccharide is composed of structural domains rich in galacturonic acid (Fig. 3a–d). The main domains are the homogalacturonan (HG) and rhamnogalacturonan I (RGI) (Ropartz & Ralet, 2020).

HG regions consist of about 72–300 linearly-linked galacturonic acid residues that can be esterified by methanol. The molar percentage of methyl-esterified galacturonic acid (degree of

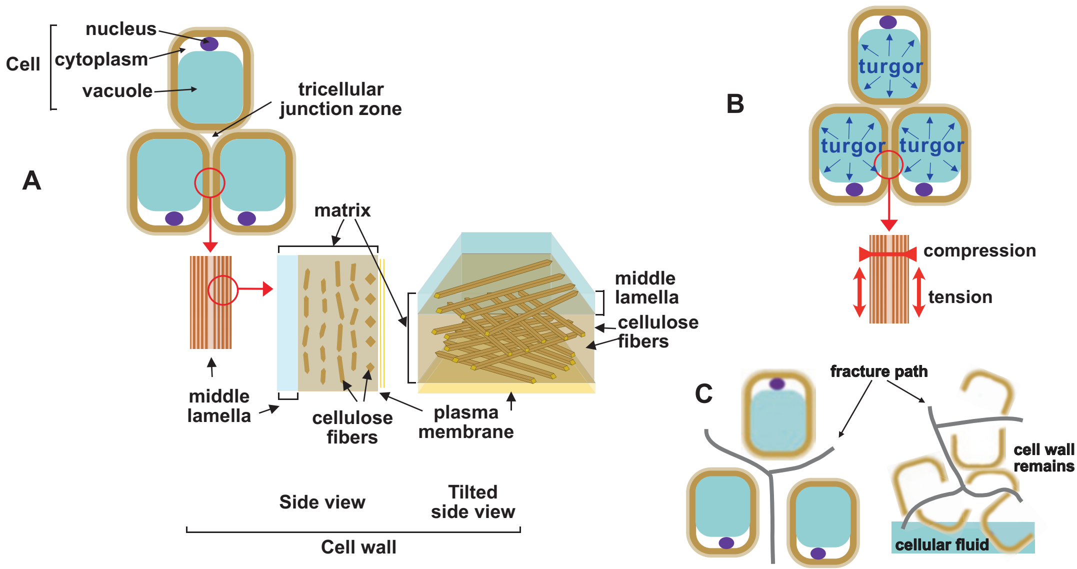

Fig. 2 Cell and cell walls: schematic representations of: (**a**) cell wall architecture in typical parenchyma tissue of V&F: the matrix is mainly composed of pectin and hemicelluloses with low amounts of proteins; it embeds layers of cellulose fibers with different orientation per layer; the middle lamella is essentially composed of pectin; (**b**) forces applied by turgor pressure to cell walls; (**c**) fracture paths in mealy (left, fracture goes mainly through the middle lamella) and juicy (right, fracture goes indistinctively through cell wall and middle lamella and frees vacuolar content as juice) V&F

methyl-esterification or DM) distinguishes different interaction mechanisms of pectin in the presence of calcium (DM < 50) or sucrose in acidic conditions (DM > 50). The distribution of methyl-ester defined as the "degree of blockiness," is also related to gelling characteristics (Jermendi et al., 2022).

RG-I pectic domains, which represent 20–75% of the pectin, are built on about 30–150 alternating galacturonic acid and rhamnose residues on which are linked arabinan, type-I and/or type-II arabinogalactan (AG-I, -II) side-chains. Type I and II arabinogalactan differ in linkages and branching. AG-I are common to V&F pectin, such as of citrus, potato, soybean, lupin, apple, onion, tomato, cabbage and kiwi, while AG-II is also found in apple, lemon, beet and grape (Voragen et al., 1995). In V&F belonging to the family of spinach and beet (Amaranthaceae family), AG-I can be esterified by ferulic acid (Mnich et al., 2020). Both HG and RGI bear acetyl esters on the galacturonic acid residue and RGI are more acetyl-esterified than HG. Side-chain proportions vary with fruit origin, but their detailed sequence, length, and distribution remain a subject of studies.

Minor structural domains are rhamnogalacturonan II (RG-II), which is ubiquitous in plants, xylogalacturonan (XGA) found in some fruit and seeds (apple, water melon, pea-hull), and apiogalacturonan (AGA), which is limited to aquatic plants. All of them are built on a HG backbone. RG-II is present in tissue and enzymatically produced juices from apple, carrot, grape, tomato, bilberries, black current, sugar beet, and radish root (Doco et al., 1997; Hilz et al., 2006). It is ramified on galacturonic acid by six types of methyl- and acetyl-esterified complex side-chains (Ndeh et al., 2017). XGA and AGA also deviate from HG with branches of single or small oligomers of xylose or apiose, respectively, on galacturonic acid residues.

Different proportions of these pectic structural domains distribute in molecules forming a continuum. Pectin is commonly depicted as an array of molecules with varying amounts of HG

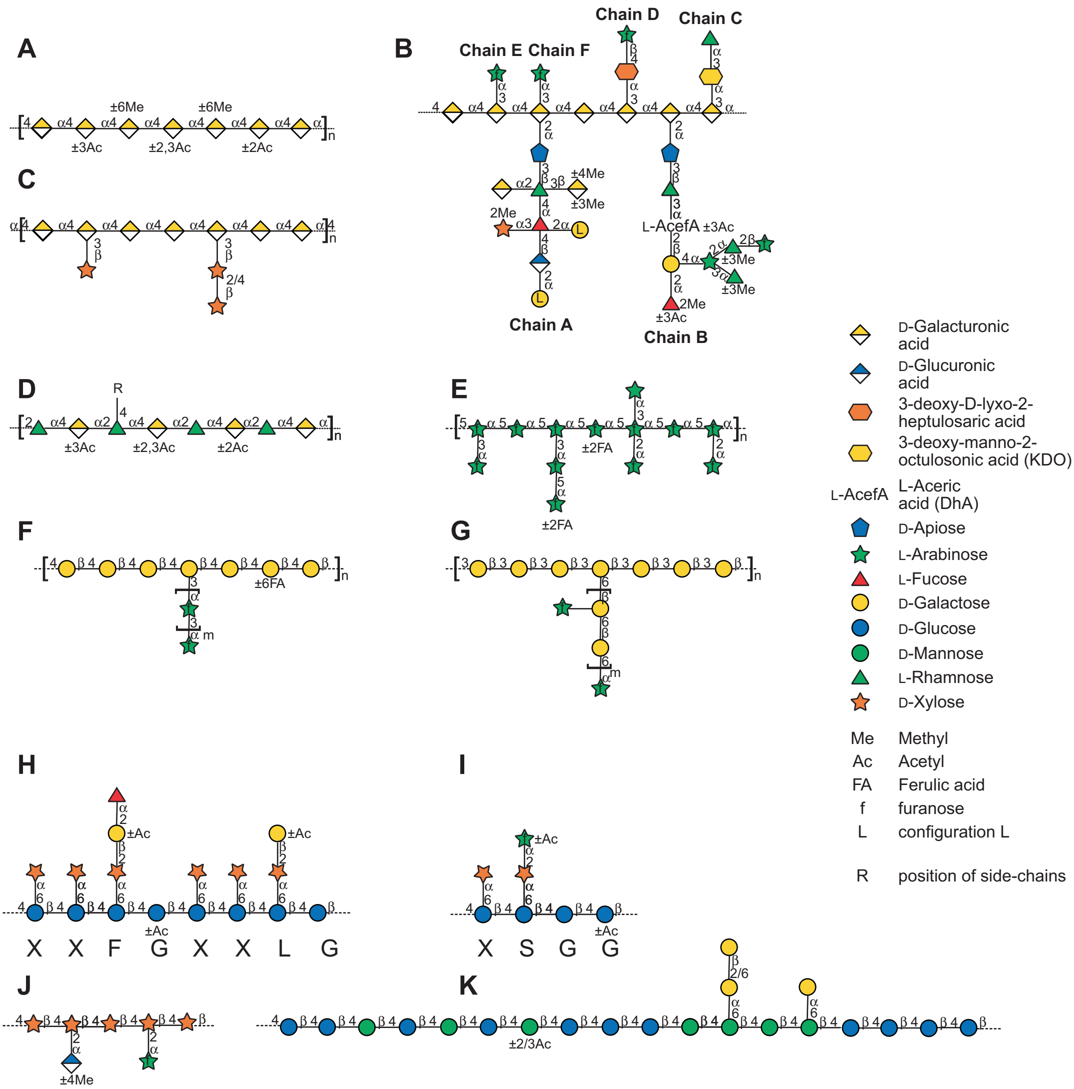

Fig. 3 Schematic chemical structures of cell wall matrix polysaccharides: (**a**–**g**) Pectic structural domains, (**h**–**k**) Hemicelluloses. (**a**) homogalacturonan; (**b**) rhamnogalacturonan II with its different side-chains; (**c**) xylogalacturonan; (**d**) backbone of rhamnogalacturonan I; (**e**-**g**) rhamnogalacturonan side-chains: (**e**) arabinan; (**f**) type I arabinogalactan, (**g**) type II arabinogalactan. (**h**, **i**) XXXG and XXGG-type backbone xyloglucan blocks, respectively, underneath letters correspond to the glucose-based structure; J, glucuronoarabinoxylan; K, galactoglucomannan with block and alternating sequences distributions. Sugar symbols are from https://www.ncbi.nlm.nih.gov/glycans/snfg.html. Number and Greek letters refer to carbon involved in linkage and to sugar anomers, respectively

("smooth") and RG-I ("hairy") domains (Voragen et al., 1995) with connections between HG and XGA domains to the RGI domain (Coenen et al., 2007). An alternate model to this "linear" presentation consists of a "brush-like" structure with a backbone formed by RG-I and different distributions of branches composed by HG, XGA, RG-II domains (Vincken et al., 2003; Yapo, 2011). This structural complexity is illustrated with the pectin from strawberry, tomato, aubergine, and apple which HG and RG-I distribute according to their methyl-esterification and side-chain substitution patterns (Cornuault et al., 2018). Atomic force microscopy imaging of pectin molecules led to the proposal of another structure where HG would be branched by HG side-chains in a galacturonogalacturonan (GaGA) model (Posé et al., 2018).

3.3.1.2 Hemicelluloses

Together with pectin in the matrix polysaccharides, V&F alkali-soluble hemicelluloses encompass three families of complex polysaccharides: xyloglucan (XyG), glucurono(arabino)xylan (GuX), and galactoglucomannans (GgM) (Fig. 3h–k) (Scheller & Ulvskov, 2010). While XyG is the main hemicellulose of cell walls and in most fleshy fruits, GuX and GgM are generally present in minor proportions depending on fruit species; notable exceptions include GuX in pineapple (Brummell & Schröder, 2009), goji (Redgwell et al., 2011), and tucuma fruit (Cantu-Jungles et al., 2017), and GgM in tomato (Melton et al., 2009).

The chemical structure of the major XyG family is built on glucan chains ramified by xylose organized in regular blocks (Schultink et al., 2014). Galactose, fucose, arabinose, xylose, or uronic acid residues can extend the xylose side-chain and some of these may be acetyl-esterified (Gille & Pauly, 2012). Most consumed fruit and vegetables have XyG built on the XXXG-type structure (X and G stand for xylosyl-glucose, and non-substituted backbone glucose, respectively, see Fig. 3) with side-chains ending with fucose (Hsieh & Harris, 2009). In contrast, in Solanaceae fruit (tomato), XyG building blocks are mainly based on the XXGG-type structure with arabinosylated-side chains and generally lack fucose. Further variations on the XXXG-type structure exist with the X structure extended further by xylose (Hilz et al., 2007) or with side chains lacking fucose but containing arabinose, as in olives (Vierhuis et al., 2001). Non-substituted glucan segments are also part of XyG, as observed in apple, mango, orange, avocado, squash, pomegranate, rhubarb, amaranth, and quinoa (Chen et al., 2022c; Steck et al., 2021).

Galactoglucomannan is built on glucose and mannose residues either alternating or as blocks more or less ramified on the glucose or mannose residue by galactose and di-galactose (Melton et al., 2009). GgM can be linked to GuX sequences or substituted by pentose and is acetyl esterified on mannose and/or galactose residues (Gille & Pauly, 2012). GgM is particularly prevalent in tomato fruits (about 6% cell wall dry weight) (Assor et al., 2013) and is a minor hemicellulose in other fruits, such as kiwis (Schröder et al., 2001), apples (Ray et al., 2014), Ponkan mandarin fruit peels (Colodel et al., 2018), gabirobas (Barbieri et al., 2017), and bananas (Cheng et al., 2009) .

Glucurono(arabino)xylan is present in trace amounts in flesh and peel of fleshy fruits and is found in higher proportions in pear stone cells (Brahem et al., 2017; Brummell & Schröder, 2009). GuX is built on xylan chains partially acetyl esterified and branched by glucuronic acid or its 4-O-methyl ether residues (Brummell & Schröder, 2009). In apples, arabinose occurs as a branch of the xylan chain (Ray et al., 2014). The glucuronic acid to xylose ratio varies markedly according to species and organ; for example, this ratio is: 1:32 in *Benincasa hispida* fruit and 1:6 in prickly pear skin (Habibi et al., 2003; Mazumder et al., 2005).

3.3.1.3 Cellulose

The chemical structure of cellulose, a water- and alkali-insoluble glucan, consists of a linear chain made of 1000 to 30000 glucose units according to its source (Fig. 4). In most parenchymatous V&F with cell walls resembling that of developing plant tissue, 18–24 glucan chains assemble through hydrogen bonds and Van der Waals forces to form elementary fibers of about 3 nm thickness (Jarvis, 2022). These are composed of crystalline structures covered by paracrystalline chains which alternate with amorphous domains. These fibers further assemble in larger cellulose fibers aggregates of approximately 15–30 nm in width in apple, carrot, cucumber, tomato, celery (Cybulska et al., 2013; Lahaye et al., 2020; Szymańska-Chargot et al., 2017; Thimm et al., 2000). They have a mean crystallinity of 12–29%

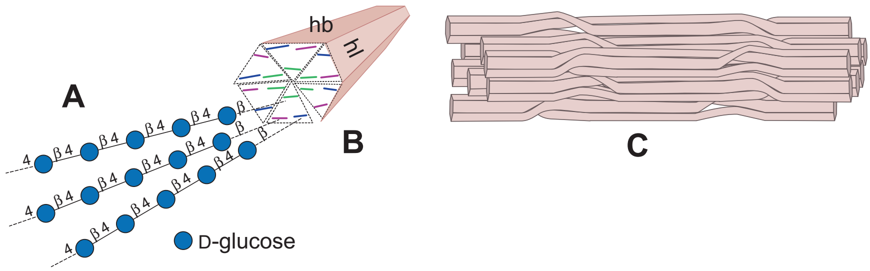

Fig. 4 Cellulose: (**a**) chemical structure of cellulose, (**b**) elementary cellulose fiber with hydrophobic (hb) and hydrophilic (hl) faces; (**c**) cellulose fiber composed of aggregated elementary fibrils (side view). Partially disorganized and organized regions distribute along fibers. (Inspired from (Cosgrove, 2022)). Sugar symbols are from https://www.ncbi.nlm.nih.gov/glycans/snfg.html. Number and Greek letters refer to carbon involved in linkage and to sugar anomery, respectively

for apple, 31% for celery, and 34% for tomato to 57% for carrot. In the aggregation process, pectin, hemicellulose, or water can insert between elementary fibrils, preventing crystallites fusion (Jarvis, 2022). These insertions also offer a mean for fibers to slide under constraint and to anchor polysaccharides and other polymers to establish the 3D cell wall network. These interactions benefit from the hydrophilic and hydrophobic surfaces of cellulose crystals (Jarvis, 2022) as proposed in the tomato cutin-cell-wall assembly between highly crystalline cellulose, hydrophobic cutin polyester and highly methyl-esterified pectin (Philippe et al., 2019).

3.3.2 Pectin and V&F Texture

Pectin proportion with regard to cellulose and hemicellulose contents and proportions of pectic HG and RGI domains markedly differ between firm and soft fruit textures, as, for example between apple and sweet cherries (Lahaye et al., 2021). These polysaccharides contribution to texture will also depend on their fine structure and the cell wall environment and architecture.

3.3.2.1 Role of Charges and Apoplast Physicochemical Conditions

Pectin interactions in the cell wall are mainly inferred from their in vitro texturing ability. Calcium and divalent cations mediated dimerization of non-methyl-esterified HG segments form "egg-box"-like junction zones leading to tridimensional gels (Fig. 5a) (Cao et al., 2020). Such ionic interactions have been extended to plant cell wall notably for the pectin-rich middle lamella in the cell-cell bounding (Jarvis et al., 2003). Total calcium content in V&F ranges from 3 to 40 mg/100 g fresh tissue (Vicente et al., 2022) and a part of it concentrates in the cell wall (Almeida & Huber, 1999). However, in cider-apples, the bulk tissue calcium content was more than a decade lower than what could be fixed by the unesterified pectin content in the cell walls, leaving the pectic acid groups partly ionized by potassium, the major ion, or protonated (Vidot et al., 2020). Furthermore, calcium content and pectin DM were not related to the cider-apples tissue firmness. In fact, the predominance of the calcium-mediated pectin HG "egg-box" interactions in cell wall biomechanics is actually questioned (Hocq et al., 2017). Nevertheless, infusion of calcium in fruit tissue following or not the removal of methanol esters of pectin by pectin methylesterases remains a well-known mean of improving V&F tissue firmness (Guillemin et al., 2008; Van Buggenhout et al., 2009).

Pectin controls cell wall swelling in relation with its water-solubility, which is a major consequence of the ripening metabolism associated with soft-textured fruit (Redgwell et al., 1997). As a polyelectrolyte, due to the presence of the charge on galacturonic acid, swelling depends on the ionic composition and strength as well as on the pH (MacDougall et al., 2001). However, for crisp/firm V&F, with limited pectin methyl esterification removal during fruit development/ripen-

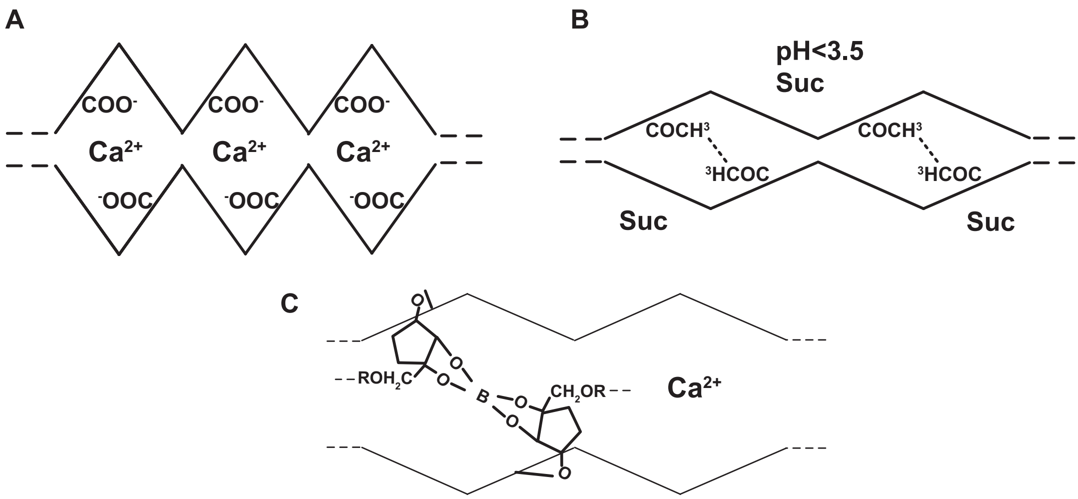

Fig. 5 Possible cell wall interactions of pectin: (**a**) calcium-mediated ionic cross-linking of methyl-ester-free HG domains in "egg-box"-like junction zones; (**b**) hydrophobic interactions between highly methyl-esterified HG domains mediated by high co-solute concentration (Suc: sucrose but in the wall this may also be by other solutes, such as glucose or fructose) and acidic pH (below the pKa of galacturonic acid); (**c**) borate-mediated cross-link between apiose residues of the **a** and/or **b** chains of RGII domains, stabilized by calcium

ing, pectin interactions are inferred from the *in vitro* gel formation in dilute solutions implying hydrophobic interactions promoted by acidic pH to screen the galacturonic acid charge and high co-solute concentrations, such as sucrose, to decrease water activity (Fig. 5b) (Lopes da Silva & Rao, 2006). Besides HG, RGI domains with their side-chains form entanglements contributing to create *in vitro* interactions in acidic conditions or in the presence of cations (Zheng et al., 2020). Unlike in solution, pectin in cell wall is confined, which likely confers different reactivities and interactions. Solid-state ^{13}C NMR experiments on model plants revealed different pectin molecular mobilities in relation with water and pH, reflecting dissimilar aggregation and interactions (Kirui et al., 2021; Phyo et al., 2018). Further solid-state ^{13}C NMR kinetics experiments indicated that pectin hydration in apple tissue was positively related to flesh storage modulus (Lahaye et al., 2019).

Model assemblies based on bacterial cellulose synthesized in the presence of cell wall polysaccharides offer means of accessing polysaccharides interaction mechanisms underlying mechanical properties in condensed composites. In both model composites and V&F cell walls, the ability of water to flow within the more or less porous material under stress creates internal pressure which contributes to the poroelastic mechanical properties (Lopez-Sanchez et al., 2020).

3.3.2.2 Role of Substitutions and Side-Chains

Acetyl-esterification of pectin is known to decrease the gelling characteristics due to steric hindrance altering chain-chain interaction notably from sugar beet and carrot pectin. Likewise, xylose substitutions in XGA domains have a similar impact affecting gelling characteristics and cell-cell adhesion (Willats et al., 2004). By extension, both these substitutions are expected to alter the cell wall mechanical properties and thus texture in V&F. Side-chains in RGII and RGI domains also participate to the cell wall assembly and mechanical properties.

Arabinan and galactan side-chains of RG-I domains bind to cellulose (Lin et al., 2018; Zykwinska et al., 2007) and appear key contributors to V&F mechanical properties and texture (Gwanpua et al., 2015; Lahaye et al., 2020; Ng et al., 2015). In apple, cell wall galactose and arabinose contents were positively related to storage modulus in turgid tissue but negatively in plasmolyzed tissue. Side-chains interactions with cellulose may control turgor-induced stress contributing to flesh firmness, but, when turgor is lost, steric hindrance from pectic side-chains with cellulose may limit the glucan chain load-bearing function (Lahaye et al., 2018). Furthermore, hydrophobic galactan and hydrophilic arabinan RG-I side-chains (Klaassen & Trindade, 2020) likely affect differently water flux in porous cell wall (Lopez-Sanchez et al., 2020). Their high molecular mobility observed by solid-state ^{13}C NMR analyses (Ha et al., 2005) compared with the backbone of RG-I and HG pectic domains (Kirui et al., 2021) would support a more important role in restraining water flux than in interacting with cellulose. Texture and mechanical tissue breakdown of contrasted tomato fruit was distinguished on the proportion of these solid-state ^{13}C NMR mobile side-chains (Devaux et al., 2005). The contribution of these side-chains to cell wall water flux regulation and interaction with cellulose and cell wall cross-linking remains to be further studied with regard to their contribution to F&V texture.

Ferulic acid linked to pectin RG-I side-chains also forms cross-links thought to participate in cell wall mechanical properties, notably in lignified tissues (Mnich et al., 2020). Although such cross-links are candidates in the regulation of cell-cell adhesion in beet (Waldron et al., 2003), they do not appear as a major factor affecting the root texture (Schäfer et al., 2020).

RG-II domains occur mainly as dimers linked by a borate diester between apiose residues and are stabilized by calcium (Shi et al., 2017)(Fig. 5c). Such dimerization is essential for the proper development of plant and mechanical properties of organs (Ryden et al., 2003; Voxeur et al., 2017). It regulates cell wall porosity (Fleischer et al., 1999) and, in the light of the role of water flux on cell wall mechanical properties, although RGII is a minor pectin structural domain, it is expected to play a role in V&F texture.

3.3.3 Hemicelluloses and Cellulose Role in V&F Texture

Today, the function of hemicelluloses in V&F texture remains unclear. Hemicelluloses form a part of a continuous pectin-hemicellulose matrix with covalent links between XyG and pectin (Cornuault et al., 2018), xylan and pectin (Broxterman & Schols, 2018), and GgM and GuX (Prakash et al., 2012). Xyloglucan, the major hemicellulose, has long been associated with cellulose in the cell wall stress bearing function as they tether the fibrils. However, this role is now questioned as only a very minor part of it is involved as “biomechanical hotspots” in the control of cellulose fibrils slippage (Cosgrove, 2022). In model plants, absence of XyG in cell wall can be replaced by pectin and GgM (Sowinski et al., 2022). Nevertheless, these minor interconnections play a role in V&F softening, as expansin, a cell wall protein that regulates them, controls V&F softening (Marowa et al., 2016; Minoia et al., 2016). Glucuronoarabinoxylan and galactoglucomannan also bind cellulose (Hannuksela et al., 2002; Yu et al., 2018), but less is known on the function of these polysaccharides in V&F cell walls. In tomato, the three hemicellulose families are present in key cell wall areas for cell adhesion (middle lamella, cell junction) at various developmental stages of the fruit (Guillon et al., 2017; Ordaz-Ortiz et al., 2009; Takizawa et al., 2014).

V&F hemicellulose composition and proportions vary with species (Houben et al., 2011) and with development (Lahaye et al., 2021). In model studies, mechanical properties of hemicellulose-cellulose composites depend on the proportion and the fine structure of GgM and GuX added (Berglund et al., 2020). GgM contributes to cellulose crystallization, aggregation, and toughening of fiber bundles under compression, whereas GuX favors elongation of cellulose aggregates under tensile strain. The main V&F hemicellulose, XyG, was reported to increase creep in XyG-cellulose composite under tension stress (Chanliaud et al., 2002). XyG-cellulose interactions are controlled by molecular weight, the presence of unbranched glucan segments, galactose, and to a lesser extent fucose (Chen et al., 2022b; Whitney et al., 2006). Thus, variations in hemicelluloses composition and structure can result in variation of the physical dimension of cellulose fibers, and the interactions and dispersion in the hemicellulose-pectin matrix. In different apple varieties, cellulose fibers thickness (25–35 nm) measured by atomic force microscopy was positively related to crispness, juiciness, firmness, and acoustic emission (Cybulska et al., 2013). By solid-state ^{13}C NMR relaxometric measurements of apple cell walls, cellulose ordering at the molecular level (<50 nm scale) was negatively related to storage modulus of the flesh: the more cellulose fibers were "dispersed" in a hydrated pectin matrix, the higher the storage modulus was (Lahaye et al., 2020) (Fig. 6).

3.3.4 Proteins

Several cell wall proteins play a role in V&F texture. Despite that enzymes and expansins are commonly found in V&F, their textural role will not be covered in this chapter due to space limitation. Influence of these proteins on the texture of V&F can be seen in reviews by (Frankova & Fry, 2013; Toivonen & Brummell, 2008). Main focus of this chapter will be on the extensin and arabinogalactan proteins, two minor glycoproteins, and proteoglycans which participate to the cell wall architecture of V&F.

3.3.4.1 Extensin

Extensin represents a group of glycoproteins that share a backbone protein rich in hydroxyproline and serine in sequences of Ser-$(Hyp)_{2<n<5}$ (Showalter & Basu, 2016). Most hydroxyproline residues are glycosylated and tyrosine residues can be present as oxidatively linked isodityrosine (tyrosine dimer) or pulcherosine (tyrosine trimer) to form intra- and inter-molecular cross-links. Such cross-linkages form a network thought to stiffen cell wall, to reduce hydration, and to participate to cell-cell adhesion. The presence of blocks of lysine residues was shown in model systems to promote electrostatic interaction with pectin HG domains, with possible consequences on pectin mobility and wall swelling (Marudova et al., 2004). Although reported in many V&F, such as carrot, potato, tomato (Li & Showalter, 1996), grape pulp is particularly rich in extensin, notably during berries softening (Gao et al., 2021). In model grape cell system, oxidative-mediated cross-linking of extensin led to the partially reversible reduction in the wall hydration, sensitive to matrix charges (Pereira et al., 2011). The consequence of cross-linking, wall hydration, and berry mechanical properties/texture remains to be established.

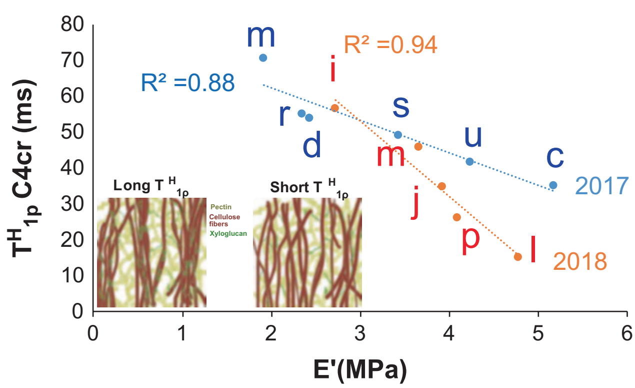

Fig. 6 Relation between apple flesh storage modulus (E') and solid-state ^{13}C NMR proton relaxation $T_{1\rho}^{H}$ on carbon 4 of glucose residues in the crystalline part of cellulose (C4cr) on 2 harvest years (2017 and 2018). Long relaxation times reflect high structural ordering. m: Douce Moen, r: Reinette d'Armorique, d: Golden Delicious, s: Granny smith, u: Guillevic, c: Choupette, i: Cidor, j: Judor, p: Petit Jaune, l: Douce Coet Ligné; dotted lines: regression lines with coefficient of determination (R^2). (Data for 2017 are from (Lahaye et al., 2020), data for 2018 are from (Lahaye et al. unpublished)). Insert: interpretation of aggregated cellulose organization in cell wall of soft (long $T_{1\rho}^{H}$) and dispersed fibers in cell wall of stiff (short $T_{1\rho}^{H}$) apple flesh

3.3.4.2 Arabinogalactan Proteins (AGP)

AGP consists of a highly heterogeneous and complex family of proteoglycans sharing an important glycosylation by arabinose- and galactose-containing side-chains (Ellis et al., 2010). They also have a glycosylphosphatidylinositol lipid anchor that provides for some of them a fixation to the cell membrane. The protein part is much reduced as the arabinogalactan, basically of the AG-II type, constitutes more than 90–98% of the molecule. Extensin-like peptides are part of the core protein domains and are branched by AG-II. AGP, known in apple and pear juices (Brillouet et al., 1996; Tsumuraya et al., 2019), was observed to increase in content in the cell wall of apple during softening (Leszczuk et al., 2020b). Among their many putative functions, their chemical and physico-chemical characteristics encompass calcium interaction, aggregation, adhesion properties (Leszczuk et al., 2020a), covalent linkages with pectin RG-I domain, and arabinoxylan (Tan et al., 2013), whose consequences on V&F texture remain to be clarified.

3.3.5 Lignin, Cutin, Suberin

Water-diffusion barriers are provided by hydrophobic lignin in vascular bundles and in stone cells and by waxes and cutin in cuticles covering aerial and underground organs. They can be perceived as texturing elements by consumer and contribute to the elaboration of V&F texture.

3.3.5.1 Lignin

The low content in lignin of V&F is formed by the oxidative polymerization of the primary hydroxycinnamyl alcohol derivatives, p-coumaryl (H unit), coniferyl (G unit for guaiacyl), and sinapyl alcohols (S unit). Different types of lignin with regard to the proportions of the different monomers that compose them are deposited in a coordinated way mainly in secondary cell walls (wood-type), in vascular tubes, and in stone cells (Albersheim et al., 2011). Lignin is covalently linked to hemicellulose and pectin and thus participates to the cell wall toughening and water exclusion (Terrett & Dupree, 2019). In fruit flesh of the Rosaceae family (pears, apple, quince) as well as in asparagus, cabbages, radish, and rhubarb, lignification is of the guaiacyl-sinapyl type with variable ratio of S/G according to species and varieties (Bunzel et al., 2005; Zhang et al., 2020). This lignin composition contrasts from that of spinach, carrot and kiwi, which is enriched in G-type lignin (Bunzel et al., 2005), more typical of vascular tissues (Peter et al., 2010). Besides the grittiness perception of lignified stone cells in pears and quince, lignification has been related to firmness increase and juiciness decrease during loquat fruit postharvest ripening (Cai et al., 2006) as well as hardening of some varieties of starchy tuber, trifoliate yam, during postharvest, which make them unfit for consumption (Afoakwa & Sefa-Dedeh, 2002).

3.3.5.2 Cutin and Suberin

V&F cuticles are composites made of lipids, carbohydrates, and phenolics. Lipids, the major components, give the hydrophobic properties of cuticles and encompass epi- and intra-cuticular waxes and cross-linked lipid polymers, cutin. Waxes include different types of long chain fatty acids, alkanes, primary and secondary alcohol, aldehydes, and esters (Yeats & Rose, 2013). Cutin is a polyester of hydroxylated, epoxylated, and/or oxylated lipids of 16 and 18 carbon atoms, containing glycerol and some di-carboxylated lipids intervening in the formation of 3D networks. Phenolic compounds, such as *p*-coumaric acid and flavonoids (naringenin) and polysaccharides (cellulose, hemicelluloses, and pectin), are part of the polyester, either as ester- or covalently linked structures, such as between cutin and xyloglucan (Fig. 7) (Philippe et al., 2020; Xin & Fry, 2021). Polysaccharides distribute in a continuum from the epidermal cell wall to cutin-embedded polysaccharides (Reynoud et al., 2022). The relative composition, the organization, and the physicochemical environment (humidity) of this complex assembly control the viscoelastic mechanical properties of cuticle, contributing to V&F firmness and perceived by consumer as “thick skin” (Bhanot et al., 2021).

Suberin is the counterpart of cutin but in underground organs (roots, tuber) or in aerial skin, according to genetics or in response to cuti-

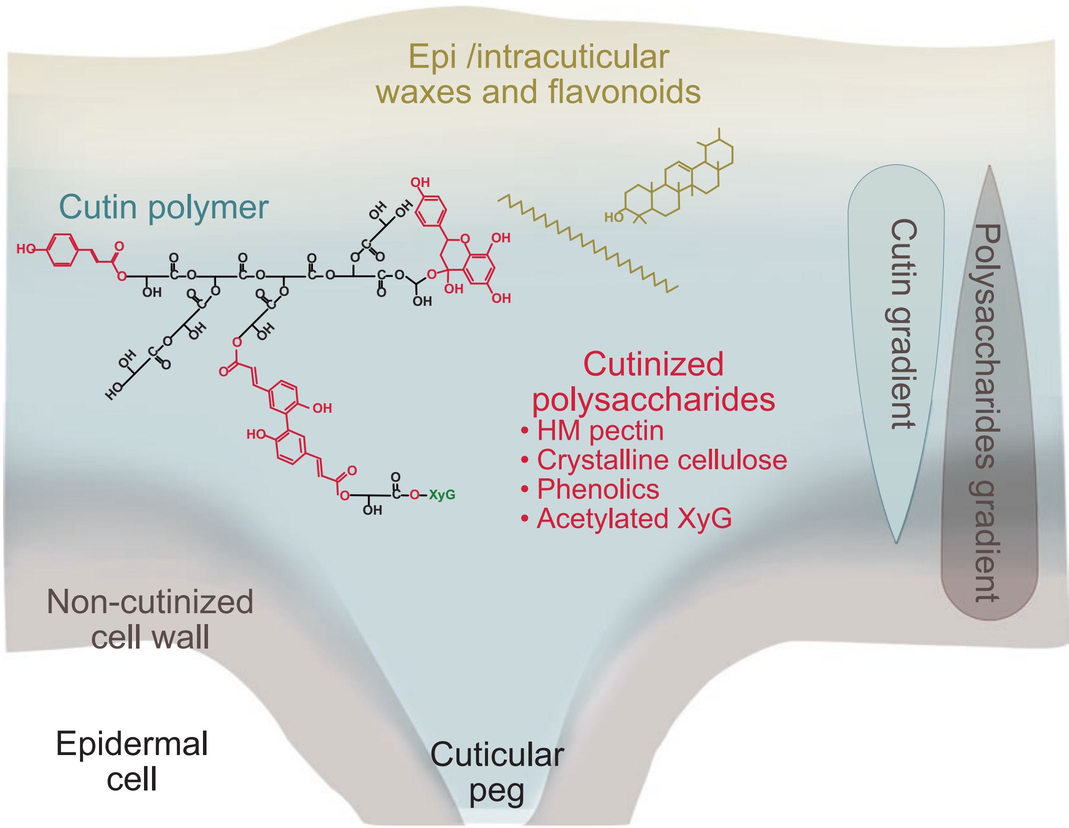

Fig. 7 Schematic representation of cuticle. Cutin polymer is made of hydroxy-fatty acids covalently linked to phenolics and polysaccharides (xyloglucan). Cutinized cell wall polysaccharides are proposed to interact non-covalently with cutin polymer. Cutin, cell wall polysaccharide, and waxes and flavonoids distribute as gradients in the cuticle. (Adapted from Reynoud et al. (2021))

cle failure due to mechanical, environmental or biotic stresses (Graca, 2015). Suberin is composed of long chain fatty acids (C16-C26) with both α and ω di-carboxylated and ω hydroxylated chains, glycerol, low amounts of ferulic acid esters, lignin-like poly-ferulic chains, G and/or S lignin (approximately 25–30%), and polysaccharides (Graca, 2015).

3.3.6 Cell Wall, a Dynamical Assembly

At the tissue level, cell walls are under different mechanical stresses: turgor pressure implies tensile stress on the wall, while neighbor cells will have a compressive stress on each other (Fig. 2). The way cell wall polymers assemble and organize during V&F development will affect the response of the cells and tissues to the different mechanical stresses. In isolated onion cell wall, cellulose and hemicelluloses and particularly xyloglucan are the main contributors controlling in-plane tension stress (creep and stiffness), whereas pectin and cellulose are the main actors in out-of-plane compression stress (Zhang et al., 2019). With regard to apple, dynamic mechanical analysis of turgid tissue infused with selected purified cell wall degrading enzymes highlighted the major contribution of pectin and minor contributions from side-chain xyloglucan and cellulose on the viscoelastic mechanical properties (Videcoq et al., 2017).

Cell wall structure, architecture, and properties are changing all along plant development and V&F texture is the result of this dynamic. Depending on genetic and environmental constraints, these cell wall dynamics are major causes of texture variability. Different plant cell wall enzymes and proteins associated with texture variations have been reviewed, notably expansin, glycosyl-hydrolases, esterases, and “cut-and-paste” enzymes (xyloglucan-, mannan-, xylan-endotransglycosylases/hydrolases) (Frankova & Fry, 2013; Toivonen & Brummell, 2008). Among them, pectinolytic enzymes play a major role in these variations due to their implication in the degradation of pectin in the middle lamella between cells, impacting cell-cell adhesion and in the cell wall leading to softening (Posé et al., 2018). The resulting pectin solubility can be positively related to mealy or, in the opposite, to crunchy apple texture (Billy et al., 2008). Furthermore, the oligogalacturonides produced could be signals for cell turgor pressure regulation (Paniagua et al., 2020). In particular, among pectin-related enzymes, an arabinofuranosidase (Nobile et al., 2011) and a pectin methylesterase (PME) (Segonne et al., 2014), were identified in the development of mealy apple texture in line with reported impact of pectin side-chains structure on such texture in apple (Pena & Carpita, 2004) and in the woolliness (~mealiness) texture in peach (Lurie et al., 2003).

Not only during late development, but the timing of pectin and hemicelluloses laying out in cell wall and their structural modifications along V&F growth remains a question with regard to the cell wall organization ending up with defined organ texture. Model cell walls gave clues on how pectin and hemicellulose can alter cellulose organization and mechanical properties of composites (Berglund et al., 2020; Lopez-Sanchez et al., 2017). Observations of different enrichment and metabolism of hemicelluloses, such as GgM and/or XyG, during early development stages of apple and sweet cherry giving rise to mature fruits of contrasted texture and mechanical properties question how early cell wall development can set the scene for V&F texture elaboration during ripening (Lahaye et al., 2021). Similar early modulations of hemicellulose composition and structure were also observed during tomato development (Guillon et al., 2017; Reynoud et al., 2022) and may represent one source of the genetic variability of texture among V&F.

Biochemical events occurring during V&F development and storage also impact texture developed during processing. Both cell wall disintegration and starch swelling and gelatinization, when starch is an important component, are the main contributors to texture of processed V&F. In potato tubers, differences in cell wall breakdown during cooking relate to the extent of pectin esterification in the middle lamella at harvest, which is differently regulated by pectin methylesterases (PME) among varieties during development besides possible other pectic structural factors (Ross et al., 2011). During storage of pulses and tubers, pectin de-methylesterification occurs alongside with phosphate removal from phytic acid (inositol hexakisphosphate), a phosphorus storage component, by phytase. This combined action is proposed in the “phytase-phytate-pectin” or “pectin-cation-phytate” mechanism involved in the development of hard-to-cook pulses and tubers (HTC) (Favaro et al., 2008; Galiotou-Panayotou et al., 2008; Wainaina et al., 2022). This mechanism proposes that on storage, phytic acid salts are degraded and liberate cations, such as calcium, that migrate to complex de-methylesterified pectin by PME to form insoluble pectate. The latter are thought to be involved in the hardening of the cell wall and to the HTC characteristics. Environmental conditions, such as high temperature and high humidity, appear to be important factors affecting this trait (Chu et al., 2020).

4 Assessment of Vegetable and Fruit Texture

Assessment of V&F texture remains a key measurement to follow the texture quality all along the production, storage, retailing, or processing steps. As reviewed by several authors (Abbott, 2004; Chen & Opara, 2013; Nicolaï et al., 2022), destructive or non-destructive instrumental measurements are applied. Yet, to access specific texture descriptors that are difficult to measure instrumentally (i.e., mealiness, etc.), sensory assessment remains an alternative way and has been implemented, for example, in texture improvement of V&F in breeding programs (Sinesio et al., 2010).

Assessing fruit firmness relies historically on the destructive puncture measurement (penetrometry: Magness-Taylor test) with defined protocols for specific V&F (Abbott, 2004). Compression tests, such as the texture profile analysis or tensile tests, are most limited to V&F research (Abbott, 2004). Assessment of mechanical properties of V&F in research involves specialized equipment, such as atomic force microscopy or rheometers combining both compression and oscillatory measurements and dynamic mechanical analysis when assessing cell wall or tissue poro- or viscoelasticity (Bidhendi & Geitmann, 2019). In these studies, plasmolysis of samples can help revealing different cell wall mechanical properties by removing the contribution of the turgor pressure. Nowadays, non-destructive optical, mechanical, and acoustic methods are increasingly searched and some are implemented in stations to allow high speed sorting and grading (Nicolaï et al., 2022).

4.1 Optical Non-destructive Texture Assessment

Optical assessment of V&F texture encompasses visible/near infra-red spectroscopy/imaging (Vis/NIR) including multi- and hyperspectral imaging that uses several light wavelengths. Reflected light assesses the ripening status and external defaults, while wavelengths in NIR can be related to sugars, organic acid, and total solid soluble contents through complex chemometrics and calibration models (Wang et al., 2015). Other optical methods are based on space- or time-resolved spectroscopy (SRS, TRS) which measure light diffusion in thin skinned V&F tissue. Scattering and absorption of light can relate to internal tissue microstructure and chemistry and have a potential in texture assessment. However, these methods are indirect and generally limited to firmness. Optical measurements report on ripening-related V&F modifications accompanying softening, such as color and sugar/acid concentrations or changes in chlorophyll, anthocyanins, carotenoids, and water absorption (Lu et al., 2020a). Moreover, light propagation depends on the cuticle thickness and optical characteristics. However, the coupling of TRS and NIR with a focus on water bands appears promising in distinguishing crunchy from mealy apples (Rizzolo et al., 2021).

4.2 Mechanical- and Acoustical-Based Non-destructive Texture Assessment

Other non-destructive assessments of texture are based on mechanical and acoustic measurements (Abbott, 2004; Nicolaï et al., 2022; Nishani et al., 2022). Registry of force and deformation during local small elastic deformation can be achieved by different devices, such as those with direct contact (rod, pendulum, small hammer) with detection by force/deformation sensors. Other contactless devices use air “puff” or laser pulse with a laser distance sensor to assess deformation and relate it to force and access stiffness. Sensors based on sound waves frequency following a small shock or forced vibrations provided by an electrodynamic shaker or a loudspeaker can also inform on the ripeness status of the V&F. Organ resonance frequencies and modes have been defined per V&F to evaluate an “acoustic” stiffness. Registry of frequencies can be achieved by an accelerometer or a rod in contact of the V&F or without contact by a microphone, by laser interferometer or a laser Doppler vibrometer (LDV). LDV appears particularly adapted to soft fruit firmness assessment by the analysis of the propagation velocity of Raleigh waves on the surface of the fruit (Arai et al., 2021).

Alternative acoustic texture assessment methods use ultrasounds. Their propagation creates compression and decompression in V&F tissue with speed determined by material density and elasticity. Deviation of initial velocity leads to attenuation of the propagating wave and can inform of changes in tissue structure related to texture (Mizrach, 2012). The limits of the method are due to air-filled spaces that attenuate wave propagation. Furthermore, direct contact or placing V&F in a wave propagating medium, such as water, is required to avoid ultrasound damping by air.

4.3 Limits and Perspectives in Non-destructive Texture Assessment

Implementation of different high-speed and non-destructive assessment methods for portable or in-line V&F grading mainly aims at eliminating defaults (internal and external) and at evaluating the maturity stage and firmness. There are discrepancies between firmness assessment by these methods and the classically used destructive Magness-Taylor penetrometer test due to the different parameters measured. Non-destructive methods mainly assess stiffness, while the penetrometer informs on the initial stiffness in compression, the rupture force through the skin, and the penetration in the flesh with the contribution of shearing forces. Furthermore, due to V&F shapes, external factors (glossiness, smoothness), and skin thickness, some non-destructive methods will not be applicable for grading and sorting and will need to be adapted, as in the case of small berries (Li et al., 2019). In addition, mechanical and rheological characteristics measured by non-destructive and destructive methods are yet unable to provide a full picture of human texture perceptions or relevant measures. For example, water status changes in apple detected by variation in acoustic responses were not sensed by a trained panel (Harker et al., 2019). Moreover, mealiness, juiciness, and crunchiness remain poorly assessed. Experimental destructive approaches exist for these perceptions, such as fruit juiciness and mealiness (Crisosto & Labavitch, 2002) or crunchiness (Giacosa et al., 2015) but non-destructive counterparts are still lacking. Integration of different non-destructive methods may increase reliability and pertinence of measurements with regard to texture perceptions and may benefit from the development of new technologies, such as MRI, micro-X-tomography and terahertz sensing (Kirtil et al., 2017; Nicolaï et al., 2022; Ren et al., 2019) for assessing tissue microstructure, and thermography (Raka et al., 2019), electrical impedance (Jócsák et al., 2019) or biospeckle (Pandiselvam et al., 2020) for evaluating texture-related physiological status of V&F. Fusion and modelling data from different non-destructive sensors (Mishra et al., 2022; Zhou et al., 2020) extended by data collected at the V&F production site (Osinenko et al., 2021) may further improve textures assessment and modeling.

5 Impact of Processing on the Texture of V&F

Starchy V&F, such as plantain, tubers (potato, cassava, yam, taro, etc.), and leguminous seeds (beans, lentils…) need processing to make them digestible. In addition, diverse types of processes are used to ensure V&F availability for longer period, ease their transport in good sanitary conditions, and to develop desired organoleptic characteristics for specific diets and cuisine. Although the review of the impact of specific processes on V&F texture is beyond the scope of this chapter, basic mechanisms underlying texture changes can be summarized. For potato or plantain, heat processing suffices to gelatinize starch but for others, like pulses, cassava and yam tubers, additional processes, such as water washing or fermentation of pounded tubers, germination of pulse seeds, dehulling, hydrothermal processes, are required to overcome their "hard-to-cook" characteristics and to remove adverse nutritional components, like phytic acid, α-galactosides, lectins, cyanogen glycosides, or tannins (Kumar et al., 2021). Basically, in starchy V&F, mealy/dry of soft/smooth textures resulting from processes depends on the content and type of starch, its extent of swelling and gelatinization, cell size, and cell wall disintegration with the release of pectin (Akissoe et al., 2011; Chigwedere et al., 2018; Favaro et al., 2008; Taylor et al., 2007).

During heating or boiling of any V&F type, pectin degradation will occur by acid hydrolysis and/or β-elimination according to local pH, ionic environment, and degree of pectin methylesterification. When present, like in pulses and some tubers, phytic acid content is thought to be an important factor responsible for cell-cell debonding (Waldron et al., 2003). It would act as a chelating agent dissociating pectin-linked Ca^{2+} and preventing cross-links between non-esterified HG domains of pectin, notably in the middle lamella (Favaro et al., 2008; Galiotou-Panayotou et al., 2008). However, the correlation between phytic acid content and softening of tuber on cooking is not always observed (Favaro et al., 2008) and other factors, like polysaccharides cross-linked by phenolic compounds (Chen et al., 2022a) and other cell wall modifications, such as hemicellulose, are possible contributors to the HTC trait (Toili et al., 2022). Texture elaboration during processing also includes the action of endogenous enzymes, such as pectinolytic enzymes that can be more or less inhibited or exacerbated according to local pH, ionic and chemical environment, temperature, and pressure (Duvetter et al., 2009). The biological, biochemical, chemical, and physicochemical variability of V&F combined with environmental constraints including postharvest handling and type of processes make the control of texture in processed V&F challenging.

6 Conclusions and Perspectives

There are high expectations for V&F texture control, not only to avoid wastes but also to have commodities better adapted for processing and to consumer desires as well as to promote their consumption. As reviewed in this chapter, V&F texture is the result of complex interacting micro- and nanostructures spatiotemporally regulated by complex biological mechanisms. Further understanding of texture elaboration would require the holistic approach of complex systems including environmental and genetic factors. Pursuing basic studies relating micro- and nano-structures and mechanical/rheological properties at the tissue and cell wall scales underlying texture perceptions will help to (1) develop suitable sensors or combination of sensors able to better detect and measure a larger panel of texture descriptors, (2) identify biological mechanisms at the protein and gene levels controlling texture under dynamic environmental constraints to ease breeding, and (3) develop models to predict texture quality all along V&F production and postharvest.

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Texture of Bakery Products

Amy Khayiu Voong and Lucas Westphal

1 Introduction to Bakery Products Key Ingredients and Structure of This Chapter

Bakery products refer to a sector in the food industry that include bread, cake, pastry, biscuits, crackers, pies and cookies. Each product is a distinctive type of baked product in its own right, but each also having overlapping similarities. These include baking materials or ingredients, and baking techniques. It is the final texture that will additionally differentiate one type of baked good to another. Texture describes a range of physical and organoleptic characteristics that collectively have a critical role in consumer acceptance, which is due to texture being related directly to product quality. In order to achieve a particular texture, it is necessary to understand the microstructure of the baked product which will be dictated by the interaction between ingredients and their behaviour during different processing parameters. Therefore, an understanding of the main components of bakery goods is vital to understand ingredient functionality to product performance.

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1.1 Flour – Types and Suitability for Different Products

Wheat flour is quantitatively the most important ingredient in baked products, but varieties are available to allow bakers to select a specific specification to enable a particular quality to be achieved. Flour types in the UK include cake flour, pastry flour, bread flour, biscuit flour, wholemeal, brown flour, treated/chlorinated (Edwards, 2007). In breads, hard wheat flours with a high protein content are required to allow for expansion during proofing and baking, which results in a loaf with high volume and tender crumb. Soft wheat flours with low-protein and high-starch content are ideal for fine crumb cakes and pastries. (Zhou et al., 2014). Most biscuit flours are low in protein ($\leq$ 9%) to limit gluten development which can lead to undesired product hardness. However, certain fermented or laminated biscuit types will require a medium strength protein flour of $\geq$10.5% to be processable and create the desired structure (Manley, 2000).

1.1.1 Flour Proteins

Flour proteins can be divided into gluten and non-gluten proteins, which are based on their functionality. The function of non-gluten proteins is not entirely clear; research suggests they are largely monomeric and have either metabolic or structural properties (Veraverbeke & Delcour, 2002). Gluten proteins make up 80–85% of total

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wheat flour protein (Ooms et al., 2018). These consist of monomeric gliadin (MW 30,000–60,000) and polymeric glutenin (MW >80,000) (Delcour et al., 2012). The quantity and ratio of gliadin and glutenin can be used to accurately predict baking performance. Gliadins and glutenin are able to form intra- and intermolecular disulphide bonds (Fig. 1) (Lagrain et al., 2008), which creates a gluten network that allows for dough expansion in bread, puff pastries and certain cakes. It is these two types of protein that give rise to elastic and gas-retaining properties of wheat flour-water doughs.

1.1.2 Starch

Starch in flour can be present in different forms. The majority of starch in an ordinary wheat flour will be in its native granular form, whilst a proportion of starch granules will have been damaged during milling of the grains. Water absorption of native starch granules is limited, whereas damage starch can absorb higher quantities of water at room temperature. A high level of damaged starch in a flour can not only increase the water requirement in a dough for dough development but also modifies the spread during baking of biscuits (Manley, 2000; Sliwinski et al., 2004). During baking of baked goods, starch gelatinises, which not only leads to an irreversible loss of molecular order of amylose and amylopectin but also increases rigidity, and further stabilises the gluten network (Delcour & Hoseney, 2010). As with all starch-based systems, the starch gelatinisation temperature (T_m) will vary depending on water content, starch damage and antiplasticising components. A low-water content and the use of sugar or salt will likely increase the T_m in pastry dough. Therefore, a T_m for starch pastry dough systems can range between 55 and 67 °C.

1.2 Sugar

Sweet bakery has been developed around the properties of sucrose, which is extracted from sugar beet or sugarcane. Sucrose is the universal standard by which we assess sweetness but in addition, sugar influences moisture retention, viscosity, starch gelatinisation, solubility of minor ingredients and acts as an energy source to feed yeasted products. These properties will dictate the properties summarised in Table 1

1.3 Fat

Fats and oils are extremely varied in form and function, but the essential building block of fat is a fatty acid and a commercial fat is a triglyceride. Fat consists of three polymorphs (α, β and β'), α being the least stable with lowest melting point and β being the most stable with highest melting point (Ghotra et al., 2002). The polymorphs

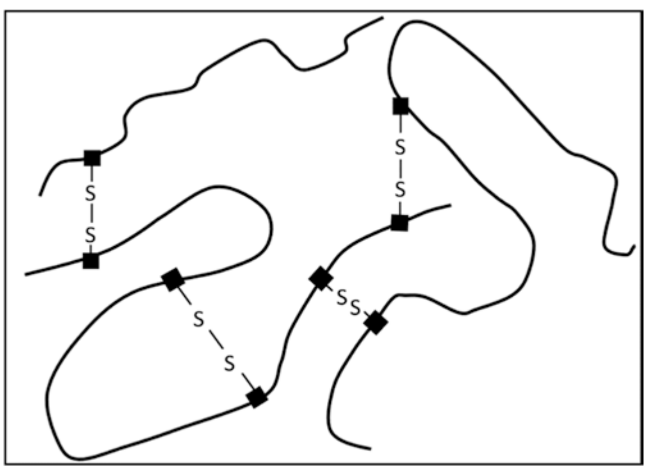

Fig. 1 Schematic representation of developed gluten structure recognised by the presence of disulfide bonds (image adapted from Patient, 1994)

Table 1 Product characteristics influenced by sugar (van der Sman & Renzetti, 2020; Edwards, 2007)

Baked product	Properties affected by sugar content
Bread	Yeast activity, proofing time, structure, softness, colour, shelf-life
Cake	Volume, structure, aeration, humectancy, colour, shelf-life, flavour, aroma
Biscuit	Aeration, flavour, colour, spreading, final texture
Pastry	Flavour, rheology

present in baking fat influences physical properties such as solid fat index, viscosity, melting, recrystallisation, and hence influences the creaming process, lamination, rollability, lubricity and sheeting ability.

2 Bread

Breads are a popular staple food around the globe. All breads share the common features that they are produced from a flour and water dough converted into a solid foam through the application of heat.

Further categorisation of breads can be undertaken on a variety of factors, like:

1. The cereal type: wheat is the commonest raw material used to produce bread flours but spelt wheat, rye, corn and rice which are also exploited around the globe.
2. Production method and fermentation (if used): Production methods for breads range from hand moulding and shaping to high-speed mixing systems linked to pressure and/or vacuum pumps. Moulding of doughs can take place by hand and be minimal such as the manual cutting of ciabatta doughs or conducted by multiple machines with various steps such as dividing, rounding, moulding and four-piecing. Lamination as well as sheet-and-cut processes are employed in industrial high-speed processes. Fermentation is often aided through the addition of yeasts and/or lactic acid bacteria to the mix and supports the rise during proofing and baking as well as impacting the development of the dough. Some products contain neither added yeasts nor lactic acid bacteria and employ chemical raising agents such as sodium bicarbonate added to aid the structure generation during baking as in Irish soda breads.
3. The product volume, which is dependent on the cereal base and production/fermentation methods used.
4. The presence of value adding ingredients, e.g. fibre, protein or seeds.

2.1 Perception and Measurement of Bread Texture

The crumb of breads can be described as a solid foam with open cells, enclosed by a firmer layer which is lower in moisture, the crust. Crumb and crust properties vary significantly across different products and although the crust only makes up a small proportion of many breads, it is crucial for some aspects of the initial textural perception as well as the chewing behaviour at the beginning of the mastication process (Scanlon & Zghal, 2001).

The physical characteristics of breads like dimensions, weight, shape and volume have a big impact on the sensorial experience of texture and simple forms of measurement can be used for their analysis but a variety of semi-automated methods have been established in the industry for their quantification. A product's (specific) volume, weight, shape and size for instance can be quantified through laser scanning equipment such as VolScan Profiler (Stable Micro Systems, UK). Image-analysis equipment like C-Cell (Calibre Control, UK) can be used to study a wealth of bread slice characteristics from dimensions to crust thickness, cells and cell wall features.

Bread texture changes throughout the consumption process and is a multifaceted sensorial experience (Guo, 2021). Depending on the type of bread and particularly crust properties, the sensorial texture experience of consumption is often initially dominated by softness, chewiness or crunchiness and these mechanical properties can be studied and quantified through destructive force deformation techniques. A review published by Guiné (2022) considered 49 papers printed between the years 2000 and 2022 and showed that >80% of studies used techniques like texture profile analysis (TPA) or other forms of compression tests to quantify key attributes of breads such as firmness and springiness which have both shown to be highly correlated to their sensorial experience (Di Monaco et al., 2008; Kim et al., 2012). Different forms of perforation tests were used by five research teams with the aim to study crust properties (Guiné, 2022). As crunchiness or crispness forms an essential part of the texture assessment of many fresh bread crusts, not only the fracture behaviour but also sound emission can provide valuable insights (Roudaut et al., 2002). To date, there is no globally accepted definition of crispness or crunchiness, but it is generally acknowledged that crispness is accompanied by the emission of higher pitched sounds (usually with frequencies > 5 kHz), whilst lower pitched noises are emitted from crunchy products (frequency range 1.25–2 kHz) (Vickers & Bourne, 1976; Dacremont, 1995; Kilcast, 2004)

As the product structure is broken down into a bolus through the act of chewing, lubrication by saliva, and action of amylases occurring in the mouth, the sensorial texture experience shifts to a new phase that is dominated by its adhesiveness, softness and increased moisture content and tends to be accompanied by a decrease in chewing rate and intensification in required force to remove materials from the oral cavity walls or teeth (Takeshita & Nakazawa, 2007; Young et al., 2016a; Gao & Zhou, 2021). Chewing rate and breakdown of the product are linked and the latter is not only influenced by the individual's physiology but also the product's composition with one important factor for the rate of disintegration of breads being the strength of the gluten network. A higher level of present gluten protein leads generally to a stronger network and slower disintegration. Therefore, breads made from lower protein flours tend to break apart more easily (Gao et al., 2015). Additionally, the presence of materials that cause physical interruption of the gluten network, like dietary fibres or non-gluten forming proteins also leads to a weakening of the crumb with even more pronounced effects on the disintegration behaviour depending on their inclusion level (Jourdren et al., 2016a). Furthermore, it has been shown in multiple studies that a thicker crust leads to an increased chewing duration, higher number of chews and increased muscle activity which is due to its low-moisture content and relatively high firmness in comparison to the crumb (Gao & Zhou, 2021).

Jourdren et al. (2016b) showed that characteristics of the bolus can have a more pronounced effect on the sensorial experience of texture than the properties perceived at the initial bite. Compositional analysis, compression tests, small deformation rheology, image analysis and sensorial techniques have been used for the analysis of bread bolus characteristics (Hwang et al., 2012; Jourdren et al., 2016a). However, the study of bread boli is complex and no standardised test method exists to date.

Swallowing of foods is triggered once the threshold for lubrication and structure breakdown are met as outlined in an early developed milestone model by (Hutchings & Lillford, 1988) describing the breakdown path of foods. For most breads, which are low in fat, the lubrication is vastly achieved through water within the product and more importantly from the saliva which explains the difference in number of chews required for a variety of crusty and non-crusty bread products.

2.2 Factors Determining Bread Texture

Texture of breads is critical for consumer acceptance and liking. Therefore, bakers have a high interest in understanding how a specific texture can be created that fits the consumer requirements. Creating a specific texture is, however, a process with multiple and complex interactions and a simplified summary of these is shown in 2. Geometrical structure and material properties both determine the final texture of breads and to understand how both features are generated, it is essential to have a good knowledge of the raw materials used and the modifications they undergo during processing. Ingredients build the fundament of the Casita structure in Fig. 2

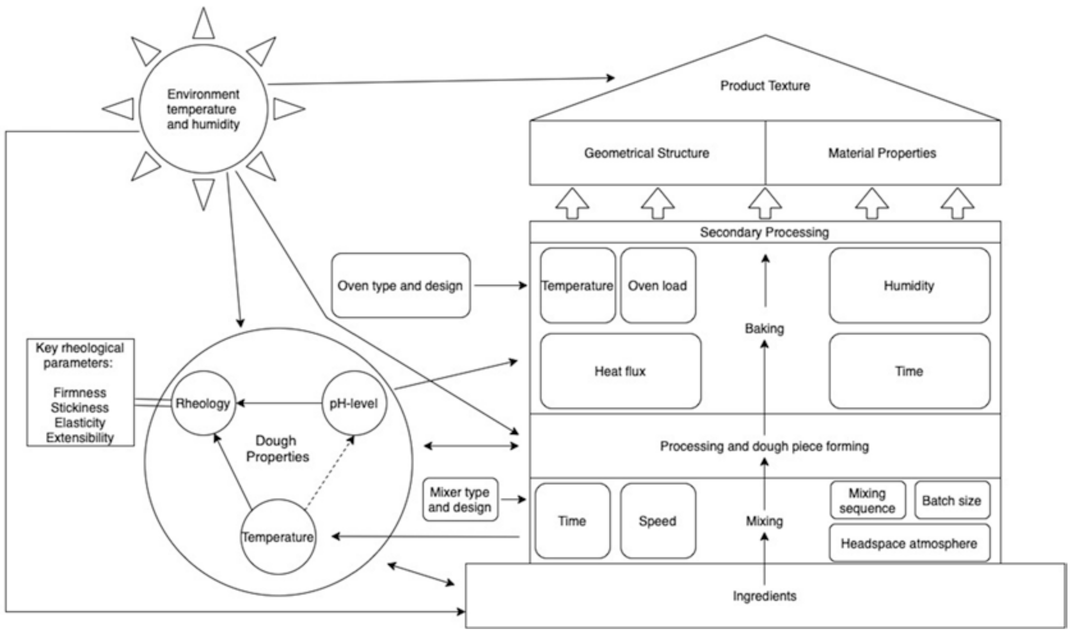

Fig. 2 Casita model, factors influencing bread texture

because, despite the vast potential for modification during the process, they are a limiting factor to the potential of a bread formulation.

Historically, breads were made with three basic ingredients: (wheat) flour, water and salt. Flour is believed to be one of the most important bread ingredients and much attention has been paid to the content and properties of its proteins and their influence on bread making quality. It is generally accepted that a higher protein content has the potential to create breads with a higher bread volume, resulting in a reduced density and consequently softer crumb (He & Hoseney, 1992). Although knowledge of the ratio of gliadins and glutenins allows for predicting baking performance, in practice however, this information is rarely available for product development purposes and the protein content therefore remains the most important characteristic that indicates the strength of the flour accompanied by rheological tests such as farinograph, extensograph or alveograph. Apart from proteins, flour lipids, non-starch polysaccharides and enzyme activity (predominantly alpha-amylase) are important for the baking performance (Cauvain & Young, 2007). Water and salt both modify the rheological properties of bread doughs and interact with flour proteins, other flour components in the dough. Whilst water is critical for the hydration and consequent development of gluten, the ionic nature of salt leads to a toughening of gluten proteins and consequently strengthening of the network structure.

Over the years, other ingredients have been introduced to bread formulations to cater for increasing consumer demands and process automatisation requirements. Common ingredients that can be found in the European bread market are yeast and/or sourdough preparations, fat, sugar, oxidising agents (e.g. ascorbic acid), reducing agents (e.g. L-Cystein), soy flour, gluten, malt extract, enzymes (e.g. amylases, lipases or cellulases), emulsifiers (e.g. DATEM, mono- and di-glycerides of fatty acids or lecithin), acids (e.g. lactic or acetic acid) and preservatives (e.g. calcium propionate).

Aside from material properties, breads cell structure (e.g. cell size, cell orientation and wall thickness) is important for the perceived crumb texture. Mixing is considered to be the most important process to create a specific cell structure (Della Valle et al., 2014). Subsequent processing steps such as dough-piece forming and proving can alter the cell structure, but their potential is limited by the structure generated during mixing and they often aim to preserve the existing structure rather than to create one (Leong & Campbell, 2008; Della Valle et al., 2014). Fats and more precisely fats with a high melting point have played a key role in the stabilisation of gas bubbles in doughs during processing and therefore contributed to the generation of a fine crumb structure and high bread volume. In most formulations today, however, this functionality is mimicked by emulsifiers (including in situ generated emulsifiers through enzyme technology), whilst vegetable oils are used to soften the crumb structure and improve dough handling properties (Hartnett & Thalheimer, 1979). The use of emulsifiers also brought further benefits such as the ability to form complexes with starch (in particular, straight-chain mono-glycerides) that lead to a delay of starch retro gradation over shelf-life and consequently extended freshness.

As mentioned previously, crispness and crunchiness are a crucial aspect of consumer acceptability for products such as baguettes or sourdough breads. Both texture parameters are linked to their crust properties which are influenced by raw materials that contribute to caramelisation and Maillard reactions but predominantly determined during baking. Crust formation is controlled during baking through temperature, time and humidity in the oven and more importantly at the product surface (Cauvain & Young, 2007). The desirable texture attributes that a bread crust can bring can be further increased through modification of the crust to crumb ratio, achieved through scoring of the dough piece before baking.

3 Pastry

The term ‘pastry’ refers to fat-rich bakery goods, which are consumed worldwide in numerous regional variants as both savoury and sweet. Pastry can be broadly divided into the following types, each with distinguishable textural properties:

- Shortcrust (pies, quiches)
- Puff (vol au vent, pie tops, sausage rolls)
- Phyllo/filo (baklava, strudel)
- Choux (éclair, profiteroles)
- Fermented (Danish pastries, croissants)

3.1 Shortcrust Pastry

Shortcrust has a dense, unlayered and crumbly texture. Table 2 highlights the key differences in composition between shortcrust and puff. In shortcrust, the gluten structure formed needs to be interrupted by using fat as the shortening agent and two stages of mixing. The first stage mixes flour and fat together to ensure flour particles are coated with fat. The second stage requires the addition of water to bind the system together and partially develop the gluten. Overmixing can result in increased gluten development, which reduces the shortening affect and results in a shortcrust pastry with a tough texture.

3.2 Puff Pastry

The characteristics of puff are recognised by a light and flaky texture achieved by creating multiple heterogenous layers of dough-margarine (Ooms et al., 2016). The quality varies substantially depending on the raw materials and processing. The essential components of a puff pastry include water, wheat flour, fat and salt. Yeast and sugar may also be required for fermented puff pastries to increase volume prior to baking, a Danish pastry can be expected to expand in volume by 200–300% during proofing then even further during the baking process (Deligny & Lucas, 2015). Variations in ratio of

Table 2 Typical composition of puff and shortcrust pastry (Patient, 1994)

	% in Puff	% in Shortcrust
Flour	39.1	58.5
Fat	39.1	29.2
Water	21.4	11.7
Salt	0.4	0.6

these individual ingredients are what determine the final texture and product classification.

3.2.1 The Lamination Process

Methods for making puff pastry can be divided into the Scotch/Blitz/rough puff, English and French methods. The Scotch/Blitz/rough puff method requires fat to be cut into small cubes (~20 mm × 20 mm), added to the mixing bowl with all ingredients and incorporated into the final dough. The Scotch/Blitz/rough puff method will result in a dough with less lift as the dough will lack continuous layers of fat, so less steam will be able to escape. Gluten will also be less developed by using Scotch/Blitz/rough puff method as fat is mixed into the dough; therefore, there is a less need for the dough to rest and relax. This method would be suitable for products like sausage rolls but not vol-au-vent, which requires height and dimensional stability.

The English and French method requires a lamination process, where the fat is rolled out in between layers of dough to form a clearly defined multi-layered system. As shown in Fig. 3, the English and French methods differ in terms of how the fat is encased. The English method requires roll-in fat and predough to be of similar thickness. The roll-in is laid on top of the predough and should cover two-thirds of the predough surface. The remaining exposed predough is folded on top of the roll-in fat, followed by a second fold of the other end. This is then sheeted and folded until enough layers have been created. During the sheeting and folding process, the dough is subject to uniaxial extension and shear under high deformation rate to achieve such thin layers (Renzetti et al., 2015). The French method follows an envelope method, whereby a rectangular sheet of fat is wrapped in the predough by folding the corners to meet in the middle. This will then be followed by a sheeting and folding process to create enough layers.

A multi-layered system of alternating fat and dough creates a laminated dough, which will rise during the bake due to steam (Fig. 4). The number of layers of fat will affect final volume and crumb structure. A low number of layers can result in height but an irregular crumb structure with voids. Although a high number of layers will give a high volume with a delicate crumb structure and tight air cells, layers can have thin interconnections loss of dough lift (Sievert et al., 2007). A typical puff pastry will have 130–250 layers of fat, though some authors say that a dough with less than 162 fat layers will result in poor crumb structure and irregular dough lift (Cauvain & Young, 2009). The number of layers will of course depend on the product requirements. Product qualities such as colour, texture, flavour and mouthfeel will be affected by the number of layers in the pastry.

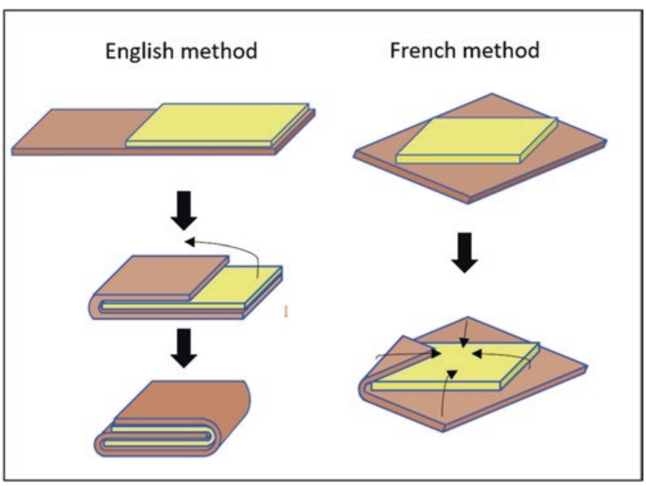

Fig. 3 Schematic representation of English and French method of folding puff pastry. (Image adapted from Ooms et al. (2016))

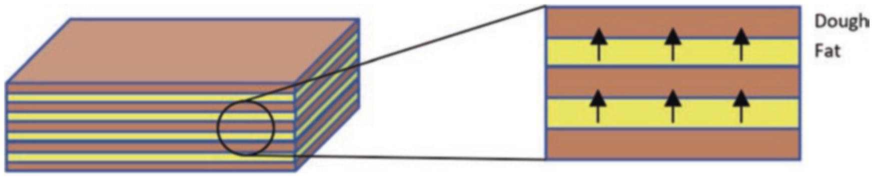

Fig. 4 During baking, steam is trapped in between the liquid fat layers, resulting in dough lift. (Image adapted from Ooms et al. (2016))

3.3 Phyllo/Filo Pastry

Phyllo/filo (meaning leaf in Greek) refers to light, flaky and crisp pastry which is due to creating thin sheets of unleavened wheat flour dough layered with melted butter or fat. High protein flour promotes elasticity, which allows phyllo dough to be stretched to a paper-thin thickness, a distinctive feature of this pastry type. Upon baking, steam produced enables the dough layers to rise to create a desirable flaky texture. These pastry products are predominantly found in the Middle East and Central Europe.

3.4 Choux Pastry

'Choux' meaning 'cabbage' in French refers to the shape produced upon baking a lump of this pastry dough. The process requires water and shortening (2:1) to be boiled together before mixing in a soft flour. The now gelatinised flour is cooled to approximately 65°C before adding egg (Edwards, 2007). During baking, entrapped air and water converting into steam result in air expansion and paste rise. This gas is retained as gluten and egg albumen can form a film within the paste. The extensibility of egg albumin allows choux pastry to expand and will cease once albumin loses this property, coagulates and set. Finally, this leaves a crisp outer layer and hollow centre. (Daniel, 1972; Edwards, 2007; Kurti & This-Benckhard, 2015). Chicken eggs are the typical choice for choux, but research has shown that eggs with higher protein and lipid content (e.g. duck) will impart better texture and colour (Santoso et al., 2022).

3.5 Pastry Characterisation and Measurement Techniques

Sensory measurements have been used historically by bakers to assess pastry quality (Table 3). However, there is a need by the industry for instrumental methods to provide quantitative data. This is useful for quality control and research purposes when trying to understand ingredient functionality or relating physical properties to textural and sensory perception.

3.6 Factors Determining Pastry Texture

The texture of pastry dough is created by under developing the dough, i.e. halting the mixing process when a homogenous dough is obtained. During baking, the transient gluten network will deform as the dough lifts, but the gluten proteins will also set as intermolecular disulfide bonds form (Lagrain et al., 2008). It can be noted that the molten fat during baking may interfere with the gluten polymerisation, but the exact mechanism is unclear (Ooms et al., 2016).

The plasticity, consistency and melting properties of fat will influence baking quality. Puff pastry is of high fat content and can range from 50% to 100% flour basis depending on scale of production and product type (Wickramarachchi et al., 2015). The final baked product can contain 30% or more fat on a weight basis (Simovic et al., 2009).

Fat needs to be firm enough to withstand the mechanical stress during rolling, folding and sheeting. It is critical to maintain a thin, continuous and undamaged layers between the doughs.

Table 3 List of sensory and instrumental methods used to assess puff pastry quality

Parameter	Method	Description	References
Pastry lift/Specific lift	$\frac{\text{Height of pastry lift (mm)}}{\text{Pastry weight before baking (g)}}$	Used to compare pastries of different final thickness or weights.	Deligny and Lucas (2015), Gerrard et al. (2000)
Pastry development	$\frac{\text{Pastry lift (mm)}}{\text{Height of the pastry weight before baking (mm)}}$	A parameter used by bakers. Expectations range typically between 5 and 8	Cavillot et al. (2009)
Pastry volume/Specific volume	$\frac{\text{Pastry volume of the pastry cm}^3}{\text{Pastry weight before baking (g)}}$	Laser-based scanners can be used for measuring volume	Renzetti et al. (2015), Simovic et al. (2009)
Pastry irregularity	Maximum pastry height(mm) − minimum pastry height(mm)	Irregularity is related to uneven lift	Telloke (1991)
Consistency or firmness of fat or dough	Texture Analyser	An extrusion cell can be used to relate to sheeting process. Penetration tests can be used to understand firmness. Compression testing using a blade or cylindrical probe to understand maximum shear force or resistance force under deformation. Penetration tests using a cylinder probe to test for resistance force against under deformation	Pajin et al. (2011), Renzetti et al. (2015), Rønholt et al. (2014), Simovic et al. (2009)
Solid fat content in butter/margarines	NMR	Solid fat content will influence melting point, firmness and plasticity	Jung et al. (2020), Pajin et al. (2011), Rønholt et al. (2014)
Melting temperature and crystallisation temperature of fat	Differential Scanning Calorimetry (DSC)	Thermal transition can be measured	Rønholt et al. (2014)
Structure	Microscopy. Confocal scanning laser microscopy. Image analysis	Analyse cross-section of pastry for cell size and cell wall thickness. Staining can be used to identify structural composition, e.g. fat globules, protein network	Bousquieres et al. (2014), Deligny and Lucas (2015), Rønholt et al. (2014), Salmon (2005)
Dough rheology	Rheometer	Bulk rheology can be carried out to measure viscoelastic properties of pastry dough	Renzetti et al. (2015)

Adapted from Wickramarachchi et al. (2015)

Fat should not soften unduly, as this would lead to inconsistencies in forming a layered system. The layers of fat in puff pastry act as impervious barriers to restrict movement of moisture vapor and gases produced during baking. The melting properties of fat are dictated by crystalline solid fat content, which in turn influences the firmness and pliability (Wickramarachchi et al., 2015). Typically, fat blends with high saturated fats will impart a higher melting point, which is desirable for dough handling. However, melting points should also be low enough to avoid 'palate cling', a waxy aftertaste caused by unmelted fat (Tamstorf et al., 1986). During the bake, moisture in the dough system is converted to steam, which creates a leavening effect. The retained gases expand and stretch the gluten network, giving rise and volume to the structure. The effect of molten fat during baking is not clearly understood but research suggests molten fat interferes with gluten polymerisation, similar to that seen with sugar-snap cookies (Pareyt et al., 2009). Molten fat has been suggested to lubricate gluten proteins to restrict water absorption. However, crystallised fat has been proposed to physically hinder gluten proteins cross-linking (Cauvain & Young, 2006).

4 Biscuits

Biscuits are a broad category of baked goods which are made from flour (predominantly wheat) and are differentiated from other baked goods such as breads, pastries or cakes through the low-moisture content of the final product and consequently relatively long shelf-life. The term biscuit is used in the UK and many other countries to describe sweet or semi-sweet biscuits as well as savoury biscuits (crackers) or batter-based products such as wafers. Biscuits are produced and sold in shops for a range of different uses from staple foods to luxurious gifts and even pet foods (Manley, 2000).

The heterogeneous group of biscuits can be divided into categories based on their dough characteristics and their resulting commonly used dough piece forming methods. Short dough biscuits are made from doughs that are relatively high in fat and/or sugar and contain little water in the recipe. Consequently, such doughs are usually formed via rotary moulding, rout press or wire cut techniques. Whilst semi-sweet doughs are also often rotary moulded, their lower fat/sugar content in comparison to short doughs and the more present gluten development within the dough makes these doughs also suitable for sheet and cut processes. Hard doughs, on the other hand, typically contain higher levels of water and lower levels of fat and/or sugar in the dough which allow a higher level of gluten development. Hard doughs are commonly laminated for the modification of structure and sheet and cut processes are typically employed to form dough pieces. Lastly, depositing is another forming technique often employed for very soft doughs (i.e. batters) as used for the manufacture of wafers.

4.1 Perception and Measurement of Biscuit Texture

Whilst it is not possible to define any biscuit with a single attribute, certain attributes will dominate in the description of consumers for a specific product type (Nishinari & Fang, 2018). Most biscuit products can be described as dry, (semi-) solid foods and to comprehensively and accurately study the textural properties of biscuits and to design biscuits with a specific texture, it is crucial to understand the changes the product undergoes during the active phase of consumption. Overall, the changes taking place during mastication of a biscuit have been summarised by various researchers as a 'transition from dry to sticky' as the dominant textural perception change taking place (Young et al., 2016a; Guo, 2021). During the dry-phase, attributes such as hardness, crispness, crunchiness, flakiness, puffiness, fracturability, chewiness and denseness dominate the textural perception of biscuits. Guiné (2022) reviewed the mechanical testing techniques to measure the textural attributes of biscuits and found that compression tests (e.g. TPA) were the most popular method of assessment followed by cutting tests. Whilst a strong correlation has been established between instrumentally measured hardness or springiness and their sensorial assessment, perceived cohesiveness could not be predicted by instrumental measurements in the same manner and should be used with caution (Di Monaco et al., 2008; Kim et al., 2012). Crispness and crunchiness were early identified as crucial texture characteristic and are used by researchers and consumers alike to describe desirable biscuit properties (Roudaut et al., 2002). Both characteristics are linked to each other as well as the fracture behaviour, sound emission and geometrical features of the biscuit (van Vliet & Primo-Martín, 2011). Therefore, methods to study these properties are not only limited to flexure, shear and compression tests but also include sound emission techniques and physical characterisation methods (Roudaut et al., 2002; Kilcast, 2004; van Vliet & Primo-Martín, 2011). Whilst there is no consensus on the definition of crispness and crunchiness, biting of crispy foods is associated with the emission of higher pitched sounds (usually with frequencies > 5 kHz) whilst crunchy foods release sounds with lower pitched sounds (frequency range 1.25–2 kHz) (Vickers & Bourne, 1976; Dacremont, 1995; Kilcast, 2004).

It was observed (Takeshita & Nakazawa, 2007) that during the dry phase the chewing speed gradually increases, whilst saliva migrates into the biscuit (Young et al., 2016a; Nishinari & Fang, 2018). With a relatively high rate of chewing, the particle size of the biscuit is rapidly reduced and their specific breakdown behaviour, determined by cell wall thickness and size or geometry of the air cells contained within the structure highly influences the textural perception within this early stage of mastication which explains the unique eating characteristics of for example cream crackers or butter puffs in comparison to denser biscuits made from the same raw materials (Kilcast, 2004; Matz, 1962; Van Vliet & Primo-Martín, 2011). These physical properties of biscuits such as weight, shape, size, density or volume can be studied in part through simple forms of measurements such as gravimetrical techniques or displacement methods, whereas more advanced technologies such as X-Ray micro CT can provide deeper insights into features such as porosity (Sarkar et al., 2022).

During consumption, the ongoing chewing action and the transfer of saliva into the biscuit lead to moistening and softening of the product. This is also accompanied by a range of other processes, which combined facilitate the transition of the biscuit into a so-called sticky phase. Firstly, sugars solubilise, which triggers a large release of starches from the biscuit that are to a limited extend broken down by amylases that occur naturally in the oral cavity (Rodrigues et al., 2014; Mosca & Chen, 2017). Furthermore, fats are being liberated from the biscuit structure and depending on their type, melt in the mouth, providing an oily or creamy sensation and releasing flavour compounds. Additionally, saliva serves as a transmitter for taste molecules from the biscuit to our taste buds (Guo, 2021). All these processes combined lead to the transition to a sticky phase or bolus formation, accompanied by a decrease in chewing rate (Takeshita & Nakazawa, 2007) and increase in required force to remove materials from the oral cavity walls or teeth (Young et al., 2016a). In the transition from dry to sticky phase, the earlier dominating attributes usually decrease or get lost (e.g. crunchiness, crispness, puffiness) and new attributes become dominant in the biscuit texture such as cohesiveness, gumminess, adhesiveness (to teeth, palate, tongue or itself), moistness, creaminess or fattiness depending on the biscuit type and composition. The bolus of biscuits has been described by Young et al., 2016b as heterogeneous, comprising intact pieces within its mass which complicates the study of biscuit boli and explains why no standardised test method has been established to date. Compositional analysis, TPA, back extrusion, vibratory viscometry and sensorial techniques have all been used for the study of biscuit bolus rheological properties (Hwang et al., 2012; Young et al., 2016b).

A key model developed by Hutchings and Lillford (1988) describes the breakdown path of foods and shows that swallowing of foods is triggered once the threshold for lubrication and structure breakdown are met. Satisfactory lubrication for swallowing can be met not only from saliva but also fat which is important to note for short-dough products and other high fat containing biscuits as their high fat content creates the typical shorter chewing time and requires less number of chews for their consumption (Guo, 2021). A development to this model in relation to dry foods was later made by Rosenthal and Pang (2018), who suggested that foods such as biscuits or crackers form a meal during the first few bites and then hydrate to a structured dough prior to entering Hutchings & Lillford's breakdown path.

4.2 Factors Determining Biscuit Texture

Texture is a key sensorial attribute of crackers and biscuits that drives consumer acceptability. Whilst flavour and aroma are key drivers for consumer likeability, a good texture is not always noticeable by consumers in a product (Andersen et al., 2019). A defective texture, however, can render the product unacceptable regardless of the flavour.

Consequentially, it appears logical that food companies invest resources into understanding how food texture can be controlled and modified. However, designing biscuits with a specific texture is complex and a very simplified version of the various interactions is shown in Fig. 1. In summary, a product's textural attributes are a combination of the material properties used to create the products and the modifications they undergo during processing, leading to physio-chemical material changes and the creation of a geometrical structure. Whilst vast opportunities exist within processing techniques to modify the material, products cannot surpass the limitations imposed by the raw materials used to create the products, which is why ingredients form the basis of the Casita structure shown in Fig. 1. Key ingredients for most biscuit products include (wheat) flour, fat, salt and sugar. Their quality and ratio within the formulation are crucial, but requirements will depend on the product type and desired textural properties. The energy input to the dough during mixing and processing also has an impact on the level of gluten development as well as the presence of other ingredients competing for water (e.g. sugars, starches, fibres, proteins) and ingredients restricting the exposure of water to flour proteins like fats and oils. Furthermore, yeast fermentation, reducing agents like SMS and other processing aids like enzymes (including naturally occurring in flour) can modify the present gluten proteins in the dough if subjected to the right processing/environment conditions (i.e. temperature and pH-level). Beside gluten level, other important flour properties that influence processability and structure creation are the particle size and level of damaged starch as they influence water absorption of the dough and spread during baking (Manley, 2000). Biscuit fats play an important role not only in the processability of the dough as it can soften the material but also for structure creation as fat crystals can coat and consequently stabilise gas bubbles in the dough during processing. In the biscuit, the material properties of fat such as composition and configuration of fatty acid chains, their crystallisation and melting behaviour as well as their present quantities are crucial for the mouthfeel and influence the perceived softness and crispness of the biscuit as well as its creaminess and melting in mouth perception (Onacik-Gür et al., 2015). However, fats and oils in biscuits are not only used for in dough application but also vital in secondary processes such as cream fillings, chocolate coatings or oil sprays.

Like fats, sugar also contributes to dough processability by increasing the volume of the liquid phase within the dough by solubilising in the available water until a point of saturation is reached (Chevallier et al., 2000). Texture, however, is influenced by sugars' ability to melt, recrystallise and form an amorphous glass upon cooling which provides strength to the baked structure and gives many products like ginger nuts its characteristic snap when broken or bitten (Manley, 2000). Melting of sugars (influenced by its particle size) also contributes to spread during baking and consequently influences the way in which structure is created. Further impacts on biscuit texture are provided through sugars ability to caramelise during baking and their contribution to the Maillard reaction with amino acids (Starowicz & Zieliński, 2019).

Many biscuits contain one or more ingredients designated to provide additional value like (modified) starches, raising agents, acids, dairy products, eggs, fruits, nuts, seeds, cocoa, chocolates, flavours, spices, minerals or vitamins as well as processing aids like water and enzymes. Increasingly, the baking industry focuses on nutritional quality of biscuits in the UK, largely driven by the UK governments plans to implement new regulations restricting the promotion of products high in fat, salt and sugar (HFSS). As most traditional biscuit product will be effected by this change in regulation, ingredients like fibres (e.g. bran, oat fibre, inulin, polydextrose, or resistant maltodextrin) and proteins (e.g. whey, pea, oat or soy) are increasingly incorporated into modern formulations in a strive to improve their nutrient profile score. These ingredients impose new challenges for manufacturers as small levels can have a significant impact on processability and sensorial properties. Commonly encountered product issues from the introduction of such materials are an increase in product firmness or loss of crispness, loss of melting in mouth behaviour and grittiness as well as an impact on the products colour and flavour (Laguna et al., 2014; Raymundo et al., 2014; Guiné et al., 2020). Luckily, the creation of nutritionally optimised products with desirable textural properties is feasible if a holistic product design approach is used with careful raw material selection and suitable processing methodologies tailored to the product type and targeted texture.

5 Cake

Cake is recognised as a sweet baked good with a short and tender crumb. The main constituents of a cake include wheat flour, sugar, fat or oil, eggs. Mixing the ingredients will create a batter to be of an emulsion system, which exhibits viscoelastic behaviour and is able to trap air bubbles and to form a foam structure. During baking, a simultaneous reaction of starch swelling, protein denaturation and leavening will transform the liquid batter into a solid foam structure. The final moisture content can range anywhere between 18 and 28%, making cake a lower moisture content than bread but higher than biscuit (Wilderjans et al., 2013).

Cakes are classified based on a combination of recipe and processing methods; shortened vs. unshortened, high ratio vs. low ratio, batter cakes vs. sponge/foam. However, a deeper understanding of patisserie will highlight further subclassifications of cake or sponge due to varying formulations and methods (genoise, pound, egg-free, angel, chiffon). Batter cakes are prepared using a single or a multistage mixing method. The mixing process aims to create a homogenous batter system with stabilised air bubbles, which will act as nucleation points for bubble growth during baking. The high sugar content, oil content and minimal mechanical force from mixing assist in reducing the formation of a gluten network. (Lambrecht et al., 2018.)

5.1 Mixing

5.1.1 Single-Stage Mixing

This refers to the mixing of all wet ingredients together followed by all dry ingredients together, before combining the entire mixture. An emulsifier is typically added to assist in stabilising air bubbles in the lipid phase as opposed to the aqueous phase. This enhances the dispersion of fat into smaller fat globules and results in a tender crumb (van der Sman & Renzetti, 2020).

5.1.2 Multistage Mixing

This requires mixing of fat and sugar first (creaming method) which creates an o/w emulsion, with air bubbles dispersed in the aqueous phase. The creaming method creates a pale colour foam with a cream-like texture. This is followed by adding liquid egg in small portions, so that the batter does not curdle. Finally, flour is folded in, which will be dispersed in the aqueous phase (van der Sman & Renzetti, 2020).

Multistage mixing of sponge or foam cakes is made in two basic steps. The first step requires egg and sugar to be whisked to form an aerated foam. Sugar enhances viscosity and subsequently increases mixing time, amount of aeration and smaller air cells. After forming a meringue, egg, oil and flour are added in (van der Sman & Renzetti, 2020). Chiffon differs in that egg-white and sugar is whisked separately to form meringue before adding the batter, which is made up of flour, egg yolk, oil and/or water. The leavening of a sponge/foam cake will be dependent on egg as the functional ingredient, not a raising agent.

A schematic representation of the cake making processing from mixing to baking is shown below in Fig. 5.

5.2 Factors Determining Cake Texture

The major constituents of cake can be described as either tougheners (flour, egg white, milk solids, salt) or tenderisers (sugar, fat, egg yolk) (Mizukoshi, 1985). Ratios will differ depending on recipe, but ingredient functionality will not. The physical and chemical properties of these ingredients will of course change depending on the stages of cake making (Table 4). Wheat flour quality depends on variety, milling process, extraction and level of chemical treatment if any (chlorination). Gluten proteins develop to give elastic and extensible properties, which allow the dough to expand, whilst retaining air cells, the foam structure then sets as proteins coagulate. Low-protein content (~8%) and small particle size flour are ideal for producing a white cake with fine and silky texture (Zhou et al., 2014). Flour particles reduce fat and air cell coalescence by physical obstruction or by increasing the bulk viscosity, thereby slowing the rate of migration and favouring a stable emulsion.

During mixing, fat supports the stability of air cells and the entire system. During baking, fat crystals melt; some will withdraw from the air cell interface and disperse throughout the continuous aqueous phase. This leads to the cake rising whilst retaining air cells, and the surface of the cake is coated with fat. Upon cooling, fat can recrystallise and either remain at the air cell interface, suspended in the continuous phase or at the surface of the cake (Wilderjans et al., 2013).

As sugar levels can range from 25% to 30% in cake, it is a major constituent and the characteristics affected by sugar are listed in Table 1 (Bennion et al., 1997). The demand for sugar alternatives has risen due to the association between sugar and high fat diets and obesity. Sugar substitutes refer to nutritive sweeteners (fructose, glucose, corn syrup, high fructose syrups, honey, molasses, maltodextrin) and non-nutritive sweeteners (stevia, sucralose and aspartame) (Zhou et al., 2014). The disadvantage of sugar substitutes is their differing functional affects in comparison to sugar: binding agent, bulking agent and texturising.

5.3 Cake Characterisation and Measurement Techniques

The use of instrumental measurements has been shown to be useful in quantifying physical properties of cake (Table 5). This is necessary to understand the drivers in microstructural changes during shelf-life or when reformulating, and how this can affect cake texture.

6 Summary

Although bread, cake, biscuit and pastry are comprised of the same components, the physical and chemical properties of these ingredients will change depending on processing and baking techniques. By understanding ingredient functionality, the baking method can be used to manipulate the formulation to impart a desired texture, i.e. a short biscuit or a soft bread. The final texture is defined by multiple parameters; therefore, the use of multiple instrumental and sensory techniques can be beneficial to monitor product quality and to create products that deliver unique sensorial experiences.

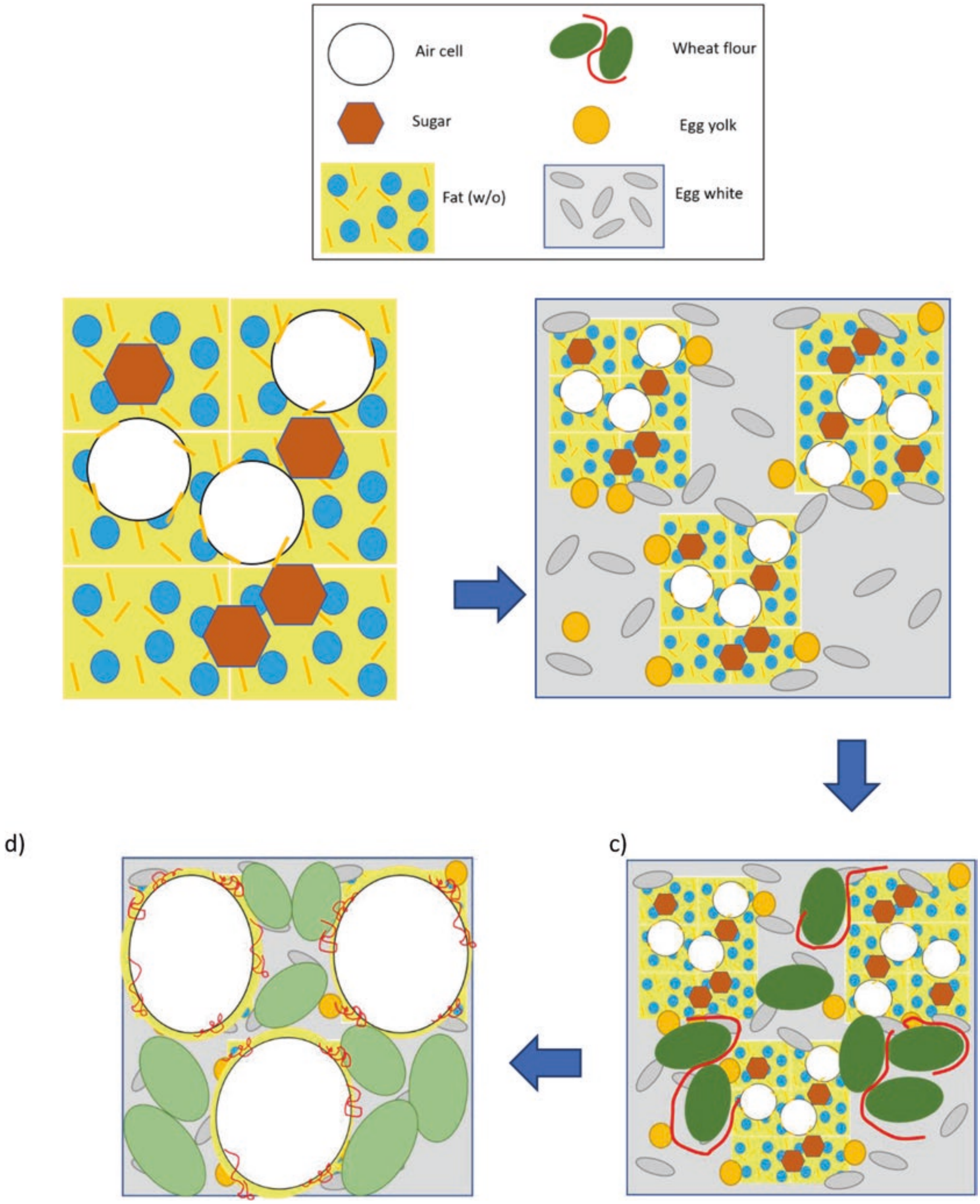

Fig. 5 Schematic representation of (**a**) Creaming process – sugar and fat whisked together to create an aerated sugar and fat system (**b**) Addition of egg – egg proteins disperse through continuous phase (**c**) Addition of flour (**d**) Baking of batter – hydration of flour proteins and starch, fat crystals melt and disperse into continuous phase or adhere to air cell interface, air cells expand, gluten protein allow for expansion, egg proteins coagulate

Table 4 Functionality of cake ingredient during mixing, baking and cooling

		Processing steps			Cake quality
	Process	**Mixing**	**Baking**	**Cooling**	
		Creates homogenous o/w emulsion. Air incorporation.	Rising and formation of foam structure Phase transitions.	Setting of foam structure	
Ingredients	**Protein: Eggs gluten**	Foam stabilisation. Gluten hydrates and contributes to viscosity.	Egg protein coagulates and set to resist further expansion. Gluten forms structure via disulphide bonds.	Aggregated protein network enables foam structure to not collapse	Crumb texture and volume
	Starch	Granules hydrate and contribute to viscosity. Starch contributes to emulsion stability.	Gelatinisation	Starch retrogradation begins and determines staling	Firmness as staling continues Crumb texture
	Fat	Create emulsion and stabilise air cells in foam.	Fat crystals melting reduces batter viscosity. Fat contributes to air cell stabilisation as air expands.	Recrystallisation affects rheology	Flavour Retards staling process
	Sugar	Crystalline sugar enhances foam formation. Dissolved sugar enhances batter viscosity. Sorption behaviour affects protein and starch hydration	Amount affects water availability for starch and protein, therefore glass transition and gelatinisation temperature influenced. Hence, baking time and temperature. Maillard reaction	Affects amylose retrogradation	Affects shelf-life (aw) Flavour Colour Retards staling process

Based on van der Sman and Renzetti (2020)

Table 5 Summary of instrumental measurements used for physical characterisation of cake

Parameter	Method	Description	References
Crumb microstructure	Microscopy, X-ray MicroCT	Microscopy can be used as a qualitative and quantitative method to visualise the structural composition	Hesso et al. (2015a), Rodríguez-García et al. (2012)
Softness/firmness	Texture analysis	Texture analysis can be used as a quality measurement to assess firmness, resilience, adhesiveness, cohesiveness and energy required to deform. This can also be assessed over shelf-life	Díaz-Ramírez et al. (2016), Wilderjans et al. (2008)
Staling (starch retrogradation)	Differential scanning calorimetry X-ray diffraction	Both techniques can be coupled to study the different phenomena occurring during staling	Hesso et al. (2015b), Palier et al. (2022)
Thermal transitions during baking	Differential scanning calorimetry	Phase transitions can be studied across a temperature range	Palier et al. (2022)
Cake batter rheology	Rheometer	Oscillatory frequency sweeps can describe viscoelastic properties of batter that is due to its formulation and hence microstructure	Hesso et al. (2015a), Palier et al. (2022)
Pasting properties of batter	Rapid Visco Analysis	Measures viscosity and pasting properties with continuous mixing across a temperature range	de La Hera et al. (2013)
Specific volume (cm^3/g)	Ratio between cake volume and weight VolScan Profiler	Indicates quality of mixing and incorporation of ingredients A VolScan Profiler	de La Hera et al. (2013)
Specific gravity	$\frac{\text{Weight of batter in a known container}}{\text{Weight of water in the same space container}}$	This ratio measures the amount of air added into cake batter. Indicates aeration and determines if the batter is too dense or not	Oldham et al. (2000)

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Meat and Reformed Meat Products

Siobhan Slayven and Kim Matthews

1 Muscle Structure and Composition

1.1 Muscle Structure

Mammalian skeletal muscle is made up of approximately 90% muscle fibres and 10% connective tissues (Listrat et al., 2016). Connective tissues (primarily collagen) can be categorised as the epimysium, which surrounds each whole muscle; the perimysium, a thinner layer which surrounds bundles of muscle fibres; and the endomysium, a very thin layer which surrounds each muscle fibre.

Muscle fibres are between 10 and 100 μm in diameter and several centimetres in length. The size of fibres increases with animal age (Listrat et al., 2016) and they can extend the whole length of the muscle (Greaser & Pearson, 1999). Muscle fibre cells are multinucleated, with the nuclei located near the periphery. They include organelles called myofibrils which are the sites of force production in the cell. They are not bound by a membrane but exist as an insoluble structure in the living cell. Myofibrils line up in bundles along the length of the muscle fibre and are around 1 to 2μm in diameter. There are approximately 500–1000 myofibrils in a cross section of a mature skeletal muscle fibre, making up around 80% of the cell volume.

Myofibrils have a striated appearance with alternating light and dark bands which are caused by the actin (thin) and myosin (thick) filaments respectively. These are also referred to as the I-band and the A-band (Ertbjerg & Puolanne, 2017). Each I-band is divided into two portions by a Z-line, and the unit between each Z-line is the sarcomere, responsible for contraction (Listrat et al., 2016). The middle of the A-band is less dense, where only thick filaments are located, and is called the H-zone. In the centre of this is a dark line called the M-line which is made up of overlapping thick filaments. Across the length of the thick filaments, there are outward projections which extend toward the thin filaments and are known as cross bridges.

The pattern in which these filaments align varies with location. Thin filaments are arranged in a square pattern near the Z-lines, but in the I-band they appear randomly spaced. Where the filaments overlap in the A-band section, they form a hexagonal pattern with each thick filament surrounded by six thin filaments.

The predominant protein present in the thick filaments is myosin. Myosin molecules are divided into two sections, referred to as the head and the rod (Ertbjerg & Puolanne, 2017). The myosin molecules catalyse the breakdown of adenosine triphosphate (ATP) into adenosine

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diphosphate (ADP) and provide energy for muscle contraction. Thin filaments are made up of actin molecules as well as the additional proteins tropomyosin and the troponins T, I and C, which regulate muscle contraction. Sarcoplasm is the cytoplasm within muscle fibres and contains soluble proteins including enzymes for the glycolytic pathway and myoglobin which carries oxygen to the mitochondria and stains cells red. The sarcoplasm also contains glycogen, the main energy reserve for the muscle cells in addition to adipose (Listrat et al., 2016). Adipose (fat) cells, found in the perimysium and outside of the epimysium, cluster together and form a pattern referred to as 'marbling'.

1.2 Muscle Contraction

Muscle contraction is carried out by the thick and thin filaments sliding past each other. The heads of the myosin bind to actin forming a cross-bridge and pull the filaments over one another. This occurs in a cyclical pattern with the attachment and detachment of these cross-bridges causing the sarcomere to shorten in length. This change in length in the myofilaments is typically less than 0.4% but the degree to which they overlap is increased. For contraction to take place, ATP and calcium ions need to be present. Myosin heads cannot bind to actin unless calcium (released by the sarcoplasmic reticulum) make the binding sites available. This happens in response to a nerve impulse. ATP, produced when glucose proteins are used to produce energy, allows the myosin head to lock into position, bind to the actin and rotate to pull the filament. Another ATP molecule then removes the myosin head and attaches it to another binding site to keep pulling and shortening the muscle.

2 Rigor Mortis

The post-mortem changes that take place as muscle converts to meat can have a marked impact on meat eating quality (Matarneh et al., 2017). Myofibrillar toughness increases early post-mortem, during the onset of rigor mortis (Garmyn et al., 2022). Following exsanguination, the muscles continue to function and anaerobically metabolise glycogen, since there is no oxygenated blood circulating. This means that ATP is still produced, which, when hydrolysed, converts into lactate and hydrogen ions. As there is no mechanism to remove these, the pH of the muscle lowers and becomes more acidic, from around 7 to 5.5. In turn, this causes a reduction in the water-holding capacity and so calcium is released, which encourages the formation of cross-bridges between the actin and myosin filaments and results in stiffening of the muscle, referred to as rigor mortis. The onset of rigor mortis occurs in individual muscle fibres at a time rather than the whole muscle in one go (Honikel, 2014). It also does not occur at the same rate across all muscles (Ertbjerg & Puolanne, 2017) nor across different species. Complete rigor mortis can take 12–24 hours in beef, 8–12 hours in lamb, 3–6 hours in pigs and 1–4 hours in poultry (Greaser & Pearson, 1999).

Typically, in Western countries, meat is allowed to enter rigor and is further aged before consumption. However, in the East, consumers generally prefer eating meat which has not yet entered rigor mortis (known as hot-fresh or pre-rigor) as they associate this with an improved taste (Ge et al., 2021). However, Xiao et al. (2020) found that there was no significant difference in the sensory evaluation of lamb pre- and post-rigor but that there were differences in texture, with pre-rigor muscles having a lower cook loss and post-rigor meat being tougher. Li et al. (2022) further supports this, reporting that pre-rigor goat meat had a better water holding capacity and colour, as well as a richer taste when analysed by the E-nose and E-tongue.

2.1 Abnormal Rigor Mortis

Abnormal rigor patterns can occur due to a change in the acidification of the muscle, caused by pre-slaughter stress. Dark, firm and dry (DFD) meat, or 'dark cutting', occurs when there are not enough glycogen reserves present in the muscle before rigor mortis sets in. This means that the muscles do not metabolise enough lactic acid to lower the pH sufficiently, and the ultimate pH will stay high, at around 6 (Warriss, 2010). DFD usually occurs after a period of chronic stress where the animal has not had time to overcome the depletion of energy and rebuild its glycogen stores. The way in which DFD meat refracts light makes it appear darker in colour, and the lattice of muscle fibres gives the meat a firmer texture and inhibits moisture loss making it 'dry'. Similarly, pale, soft and exudative (PSE) meat also follows an abnormal pH trend following slaughter. This is more typically seen in pork and can follow a period of acute stress (usually within 1 hour prior to slaughter) such as heat stress (Gonzalez-Rivas et al., 2020). The rapid fall in pH while the temperature is still high directly denatures proteins, and there may also be some effect of protein oxidation (Barbut et al., 2008). Although described as soft, this relates to the raw product and, where differences are observed, the cooked meat is generally tougher. PSE meat is lighter in colour and the arrangement of fibres means that more fluid exudes from the meat.

Other abnormal rigor patterns can occur due to intervention in post-slaughter treatments, for example thaw rigor. This is where muscles are frozen pre-rigor and, upon thawing, there is a release of calcium ions which encourage the muscle to contract (Ertbjerg & Puolanne, 2017). As the muscle freezes, ice crystals grow and penetrate the sarcoplasmic reticulum, which, once thawed, provides a rapid surge of calcium ions into the sarcoplasm, faster than the calcium pumps can remove them. Consequently, there is an increase in drip loss and toughness. The toughening of muscles following thaw rigor is much more harsh than that which occurs from cold shortening, which progresses much more slowly (Ertbjerg & Puolanne, 2017). Slower thawing can prevent this contraction taking place, but it can be eliminated by freezing meat only after it has entered full rigor.

3 Influence of Live Animal Factors

Both pre- and post-slaughter factors can affect the sensory properties of meat. When considering texture, however, pre-slaughter treatments generally have a less significant impact than those post-slaughter.

3.1 Effects of Breed and Genetics

Generally, breed has a relatively small effect on tenderness in any species; however, there is within-breed variation in meat texture as evidenced by the growing inclusion of texture traits in genetic evaluations.

In cattle, the most important effect of genotype on eating quality is the toughness observed in beef from cattle of *Bos indicus* (Zebu or Brahmin) breeding (Gazzola et al., 1999; Harper, 1999; Wheeler et al., 2010). This may be the result of greater stability of the proteinase inhibitor calpastatin (Whipple et al., 1990).

Among the *Bos taurus* breeds, results have not been consistent across studies and many show little or no effect, but taken overall, there are small tenderness advantages for Aberdeen Angus and Hereford (Sinclair et al., 2001; Tatum, 2006) which tend to be earlier maturing with more intramuscular fat. On the other hand, cattle sired by a Belgian Blue, a very lean highly muscled breed, have also produced higher tenderness scores than other breeds (Homer et al., 1997; Groth et al., 1999).

Although Dransfield et al. (1979) concluded that breed does not have any effect upon the tenderness of lamb, there is some evidence that hill breeds have more tender meat, and the selection for more heavily muscled sheep can reduce tenderness (Álvarez et al., 2022). Studies on lambs expressing the Callipyge gene have shown the loin to be significantly less tender than lambs without this gene (Koohmaraie et al., 1996). The leg is generally unaffected when roasted, but it can also be tougher when grilled as steaks (Shackelford et al., 1997) but not in every case (Goodson et al., 2001).

Studies with pig meat from the Hampshire and Duroc breeds (Hiner et al., 1965) and the Swedish Landrace and Yorkshire breeds (Malmfors & Nilsson, 1978) suggest that breed differences should be taken into account in evaluation of texture in pork, with breeds which have been less intensively bred for production traits being more tender (and having higher proportions of red muscle fibres (Maltin et al. (1997)). Furthermore, genetic selection of Duroc pigs for lean muscle growth removes the eating quality advantage, with a corresponding shift in muscle fibre type (Lonergan et al., 2001).

3.2 Effects of Fatness

Higher levels of intramuscular fat are associated with improved tenderness (Buchter, 1986; Dikeman, 1987). While this is used in major grading schemes (such as USDA beef grading), there is considerable overlap between grades and the relationship between fatness and tenderness is low according to Campion et al. (1975). Low levels of intramuscular fat are generally associated with low external fat cover, and in some cases, a strong relationship found between intramuscular fat and tenderness may be a result of the insulating effect of the external fat, preventing cold shortening. This was nicely demonstrated in lamb by Smith et al. (1976).

3.3 Influence of Sex

Two extensive reviews (Purchas, 1991; Chrystall, 1994) summarised the effects of sex upon tenderness. Researchers have reported that young bulls cannot be marketed with the same confidence as steers with the same ages. Meat from bulls is generally thought to be tougher than that from steers; however, this is not always found. Sinclair et al. (1998) and Fisher et al. (2001) observed that bulls from a suckler herd had increased tenderness when compared to randomly selected steers or weaned animals, respectively.

Sex differences for texture between castrates and intact male pigs are relatively small, but these comparisons have not been studied as extensively as in beef (Dransfield, 1994). Overall, it can be concluded that, when slaughtered before 12 months of age, ram (uncastrated male), ewe and wether (castrated male) lambs result in meat with similar tenderness. Beyond 12 months there may be a disadvantage to ram lambs (Álvarez et al., 2022).

3.4 Effect of Animal Age and the Role of Connective Tissue

There is clearly an effect of age on tenderness (see the review by Harper (1999)). Prost et al. (1975a, b) examined the tenderness of different muscles from cattle of different ages. Generally, animals of 2–5 years of age resulted in tougher meat than those of 1.5–2 years of age. The *Psoas major* (fillet) did not differ in tenderness and the *Quadriceps femoris* (thick flank) was not significantly different.

It is difficult to separate the effects of age, weight and season in lambs. Generally speaking, older/heavier lambs are tougher (Álvarez et al., 2022). In particular, spring born lambs slaughtered in the autumn/winter are likely to be tougher than those slaughtered in the summer.

The association between increasing age and decreasing tenderness does not seem to be related to an increase in the total presence of connective tissue, but rather an increase in the proportion of heat-stable collagen cross-links (Robins et al., 1973) associated with a decrease in collagen solubility (Gerrard et al., 1987). These heat-stable cross-links are resistant to cooking, thus making the meat tougher (Bailey & Light, 1989).

3.5 Influence of Growth Rate and Plane of Nutrition

Sub-optimal growth rate and nutritional stress increase toughness. Within feedlot systems, finishing cattle on high energy rations (associated with higher growth rate) is found to increase tenderness. This may be a consequence of variable enzyme activity at the time of slaughter (Aberle et al., 1981), or greater collagen solubility (Rompala & Jones, 1984). The effect is not seen across all muscles, mainly benefitting the *Longissimus dorsi* (striploin) (Archile-Contreras et al., 2010).

Others have found that there is a positive effect of growth rate on tenderness within a group of cattle (Perry et al., 2002; Perry & Thompson, 2005) but did not account for differences between groups. This suggests that reducing variation in growth rate within a group might be an important means of reducing tenderness variation, whereas manipulation of growth paths is not guaranteed to enhance tenderness. Oury et al. (2007), however, found that those commercial production systems with the highest plane of nutrition (and younger animals at slaughter) resulted in the most tender meat.

Nutritional stress followed by compensatory growth does not have any adverse effects on meat quality, including tenderness (Hogg et al., 1991).

3.6 Stress Conditions and Pre-slaughter Handling

In addition to the specific muscle quality 'defects' related to stress-induced pH changes (as discussed in Sect. 3.2), there is increasing evidence that stress prior to slaughter can result in tougher meat *per se* (Ferguson & Warner, 2008; Sierra et al., 2021). This may be the result of protein oxidation influencing the activity of enzymes post-slaughter.

There is also evidence that animals with nervous behaviours prior to slaughter result in tougher meat (Gruber et al., 2010), although selection for temperament does not result in more tender meat.

4 Effects of Stunning and Slaughter

Slaughter can be defined as the killing of animals for food, and it is usually instigated or followed by exsanguination (also known as sticking or bleeding) which refers to draining the carcase of blood. Prior to slaughter, animals may undergo a procedure to render them unconscious and ensure they do not feel any pain from slaughter; this is referred to as stunning. 'Simple' stunning causes a temporary effect of senselessness which must be followed by a procedure to kill the animal, but in some cases, stunning is irreversible and the main cause of death. Stunning can also make it safer for the operative to approach the animal to carry out the bleeding procedure. Stunning methods used include the following:

- Electrical head-only or head-to-back tongs (lamb, pigs)
- Electric water bath (poultry)
- Electric stun box with programmed electrical inputs to result in stunning, cardiac arrest (also available without) and immobilisation (cattle)
- Penetrative or non-penetrative captive bolt (cattle, lamb)
- Gas (CO_2) (irreversible) (poultry, pigs)

Depending on the electrical parameters used, electric water baths may induce cardiac arrest and result in death of the animal. Penetrative captive bolt delivers a cartridge shot to the brain which makes recovery difficult.

The process of slaughter itself, as described above, is understood to not have an impact on meat quality. There is, however, some effect of stunning method on the carcase and meat quality. Channon et al. (2003) reported that fewer meat quality defects were seen when using CO_2 rather than electrical stunning with tongs (head only and head-to-back positioning). Blood splash (the rupture of blood capillaries) is also thought to have some correlation to stunning method. Gregory (2005) explains that generalised body contractions which can arise from electrical stunning can cause severe external pressure on the venous and arterial systems which could cause them to rupture.

During religious slaughter practices such as those for the Islamic and Jewish communities, slaughter is often carried out without prior stunning. These procedures are based on rules laid down in the *Holy Quran* and the *Torah*, for Halal and shechita slaughter, respectively. In some instances, Muslim authorities may allow the use of reversible pre-slaughter stunning; however, the Jewish community do not (Fuseini et al., 2016). As animal welfare is still of paramount importance during religious slaughter, scriptures stipulate procedures which must be followed to ensure minimal distress to the animal. For example, the knife used to make the neck cut during Halal slaughter must be sharp, and slaughter must be carried out with one single movement of the knife (Fuseini et al., 2016). The effect of religious slaughter on carcase and meat quality has been widely researched and findings debated. Some findings show that the meat from cattle slaughtered without pre-stunning exhibit a higher ultimate pH (Zurek et al., 2021; Barrasso et al., 2022) which may impact the texture, colour and processing capabilities of the meat.

5 Effects of Post-slaughter Treatments

5.1 Chilling

Carcases should be kept in an environment which has a stable temperature and humidity to help reduce any microbial load from growing (Hussain et al., 2021), which not only deteriorates the meat but also poses risk of foodborne diseases (Ren et al., 2022). Cooling rates vary across different muscles within a carcase (Hannula & Puolanne, 2004) as well as across different species. Sheep, for example, cool quicker than cattle as they are smaller and have a thinner layer of subcutaneous fat (Kannan et al., 2014). The same can be seen within species, whereby animals with less fat cover cool more quickly. Key parameters need to be met for optimal chilling, particularly making sure that there is a good air flow within the chiller and adequate space around carcases to reduce their temperature efficiently.

An important consideration for chilling is the rate at which the pH lowers. It is widely accepted that a beef carcase should not reach 10 °C until the pH has lowered to around 6.1 which takes around 10 hours (Warriss, 2010). This is to avoid any adverse effects, primarily cold shortening, which has been well researched since the 1960s, initially by Locker and Hagyard (1963). This is known as the pH temperature window. Once the pH has fallen below 6.0, the tendency for cold shortening is reduced (Ertbjerg & Puolanne, 2017).

Vieira and Fernández (2014) explored three different speeds to assess the impact on the tenderness of lamb *Longissimus thoracis et lumborum*. They found that a slow chilling regime (carcases held at 12 °C for 7 hours and then 2 °C for 24 hours) gave the highest level of tenderness when compared with a conventional chill (2 °C for 24 hours) or an 'ultra fast' chill (−20 °C for 3.5 hours followed by 2 °C for 24 hours). Unsurprisingly, there was a noticeably shorter sarcomere length following ultra fast chilling.

5.2 Electrical Stimulation

Electrical stimulation is used to help reduce the variability in meat quality between carcases and aims to prevent cold shortening, which can decrease tenderness. The stimulation of muscles increases the rate at which the pH falls post-slaughter and accelerates the onset of rigor mortis, enabling the carcases to be moved through processing quicker. This is useful in commercial plants as carcases are often rapidly chilled and, without the use of electrical stimulation, cold shortening could occur. As well as preventing toughening through cold shortening, electrical stimulation may also increase tenderness through proteolysis, the modification of muscle structure and stretching of the sarcomere (Mikołajczak et al., 2019; Kaur et al., 2021). Further to this, a quicker chill rate following electrical stimulation also leads to a less favourable environment for microorganisms' growth and so an improved shelf life can also be seen (Hussain et al., 2021).

Traditionally, electrical stimulation has been delivered by low and high voltages, typically to carcases as a whole. Low voltage is considered up to 100 V and applied within 5 minutes of exsanguination, whereas high voltage is over 500V and applied up to 60 minutes post-slaughter

(Warriss, 2010). Pearce et al. (2009) discussed the use of medium voltage stimulation whereby the current remains constant and only one carcase is presented at a time, allowing the voltage to vary (peaking at 300V). Maintaining a constant frequency of 15Hz saw a higher number of carcases reaching the required pH temperature window and higher levels of tenderness achieved.

5.3 Carcase Suspension Methods

In most commercial processing plants, carcases are suspended from the Achilles tendon, which extends the hind leg and puts a slight backward bend into the spine. Although this method can work well for carcase processing, the more expensive cuts of meat (in the hind quarters) have a greater opportunity to shorten and therefore a higher chance of being impacted by cold shortening should the correct pH-temperature window not be reached (Pogorzelski et al., 2022). This can be particularly important with beef carcases due to the size and economic impact of these muscles.

Suspending carcases by the hip/pelvis using the aitch-bone allows the muscles in the hind leg and along the back to be stretched during the rigor mortis period, which can help to increase the tenderness and reduce the likelihood of cold shortening occurring in these muscles (Ertbjerg & Puolanne, 2017). In this position, the tenderness of these muscles can be improved by up to 40% (Pogorzelski et al., 2022). Ahnström et al. (2012) also found that hip suspending beef carcases helped to reduce the length of ageing by 7 days with lower shear force values reported. Nian et al. (2018) saw similar results with the tenderness of beef carcases 'accelerated' when using hip suspension. If carcases are suspended for a period of time for ageing, it is also thought that hip suspension would be beneficial to increasing tenderness since the muscles are not so tightly contracted and there is less overlap of the actin and myosin filaments and, therefore, more availability for proteolytic enzymatic activity (Kamatara et al., 2014).

Despite the widely reported advantages to meat quality following hip suspension, there are limitations to its practical application. The shape of the hind quarter muscles changes and so labour and butchery changes need to be accounted for. The overall change of carcase shape may also mean that chiller and storage space is compromised. Nevertheless, it is used commercially in countries across the world, particularly for beef (Pogorzelski et al., 2022).

5.4 Ageing

Following rigor mortis, naturally occurring proteolytic enzymes break down the structure of meat resulting in an increase in tenderness (Kannan et al., 2014). This is seen to rapidly occur between 3 and 7 days in beef (Kim et al., 2018) and can continue up until 28 days post-slaughter. The early tenderisation is mostly due to calpain proteases breaking down the myofibrils and, following this, the intramuscular connective tissues weaken (Kannan et al., 2014). Research also supports the effectiveness of several other enzymes in post-mortem protein degradation (Ertbjerg & Puolanne, 2017), such as caspases. Although ageing may have some impact on lessening the extensive toughness of cold shortening, it is thought that this is limited as the actin and myosin filaments tightly overlap, reducing the availability of proteolytic susceptible sites (Kim et al., 2018). As well as tenderness, the flavour profile of aged meat can change. Proteolysis and lipolysis break down flavourless molecules into smaller fragments which increases the amount of free amino acids (Terjung et al., 2021). Free amino acids are key in the flavour development of meat which occurs during biochemical reactions upon cooking (Zhang et al., 2022).

During ageing, whole carcases or smaller specific cuts (such as ribeye) are stored in controlled refrigerated conditions; air circulation and relative humidity are key for reducing microbial growth during this time. Ageing is typically carried out in one of two ways: wet-ageing or dry-ageing. Through wet-ageing, meat is sealed in a vacuum bag and ageing is carried out anaerobically. This method does not result in too much yield loss (through evaporation or trimming) and is practical for the industry (Zhang et al., 2022). Dry-ageing is carried out aerobically with meat left open to the environment. This creates a unique flavour profile (Kim et al., 2018) which is considered a premium, with flavours being described as buttery, beefy and nutty (Zhang et al., 2022). As there are higher losses in yield, from evaporation and trimming the external discoloured edges, there is often a premium price attached to dry-aged meat. Upon review of dry- and wet-aged beef, Terjung et al. (2021) explain that the tenderness is similar. Semi-permeable dry-ageing bags have been seen to reduce the yield loss in comparison to dry-ageing and also improve the flavour profile when compared to wet-ageing (Dashdorj et al., 2016).

6 Effects of Processing

6.1 Hot-Boning

Removing muscles or sections of meat from the carcase before it has been chilled is referred to as hot-boning. This typically happens around 1 hour post-slaughter (Jose et al., 2020) and before the carcase enters complete rigor mortis. Different muscles cool and enter rigor at different rates and so there is variation in the effects of hot-boning on texture and quality across different muscles. Processing meat in this way can increase the overall yield (due to lower drip losses) as well as save on chiller space in the processing plant. However, due to the shortening of the sarcomere length, meat may increase in toughness and become darker in colour, though this is not seen across all studies and species. Ithurralde et al. (2020) found that hot boning had no impact on the colour of sheep meat. Due to the potential downgrading of quality, hot-boned meat may be used for lower value cuts or meat which is used for ground meat products (Jose et al., 2020). The use of electrical stimulation can impact the rate of glycolysis and the subsequent decline of pH within muscles and can therefore improve the tenderness of hot-boned muscles (Balan et al., 2020).

6.2 Use of Proteolytic Enzymes

Prime cuts often make up a small percentage of a carcase and the remaining cuts may not be favoured for their lack of tenderness. Given the importance of tenderness in eating quality acceptability, mechanisms for improving tenderness can be of great economic importance. Tenderness is often a result of the enzymatic breakdown of muscle fibres which happens, to an extent, naturally (see Sect. 5.4). The addition of enzymes through mechanical methods, such as dipping meat into a solution or injecting a solution directly into the meat, can also help to break down fibres in a similar way and improve tenderness (Gerelt et al., 2000). Research has also shown that the use of proteolytic enzymes can also overcome the toughening effects of cold shortening (Rhodes & Dransfield, 1973), though this was seen through injection of papain pre-slaughter. Some common exogenous proteases are retrieved from plants such as bromelain (pineapple), papain (papaya), ficin (fig), actinidin (kiwi) and zingibain (ginger). Although successful in tenderising meat, bromelain and papain may sometimes give a mushy texture and 'off' flavours (Behkit et al., 2014). The use of actinidin and zinigain have gained more interest in recent years as they have a more mild effect and less detrimental impact on the eating quality than bromelain and papain (Warner et al., 2022). Han et al. (2009) saw that actinidin could contribute 'efficiently and effectively' to meat tenderisation when looking specifically at lamb *Longissmus dorsi*. However, Ramil et al. (2021) found that bromelain from pineapple and jackfruit by-products, used at different concentration combinations, could improve beef tenderisation without impacting quality parameters such as texture and sensory attributes.

6.3 High-Pressure Treatment

In the context of meat processing, hydrostatic pressure is the pressure applied to a product when it is contained within a liquid pressurised in an enclosed container. Interest in high hydrostatic pressure (HHP) treatment of food originally developed because of its potential in preservation. Nevertheless, HHP has some important effects on meat texture, through the rupture and reformation of molecular bonds within and between protein molecules, resulting in protein denaturation, aggregation or gelation (Sun & Holley, 2010). This can lead to meat being toughened or tenderised depending on the duration of treatment and its interaction with other processing conditions (e.g. heat treatment). These effects can be used to enhance properties of conventional products or create new textured products, although the most consistent effects are seen in pre-rigor meat.

6.4 Curing

Meat curing may be defined as the addition of salt to meats for the purpose of preservation (Martin, 2012). Often this also includes the use of nitrates or nitrites to enhance preservation and provide a distinctive colour and flavour. The addition of curing salts without water (dry curing) results in changes to meat texture associated with a loss of water from the muscle (such as Parma ham) producing a unique mouthfeel depending on the curing conditions and resulting moisture content. Many of these products have a low moisture content and are designed to be eaten without cooking. The use of salts in solution generally results in an increased water content and an increase in tenderness, for example, in gammon or cooked hams.

7 Reformed Meat Products

Meat products vary in texture for several reasons: the extent to which comminution (mincing) has been carried out, their ingredients and the formation of structural matrices, usually from the proteinaceous components of meat. Fat is important for the quality of meat products because of its ability to impart specific characteristics (Goutefongea & Dumont, 1990) and, alongside water, the provision of juiciness and tenderness (Rust, 1987).

7.1 The Texture of Coarse-Ground Meat Products

In coarse-ground meat products, the microscopic structure of the muscle tissue is retained, so the inherent texture of the muscle will contribute to overall product texture, and the fat is retained in fat cells or clumps of cells. These have a texture which is described as crumbly. During product manufacture, the texture of the overall product is largely determined by the processing conditions and the ingredients used.

7.1.1 Effect of Processing Conditions on the Texture of Coarse-Ground Meat Products

Various changes to processing affect meat patty properties. More tender (softer) patties can be produced by:

- Reducing the particle size (Roth et al., 1999)
- Using hot-boned beef (Williams et al., 1994)
- Adjusting freezing conditions (Berry, 1993)

If water is added, increasing the grind size has also been shown to improve the cooking characteristics (Hoogenkamp, 1991). Increasing the temperature during comminution of British sausages results in increased cooking losses but a softer texture (Brown & Ledward, 1987).

7.1.2 Effect of Composition on the Texture of Coarse-Ground Meat Products

Reducing the fat content of meat patties and sausages and replacing with lean meat generally reduce their tenderness, juiciness and overall acceptability and increase mealiness and cohesiveness (Cross et al., 1980; Kregel et al., 1986; Troutt et al., 1992; Wong & Maga, 1995).

Added water increases the tenderness and juiciness of meat patties and coarse ground sausages (Nakai et al., 1976; Miller et al., 1993) and can generally be used to enhance the texture of low-fat versions, to the extent that an equivalent or better product can be produced (Frederick et al., 1994). Given the right ionic conditions, the meat protein acts to take up water by swelling to a gel (Hedrick et al., 1994).

A huge variety of ingredients have been tested for their effect on product eating quality and texture. Often these are used to help hold water in the product to provide a softening effect (e.g. when fat content is reduced). Many of these are effective and ingredient selection is dependent on the product, consumer expectations and non-technical factors (such as legislative requirements, price and availability). Some are included to enhance the nutritional properties, such as added fibre (Younis et al., 2022).

Changing the type of fat used as an ingredient, can have an effect on texture. Use of a softer fat has a softening effect, e.g. the use of pork instead of beef fat to soften patties whilst at the same fat content (Parizek et al., 1981).

7.2 Structure of Finely Comminuted Meat Products

Finely comminuted meat products are more properly described as batters or pastes, but are often referred to as emulsions (Ugalde-Benítez, 2012). The most well-known and researched sausage of this type is the frankfurter, a cured emulsion sausage usually prepared with beef and/or pork lean and pork fat with water, seasonings and curing agents. It can, however, be made with meat of any species. The meat content may include mechanically separated or 'reclaimed' meat. Other examples include bologna and wiener (sliceable emulsion products) and knackwurst.

Both the physical entrapment of fat within a protein gel and the emulsification of fat, by coating of droplets with protein, seem important (Barbut, 1995), as does the gelation of salt-soluble proteins on cooking (Comer, 1979). The 'liquid' phase of the emulsion consists of a fine protein matrix, usually formed by actin and myosin from the contractile muscle tissue and supplemented by collagen and added proteinaceous ingredients (such as egg or whey protein). Within this matrix, tiny pores and capillaries entrap added water and fat. The protein within the emulsion forms structural associations such as protein-protein, protein-water and protein-fat interactions. These are responsible for the swelling, gelation and emulsification of meat batters (Schmidt, 1987; Hoogenkamp, 1995).

During processing, ingredients are chopped together to produce an evenly mixed smooth paste prior to cooking. The fat disintegrates in two stages. Initially the fatty tissue disintegrates into natural fat cells. The result of the second stage depends on the hardness of the original fat. If the fat is soft then it results in the production of homogeneously divided particles, each surrounded by a protein membrane. If the fat is hard, then coalescence can occur resulting in separation of the fat ('rendering out'). This can also occur if the myosin:collagen ratio is too low; fat particles coated in collagen rupture on heating, resulting in loss of fat (Pearson & Tauber, 1984). Alleviating this problem is generally achieved by reducing the fat particle size which can be brought about by modifying the processing conditions (Ackerman et al., 1971; Lee et al., 1981).

7.2.1 Effect of Processing Conditions on the Texture of Finely Comminuted Meat Products

The processing conditions are key in determining the texture of emulsion-type meat products. Reducing the chopping time softens the product but reduces overall liking (Lee et al., 1987). Conversely, over-chopping gives rise to a firmer texture due to more protein extraction (Sutton et al., 1995). The optimum chopping time is recipe dependant, with rigid gel formation occurring at a higher chopping temperature in higher fat batters (Barbut & Mittal, 1989). The final temperature produced by chopping affects product texture and emulsion stability (Hensley et al., 1993; Sutton et al., 1993; Jiménez Colmenero et al., 1996).

The order of addition of the ingredients to the batter is also a determinant of final product texture, for example massaging the lean with the added water before adding the fat has resulted in a firmer product (Sylvia et al., 1994).

Other manipulations of the processing conditions that have been shown to modify the product texture include the following:

- Subjecting meat batters to hyperbaric pressure (1000–2000 bar) which increases firmness of meat batters (Mandava et al., 1984).
- Cooking at a high relative humidity that results in softer frankfurters (Simon et al., 1965).
- Higher final cooking temperatures resulting in a harder, more brittle frank. The minima for cohesiveness and elasticity occur at around 70–75 °C (Singh et al., 1985).
- Increasing particle size (by varying mincing plates) to increase hardness of batter products (Small et al., 1995).

7.2.2 Effect of Composition on the Texture of Finely Comminuted Meat Products

Salt concentration needs to be optimised for each recipe as it is important for the extraction of myofibrillar proteins in the formation of emulsions which has an influence on product texture. Reducing the concentration will result in reduced hardness or firmness (Matulis et al., 1995). If lower salt concentrations are required for optimum flavour, then protein extraction may become a problem. This could be resolved by adding all the salt to the lean meat, to achieve extraction before the other ingredients are added (Jantawat & Carpenter, 1989).

As with patties, reducing the fat content and replacing with lean results in a tougher, drier, less acceptable product with little or no change in flavour (Hand et al., 1987; El-Magali et al., 1995). It is not the type of fat but simply its presence that is primarily important in frankfurter texture (Mandigo & Eilert, 1993). Indeed vegetable fats can be used with little or no effect on product texture (Marquez et al., 1989; Christensen & Zeuthen, 1994). Increased levels of fat result in a more diffuse gel which is therefore weaker and so contributes to the softness and juiciness of emulsion type sausages.

The addition of water to products (at rates up to 30% of the formulation) has been found to have similar effects on texture to that of fat (Claus & Hunt, 1991; Hensley & Hand, 1995). The product becomes softer and more juicy. Water cannot, however, be exchanged for fat on a one for one basis. The effect of water seems to be more extreme than fat due to greater disruption of the protein matrix (Gregg et al., 1993; Hensley & Hand, 1995).

Non-meat proteins can be used to strengthen the protein matrix of low-fat emulsion-type sausages, to give a firmer texture (Ensor et al., 1987). Successful results have been achieved with whey protein concentrate, calcium reduced non-fat dry milk and soy protein isolate (Sofas & Allen, 1977; Decker et al., 1986; Ensor et al., 1987; Yang et al., 1995). On the other hand, low-binding meats such as heart or mechanically separated poultry meat can be used to soften the texture (Rongey & Bratzler, 1966).

The acceptability of product texture can be subjective, yet there are optimum textural attributes which must be determined for each individual product, with its target consumer in mind (Carballo et al., 1995).

8 Measurement of Texture in Meat and Meat Products

8.1 Sensory Methods

Sensory attributes can be measured using objective (instrument or trained taste panel) or subjective (consumer taste panel) methods. Trained taste panels can identify a range of characteristics based on requirements. Panels first work together to discuss definitions of traits such as 'tenderness', as this can have a different meaning to different people (Warner et al., 2021). Once decided, samples are cooked and prepared away from the panel so as not to influence their senses, and they judge each in a blind trial.

The method for sensory assessment of reformed meat products is similar to that used for whole cuts, evaluating aspects such as tenderness, juiciness and flavour. To further define differences in product attributes, sensory profiling has been used. In most cases, this involves panelling with scores being given for a wider range of attributes, pre-determined by the experimenter. In some cases, free choice profiling is used with panellists nominating the attributes needed to fully describe the product and a short list being drawn up by consensus.

Szczesniak (1963) proposed a terminology and definitions, which would allow sensory profiling and instrumental assessment to be directly comparable. This is described in Sect. 8.3 on methods to assess the textural properties of meat products.

8.2 Instrumental Assessment of Meat Cuts

An early developed method for instrumentally assessing meat texture is the Warner-Bratzler shear force test; K.F. Warner and associates established the idea of shearing a cooked sample of meat as an indication of tenderness, and L.J. Bratzler outlined the specifics of the blade and cutting speed. This is still one of the most widely used tests today due to its repeatability and correlation with consumer sensory ratings (Silva et al., 2015). One of the most important factors to consider when carrying out shear force work is the orientation of the muscle fibres within the cores to be sampled (Wheeler et al., 1997). It is key to ensure that the fibres run perpendicular to the blade so that the maximum force can be measured. Silva et al. (2015) explored the effectiveness of using cuboidal/square cores as opposed to the traditionally used round cores. The experiment showed that square cores give more accurate and sensitive results which are more like the differences seen between steaks which are judged by a taste panel. This work supported the findings of a smaller study earlier performed by Thiel et al. (1997). Holman et al. (2015) found that six cuboidal cores is the minimum number required to attain reliable results whilst still allowing trials to be repeatable; any more than this only saw negligible improvements in error.

Secondary to the fibre direction, the cooking method can have a significant impact on the results of shear force and standardised protocols can reduce variability and improve the repeatability. Methods of direct heat source, such as griddle plate, tend to cook beef samples quicker and give lower shear force values compared to oven cooking with low humidity and high temperatures (Fabre et al., 2018).

8.3 Assessment Methods Used for the Textural Properties of Meat Products

The most important factor in comparing meat products with altered formulations or processing conditions is acceptability to the consumer. However, because the textural properties of meat products are difficult to define, their assessment is quite complicated and a large number of methods have been used (Schreuders et al., 2021).

Szczesniak (1963) proposed the following terminology and definitions, which corresponds to the most common usage. Many researchers, however, use their own terms, often without defining them.

Hardness	The force required to give a certain deformation.
Cohesiveness	The strength of the internal bonds making up the body of the product.
Viscosity	The rate of flow per unit force (not relevant to cooked meat products).
Elasticity	The rate at which a deformed material goes back to its undeformed condition after the deforming force is removed.
Adhesiveness	The work necessary to overcome the attractive forces between the surface of the food and the surface of other materials with which the food comes in contact.
Brittleness	The force with which the material fractures. It is related to hardness and cohesiveness. In brittle materials, cohesiveness is low and hardness can vary from low to high.

Chewiness	The energy required to masticate a solid food product to a state ready for swallowing. It is related to the parameters of hardness, cohesiveness and elasticity (the second definition of chewiness given under the mechanical assessment of attributes below).
Gumminess	The energy required to disintegrate a semisolid food product to a state ready for swallowing. It is related to the parameters of hardness and cohesiveness.

Various mechanical measurements are used to quantify product texture. Essentially, these are either compression or punch methods. Compression equipment uses a flat plunger to push into the product to a fixed proportion (usually 75–80%) of its original height twice. The parameters are taken from a force/time curve as follows (Friedman et al., 1963; Bourne, 1978; Beilken et al., 1990; Xiong et al., 1995):

Fracturability[a] or brittleness	The force at the first significant break in the curve (may not always occur before peak force).
Fracturability[a]	The differential between the first and second peaks.
Hardness (H)	Force used to achieve the initial penetration.
Cohesiveness (C) or degree of breakdown	Ratio of work done on the first penetration to that on the second (positive area under curve). The areas can also be considered separately as first and second bite area.
Gumminess or chewiness[a]	H × C.
Elasticity (E) or springiness	Measured as the distance from the start of the curve to contact with the sample at the start of the second compression expressed as a ratio against the same measurement for an inelastic substance (e.g. clay). Alternatively, a simpler but less valid method is to measure the height the food recovers between the end of the first cycle of compression and the start of the next.
Chewiness[a]	H × C × E.
Adhesiveness	Negative force required to pull the plunger away from the sample

[a]Alternative definitions

It should be noted that measurement results vary slightly with the instrument being used due to differences in the rate of compression and the flexibility of the instrument. Brittleness and adhesiveness never occur in the same food product according to Friedman et al. (1963).

9 Summary

In writing this chapter, some areas have recent research or reviews which have been drawn upon, and in other areas, the science is well established and little new information is available. The texture of meat is influenced by many factors, ranging from animal type, through slaughter and processing, to post-slaughter treatments and processes. Reformed meat product texture is largely determined by the ingredients used and the processing conditions applied. Methods for assessing quality, and in particular texture, have been described.

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Texture of Fish and Fish Products

Xiuping Dong

1 Introduction

Fish plays an important role in the human diet because it is nutritious and easy to digest. It contains a variety of nutrients such as high-quality protein, amino acids, polyunsaturated fatty acids, vitamins, and minerals. In addition, fish has low cholesterol and saturated fat content (Ben Atitallah et al., 2019). As a superior source of protein, fish is important for ensuring global food security. The consumption of fish products is gradually increasing as consumers learn about the health benefits of fish (Thilsted et al., 2016).

Stabilization and regulation of the quality of fish and fish products are very important in promoting the development of the fish industry. The consumption quality of fish and fish products depends largely on their textural properties (Nollet & Toldrá, 2010). Textural parameters are frequently employed to examine and evaluate fish quality along the fish value chain by measuring the impact of handling and processing methods on the shelf life of fish products and the partiality and satisfaction of consumers (Cheng et al., 2014).

The texture of fish can be affected by many factors (Nollet & Toldrá, 2010). It has been confirmed that storage temperature during the handling and operating process generally has a distinct effect on fish textural properties (Lin et al., 2022). Fish texture is influenced by many interacting factors including physical factors (species, age and size, feeding ingredients, sample heterogeneity, and gaping), chemical factors (water content and distribution, fat content and distribution, and collagen content), and diverse treatments (storage time and temperature, freezing, chilling, salting, pickling, and fermentation) (Cheng et al., 2014; Grethe Hyldig & Nielsen, 2007).

Understanding the mechanisms by which physicochemical factors and processing conditions affect the textural properties of fish can help in the design of appropriate handling procedures, which are a prerequisite for maintaining or creating the best eating quality of fish and fish products. Therefore, this chapter starts by considering the measurement of fish texture, with special reference to sensory texture and analytical texture. This is followed by a brief description of the textural properties of fish and the factors influencing them, with a focus on the textural properties of different fish products. The study of the formation mechanism of fish product texture is considered together with its influencing factors in enabling us to identify new potential methods to improve fish product texture (Fig. 1). Finally, the chapter will conclude by assessing where there may be key deficiencies in our understanding of

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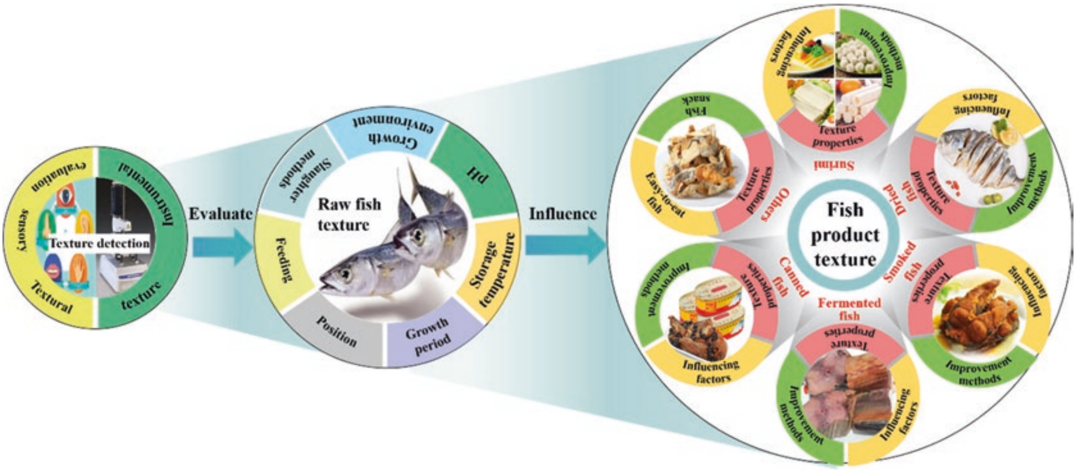

Fig. 1 Textural properties of raw fish and fish products

fish texture, influencing factors, and improvement methods, and offer suggested areas of research.

2 Key Detection Techniques for Texture of Fish and Fish Products

The detection methods of texture are of great significance for evaluating and regulating the effect of textural properties on the quality of fish and fish products. Sensory evaluation and instrument methods are currently the most commonly used to assess the textural properties of fish and fish products.

2.1 Sensory Evaluation of Texture

Sensory evaluation is a systematic method used to evaluate the appearance, odor, flavor, and texture of food, and can also be used to evaluate the impact of changes in raw materials, processing, packaging, and storage on the quality of fish and fish products, and verify the acceptability and preferences of consumers (Meilgaard et al., 2016). Fish companies rely on experienced experts for product quality control and the development of processed products. Currently, sensory evaluation is the most widely used and effective method to evaluate the texture of fish and fish products in the fish supply chain (Fig. 2) (Huang et al., 2021).

Sensory evaluation is used as a means for both quality control and consumer assessment of the product, thus aiding in the improvement of end-product quality (Huang et al., 2021). For texture evaluation of fish and fish products, the industry usually uses the "finger method" to measure the degree of firmness of raw fish fillets, which determines suitability for further processing. This method consists of simply pressing the skin or fillet with a finger, and so depends heavily on the subjective assessment of a panel of experts.

The catch damage index (CDi) and processed fish damage index (PFDi) are widely used for the evaluation of the appearance and texture of fish during the harvesting session (Esaiassen et al., 2013, 2004). The CDi, originally developed by Esaiassen et al. (2013), focuses on assessing the vital status and visible damage of the fish. Digre et al. (2016) further modified the CDi by adding scoring criteria for gear damage, pressure injuries, and blood trauma (eyes, skin, gills, and fins). However, it is difficult to assess internal textural damage within the fillet with the CDi. The PFDi remedies this (Savina et al., 2016).

Several specialized schemes for the sensory evaluation of fish have been put forward and include the spoilage test, the palatability test

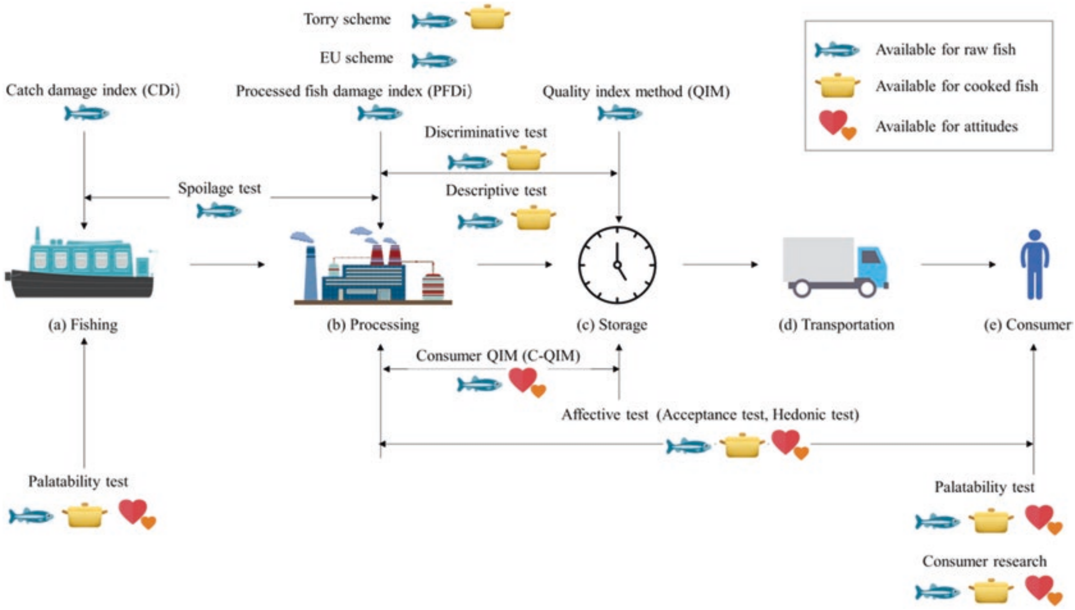

Fig. 2 A macroscopic view of the range of applications of sensory evaluation methods for fish and fish products. (Huang et al., 2021)

(Stansby, 1951; Stansby & Lemon, 1941), the Torry scheme (Keay, 2001; Martinsdottir et al., 2009), the EU scheme (Aubourg et al., 2004), and the quality index method (QIM) (Bremner, 1985). It is worth noting that these methods are comprehensive in assessing fish sensory attributes, measuring texture as well as flavor and appearance. This is because multiple sensory attributes contribute to the overall quality, making it impossible to assess the overall quality from one specific attribute alone. Currently, the popular QIM for improving sensory evaluation with different scores indicating the firmness and freshness quality of fish have been implemented in several European countries (Tiyo de Godoy et al., 2019). To add information on consumer attitudes, the consumer quality index (C-QIM) can be seen as an extension of the QIM method (Hyldig & Larsen, 2003).

In addition, some generic types of sensory evaluation methods, classified by test types such as the discrimination test, descriptive test, and affective test, have also been applied to the assessment of the textural attributes of fish (Lawless & Heymann, 2010).

2.2 Instrumental Evaluation of Texture

In contrast to sensory evaluation, instrumental analysis methods for texture measurement can reduce the variability of human factors during measurement (Casas et al., 2006). The most common methods used to analyse fish and fish products are the Kramer or Warner-Braztler shear cell, puncture, tensile and compression tests, such as texture profile analysis (TPA). The selection of the type of test and operating conditions depends on the material and purpose of the study, within the restrictions imposed by the geometry, structure, and fragility of the fish and fish products.

The Kramer test is performed using a Kramer shear-compression cell. The parameters usually measured include the maximum force per sample weight, slope, and energy of the force-deformation curve. Although in the laboratory a highly linear relationship between maximum force and sample weight has been shown for surimi, this cannot be found with fillets. Thus, as suggested based on food products other than fish, it is advisable to use a constant weight of sample for the analysis (Bourne, 2002).

The Warner-Bratzler test is performed with a single V-notched blade, with the two cutting edges set at an angle of 60° and penetrating the specimen holder through a slot. Usually, the parameter measured is the maximum force exerted during the shearing. There are several methods similar to the Warner-Bratzler test, for example a fish shearing device which consists of a blade, that cuts the sample as it traverses a rectangular or circular channel (Chamberlain et al., 1993).

In the case of a puncture test, a plunger is pushed into the fish sample. The sample size should be much larger than the punch, otherwise there is a risk of compressing the fillet against the support plate, in which case the test becomes a combination of puncture and compression, or even full compression (Bourne, 2002). The "punch and die test" is a variation of the puncture test, suitable for cases when the sample is thin (Segars et al., 1975). The parameters measured are maximum shear stress, stiffness, and strain at failure. The puncture test is the most popular gel measurement technique used in the industry for evaluating surimi quality.

For the tension analysis test, samples are made into striped or dumbbell shape. This is achieved by holding the sample with two clamps, one of which is fixed, while the other moves away at a constant speed. The measured parameters are maximum force or tensile strength and energy. The force deformation curves can be corrected to a true stress-strain relationship. The overall stiffness and the hardening index can be calculated from the constant and slope of the linear curve (Kuo et al., 1990).

Compression analysis is performed by applying a uniaxial compression force, generally, between two parallel flat surfaces. For a true compression test, the probe should be much larger than the sample. From the force-deformation curves, the slope, degree of deformation produced by a set force, and energy calculated by the area under the force-deformation curve can be calculated (Barroso et al., 1998). As in other tests, the force-time curves can be transformed into true stress-strain relationships (Johnson et al., 1980). For fish fillets, the authors proposed the use of a compressive deformability modulus derived from the true stress-strain relationships, which is representative of a material's overall resistance to deformation.

Texture profile analysis is an imitative test in which the sample is compressed twice, mimicking the action of the jaw. The force-deformation curve is analyzed to determine the texture parameters, five measured and two calculated originally defined as hardness, cohesiveness, elasticity, adhesiveness, brittleness, chewiness, and gumminess (Bourne, 2002). Texture profile analysis is frequently used to determine the textural properties of fish and fish products, including surimi gels, fillets, and whole fish. Though widely used, TPA has been criticized by several researchers (Nishinari et al., 2019; Peleg, 2019). This detection method also has some limitations. First, the detection results of TPA attributes depend on the size of the sample. Changes in sample size and geometric shape may lead to changes in objective measurement values. For example, for samples with irregular shapes such as peas and nuts, pressure cannot be so easily defined (Nishinari et al., 2019). Second, the detection conditions of TPA attributes are arbitrary, and the shape of the probe and the set deformation conditions will significantly affect the size of TPA values. Third, the same texture attributes may appear in samples with different attributes, such as ripe juicy fruits and some soft cheeses. In this case, the description of the texture attributes of samples may not conform to the actual situation.

The structure of fish is very important with respect to the textural properties of fish. Microscopy has been widely used as an effective measurement tool to control and detect changes in the musculature and microstructure of fish. Kelly et al. (1966) used microscope to observe the optical density of the fish muscle cells homogenate, which was treated under freezing conditions to observe the degree of cell fragility and to get index according to certain calculation methods. The low reading showed that the muscle is soft and the high reading indicated that the muscle is hard to chew. This method is called the cell fragility method. Two types of microscopes are used for the determination of food texture structure: optical microscope and electron microscope (James & Smith, 2009). Optical microscopy is the simplest and most efficient way to obtain magnified images of muscle tissue and can describe the structure of meat and meat products (Damez & Clerjon, 2008). The use of electron microscopy can illuminate specimens and produce magnified images and provide greater resolution capabilities than optical microscopy. Common methods for investigating and detecting external and internal structures are mainly related to transmission electron microscopy, scanning electron microscopy (Tunick, 2011), confocal laser scanning microscopy (Hickey et al., 2015), and environmental scanning electron microscopy (Olson, 2017).

Clearly there are a wide range of instrumental methods available to analyze the texture of fish and fish products. For those products in which the integrity and complex structure of the fish muscle must be maintained, there are some restrictions on the suitability of the tests. Except for quality control, in which there is a need to perform simple and fast tests, most applications require a combination of more than one method.

3 Textural Properties of Raw Fish

The texture of raw fish is characterized by softness, tenderness, diversity, and variability. The muscle tissue of fish is fibrous, as with livestock and poultry, but it is softer and more delicate than that of livestock, likely because it has a low ratio of myostromin and a high ratio of myofibrillar protein. This difference is largely related to the structural morphology, protein composition, and biochemical characteristics of fish muscle.

The wide variety of edible fish species, numbering in the hundreds, provides a diversity of textural properties to fish. For example, when fresh fish is consumed as Sashimi, texture of the muscles is one of the most important factors that determine the quality of Sashimi. Hardness of the fish muscles differs from species to species. At the stage of consumption, dark-meat fish such as tuna became soft and then the fish is served as thick slice. On the other hand, white-meat fish such as flounder and puff fish are quite tough and their muscles are served as very thin slices. Such difference in the thickness of the fish muscles gives them a characteristic texture. Even in the same fish species, there are many factors including season, fishing ground, fishing season, and the fish's physiological state that can affect textural properties, which is why they are characterized by variability (Aussanasuwannakul et al., 2010; Cheng et al., 2014).

3.1 Factors Influencing the Textural Properties of Raw Fish

The texture of raw fish is influenced by many factors, including the growth environment, pH, storage temperature, growth period of fish, position, feeding, and slaughter methods (Dunajski, 1980; Grethe Hyldig & Nielsen, 2007; Johnston, 1999).

3.1.1 Growth Environment

The textural properties of fish are affected by capture seasons, which may be related to changes in nutritional status. In temperate waters, the fish food varies with the seasons. From late spring to early autumn, when food is more abundant, fish grow quickly and accumulate more body fat, resulting in a fatty and tender taste. However, in other seasons, when fish food is scarce, fish consume lipids from their livers for energy for metabolism. In the late winter, when food is particularly scarce, fish consume protein from their tissue to meet the needs of gonad development. As a result, fish are lean in late winter and early spring, with low protein and a high-water content. The texture of such fish is very soft and sometimes has a "rotten" taste.

The temperature and flow rate of the water also affect the texture of the raw fish. During the maturation stage of fish growth, the temperature changes by a few degrees Celsius, and the muscle fiber count can increase by up to 20%. The change in fiber density is sufficient to affect muscle texture. Lin et al. (2022) simulated the effect of different temperatures on zebrafish (*Danio rerio*) muscle tissue and found that the lower the temperature, the stronger the collagen deposition, making the fish denser and firmer. The flow velocity and the presence of turbulent eddies in different waters directly affect the swimming movement of fish. Longer duration or increased speed of swimming motion results in decreased muscle fiber diameter and increased muscle fiber density, and the overall effect is an increased hardness of the fish (Li et al., 2014).

3.1.2 pH

The texture of fish is strongly influenced by pH. After death, glycogen in the muscle is catalyzed by enzymes, producing lactic acid which accumulates, causing a decrease in pH. The acidity of the muscle after death depends on the glycogen content of the fish before death, which is related to fish physiology, nutritional status, the way in which the fish are killed, struggling before death, and other factors. Glycogen depletion caused by struggling before death will lead to higher pH in the muscles after death. Fish with low pH have hard, dry, or even tough textures, while fish with high pH tend to be soft, juicy, and tender.

3.1.3 Storage Temperature

Storage temperature can influence biochemical reactions, endogenous enzymes, and microorganisms that affect the texture of fish, and consequently the storage temperature has an important effect on the textural properties of raw fish. Frozen or unfrozen water has differing effects on the textural properties of frozen (and subsequently thawed) raw fish. The effect of freezing temperatures has contrasting effects on the textural properties of fish. Lowering the storage temperature can enhance in fish hardness caused by biochemical reactions (e.g., protein oxidation), enzymatic proteolysis by endogenous enzymes, and microbial growth and reproduction. On the other hand, lowering the temperature can lead to the formation of ice crystals that destroy muscle tissues, resulting in a decreased water retention in muscle with decreased elasticity and hardness. Therefore, when preserving raw fish, the appropriate storage temperature should be selected according to the expected use of the raw fish.

For products such as raw fish fillets, avoiding the destruction of muscle tissue by ice crystals. Ice crystals is desired and, cold storage (0–4 °C) is often used. As storage time increases, autolysis due to protease and lipase hydrolysis can reduce the hardness of the fish. Cold storage has a short shelf life due to the inevitable action of microorganisms and enzymes. Currently, the most commonly used method of long-term preservation is frozen storage (the central temperature of the fish is below –15°C). Compared with other preservation methods, freezing can inhibit more microbial activity. However, ice crystals expand by approximately 9% compared to the volume of free water, which causes irreversible mechanical damage to the muscle structure. The formation of ice crystals is the main reason for the softening of fish (Yang et al., 2019).

Another factor affecting the texture of fish is repeated freeze-thaw cycles caused by ambient temperature fluctuations (−30 °C to −6 °C), which may seriously deteriorate the texture of frozen foods (Cao et al., 2022a, b; Kaewthong et al., 2019). The main causes of fish texture deterioration during freeze-thaw cycles include ice crystal formation, microstructural changes, and protein denaturation (Jiang et al., 2019). In addition, the enlargement of ice crystals due to recrystallization can further damage fish tissue (Manay & Shadaksharaswamy, 2001).

3.1.4 Life Cycle

Fish in different growth stages have different textural properties. Generally speaking, older fish are firmer than young fish. In addition, the texture of fish during special growth periods can change significantly, especially the texture of female fish before and after spawning.

Nutrient and energy requirements to reach sexual maturity affect nutrition composition in many fish species, which directly affects texture. In sexually mature females, the hardness of raw fish decreases and the texture gradually weakens 3–4 months before spawning, which may be related to the accumulation of nutrients (especially fat) before spawning. The embedding of fat cells in the peri-muscular connective tissue destroys the mechanical strength of the muscle layer, making the fish's muscle tissue softer. During spawning, the hardness of raw fish increases. This may be because the high production of insoluble collagen improves muscle extensibility, increasing the hardness of the fish. At the late stage of spawning (after 16 weeks), the texture of the fish gradually recovers, despite the fat continuing to accumulate. Many edible fish have poor textures after sexual maturity, so they require rearing for a certain period so that the muscle can return to an acceptable texture quality (Ahongo et al., 2022).

3.1.5 Anatomic Position

Muscle fat distribution and storage patterns result in differences in softness and hardness. In general, the stored fat in the fish abdomen is significantly higher than that in the back of the fish. The softest tissues are the belly flap and myosepta composed mainly of adipocytes, followed by red muscles, which are not dominated by adipocytes, and finally the white muscles. The dorsal, lateral and ventral areas are made up mainly of white muscle with very little fat, so these are the parts of the flesh with the toughest texture (Nanton et al., 2007).

3.1.6 Diet

Food sources and nutrients are important factors, contributing to muscle fiber characteristics.

Appropriate dietary carbohydrate levels can improve fish growth performance while reducing protein and lipid catabolism (Ren et al., 2011). It has also been determined that an increase in dietary carbohydrates significantly affects the hardness and sticky of the back muscles of black sea bream (*Acanthopagrus schlegelii*) (Li et al., 2014). Higher dietary carbohydrate levels (19%) were found to enhance the flesh maximal strength of gilthead sea bream (*Sparus aura*ta) muscle (Li et al., 2017). A study by Jiahuan Liu et al. (2020) found that muscle pH, fluid retention, and hardness decreased significantly with increasing dietary carbohydrate levels.

Changes in dietary protein levels can also lead to relative changes in the size and total quantity of muscle fibers, which will influence the texture of fish (Valente et al., 2016). Using TPA, Pavón et al. (2018) found that the addition of concentrated beef protein during the feeding increased the hardness, chewiness, and deformation modulus of the fish muscle, but had little effect on muscle cohesiveness. This is because a high protein diet increases alkaline and sulfur amino acids, causing a lower n-6/n-3 fatty acid ratio. In addition, some researchers have also found that rearing fish with cottonseed protein concentrate as a dietary substitute can affect the amino acid composition of muscle, inhibit lipogenesis, and promote lipolysis, thereby increasing the hardness of fish (Wu et al., 2022). Furthermore, studies have found that a dietary addition of hydroxyproline can alter muscle texture by affecting the collagen synthesis, enhancing the structural characteristics of muscle and increasing the diameter and density of muscle fibers (Cao et al., 2022a, b).

Changes in muscle fiber diameter and quantity can also be achieved by adjusting the supply of an amino acid in the fish's diet (Aguiar et al., 2005). An increase in serine content may be closely related to differences in the hardness of fish flesh (Li et al., 2009). Histidine varies greatly before and after spawning and migration of fish, which leads to a change in fish texture. Adding histidine to the feed increases the pH value of muscle and reduces the formation of muscle space after fish death, giving muscle an ideal taste and texture (Frde-Skjrvik et al., 2006).

Dietary fat intake can influence adipocyte size leading to changes in white muscle composition and texture (Cruz-Garcia et al., 2011). Adding dietary essential oils to the feed can reduce the carbonylation of specific myofibrils and sarcoplasmic proteins. It also increases the stability of actin, while maintaining the muscle solubility and water holding capacity; furthermore, it reduces muscle softening during freezing (Santos et al., 2019).

In addition to the major nutrients discussed above, certain other dietary supplements can influence the size and quantity of fish muscle fibers (Ramos-Pinto et al., 2019), leading to an impact on the texture of fish (Wei et al., 2018). For example, the addition of glycol monolaurate can increase the content of crude fat in fish flesh, reducing the diameter of muscle fibers, leading to a significant change in the cohesion of muscle tissue, which manifests in a decrease in the hardness and chewiness (Wang et al., 2022). Addition of olive leaf powder to fish feed can increase the content of myofibril and acid-soluble collagen, resulting in a more rigid endocardium structure and a harder muscle texture (Arsyad et al., 2018).

3.1.7 Slaughter Methods

Slaughter method can result in a stress response that leads to an increase in lactic acid in the fish with a decrease in pH. Such metabolic acidosis accelerates the onset and intensity of muscle hardness (after rigor mortis). Current slaughter methods include sudden ice death, electroshock, carbon dioxide anesthesia, percussion, and stabbing. Mochizuki (1998) found that fish killed instantaneously had delayed muscle softening and a higher degree of muscle cracking (gaping) compared to fish killed by decapitation. Sigholt et al. (1997) found that stresses on farmed salmon before slaughter resulted in fillet softening. It is notable that bloodletting removes enzymes from the fish, which delays the softening of the flesh (Ando et al., 2001). Ogata et al. (2016) showed that neck-breaking resulted in a slower rate of stiffening than other means of slaughter.

Einen and Thomassen (1998) showed that prolonged starvation (86 days) reduced the hardness of fish, slightly altering the texture of salmon fillets (Einen & Thomassen, 1998).

4 Texture of Fish Products

Texture analyses are important in the research, quality control, and product development. Different textural properties are desirable for various fish products. For example, surimi products require good gel strength, while easy-to-eat food requires a soft texture. The textural properties of fish products are affected by factors such as raw materials, processing technology, exogenous additives, and heat treatment. Understanding the mechanisms and influential factors on structure and texture development of various fish products will be conducive to regulating their unique textural properties of specific products.

4.1 Surimi and Surimi Products

Surimi is a myofibrillar fish protein concentrate obtained by successive washing and mixing with cryoprotectant before storage (Kong et al., 2016). Surimi products with specific elasticity are produced from fresh or frozen surimi by flavoring, forming, and heating. Typical surimi products include fish cakes, fish balls, and crab sticks. Its textural properties, including gel strength and TPA parameters such as hardness, springiness, etc., as well as shear force, are often used to evaluate the quality and consumer acceptance of surimi products (Chen et al., 2022).

4.1.1 The Formation Mechanism of Surimi Products

The formation of surimi gel is divided into three processes: suwari, modori, and kamaboko (Fig. 3). Suwari (0–50 °C) refers to the loosening (denaturation) of the advanced structure of actinomycin molecules during heating, and the protein molecules in turn aggregate with each other through electrostatic interactions, hydrogen bonding, ionic bonding, hydrophobic interactions, disulfide bonding, and non-disulfide covalent bonding to form a stable three-dimensional mesh structure. During the suwari process, the myofibrillar protein solution is transformed into a gel, and a three-dimensional network is formed, but the gel structure is weak with poor elasticity.

Modori (50–70 °C) is caused by endogenous protease (such as serine protease, cathepsin B, cathepsin H, and cathepsin L) (Hu et al., 2012; Huan Liu et al., 2008; Zhang et al., 2022, 2022), which disrupts the network of actomyosin molecules. The result is a soft gel, with a reduction in the textural properties of surimi gels. Therefore, this temperature range is often avoided during surimi production to avoid gel deterioration. Modori is generally considered to be a problem during surimi production.

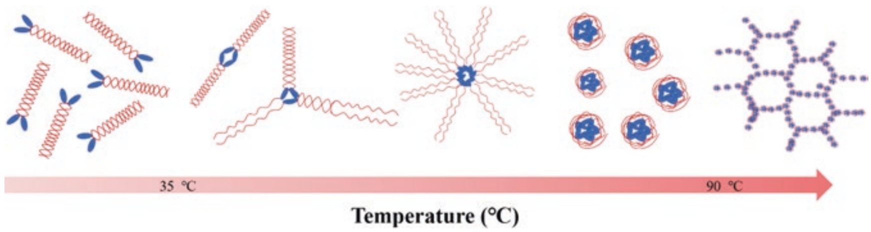

Fig. 3 The formation process of surimi gel

Kamaboko (>70 °C) results in the gel network becoming dense and ordered with an increase in temperature, and the gel strength and elasticity increase significantly. Therefore, in order to obtain good gel properties, a two-step method of heating at 40 °C for 1 h and 90 °C for 30 min is often used.

4.1.2 Factors Influencing the Textural Properties of Surimi Products

Many factors can affect the textural properties of surimi products, including the quality of the raw fish, processing methods, and exogenous additives.

4.1.2.1 Raw Fish Quality

Raw fish species (Luo et al., 2001), pH (Du et al., 2021; Zhou & Yang, 2019), and freshness (Benjakul et al., 2003; Chen et al., 2020) can all affect the texture of surimi. The elasticity of surimi products produced from different fish species varies due to differences in muscle protein composition. In general, red-fleshed fish have weaker gel strength than white-fleshed fish; freshwater fish have weaker gel strength than saltwater fish, and cartilaginous fish have weaker gel strength than hard-boned fish. The pH and fish freshness also have an important influence on the gel strength of surimi. The isoelectric point pI of fish myofibrillar proteins is 5.2–5.5, which means that the gel formed from fish in this range is the least elastic. When the raw fish pH is 6.5–7.5, molecular bonds are easily formed between protein molecules, which promotes the formation of network structure and blocks free water, at which point elastic gels are formed. Therefore, it is necessary to adjust the pH value to produce surimi products. The muscle pH value of fish is almost neutral at the moment of fresh capture, and its gel strength is high, but as freshness declines, it decreases with a reduction in pH.

4.1.2.2 Processing Methods

Gel strength is greatly affected by rinsing and heating the fish during the processing of surimi products. Rinsing removes enzymes that prevent the gelation and active substances that induce gel deterioration, while correspondingly increasing the concentration of salt-soluble proteins that play a major role in the formation of surimi gel (Liu et al., 2021; Zhang et al., 2022, 2022). In addition, rinsing can remove some of the multivalent metal ions that promote freezing denaturation of proteins, thus increasing the elasticity of the surimi.

Generally, lengthy low-temperature gelation makes the gel strength of the surimi better than short-term high-temperature gelation. Yet, too low a temperature will prolong the production cycle; therefore, a two-stage heating method is often adopted to increase the gel strength of the products. In addition, there are many other heating methods for surimi products, including steaming, boiling, roasting, and frying. The gel strength of surimi heated by different heating methods varies, and the specific method used depends on the type and requirements of the end product (Luo et al., 2022).

4.1.2.3 Exogenous Additives

Exogenous additives such as salt, antifreeze, and gel enhancers are often added to surimi during production to improve gel strength. Adding salt to surimi promotes the dissolution of salt-soluble proteins, improving gel formation and enhancing its elasticity (Tahergorabi & Jaczynski, 2012).

Theoretically, adding more salt (>12%) prior to precipitation helps in the dissolution of salt-soluble protein, yet most people's tolerance for salt is only around 3%. In general, salt, in the range of 2.5%–3.5% of the total weight of the product, is added to the production of surimi products.

Freezing and storage of fish often leads to freeze denaturation of proteins, which reduces gel strength. As a result, freeze denaturants and elasticity enhancers are always added during the production of surimi and surimi products (Walayat et al., 2022). Commonly used agents to prevent freeze denaturation and elasticity enhancers include sugars such as sucrose or sorbitol, polymeric phosphate, glutamine aminotransferase, and alkaline amino acids.

4.1.3 Methods to Improve the Textural Properties of Surimi Products

Raw fish quality, processing methods, and exogenous additives are factors influencing the textural properties of surimi (Guo et al., 2018; Monto et al., 2021). It is difficult to control the quality of raw fish, so the textural properties of surimi are normally improved by adding exogenous additives by modifying the processing methods.

4.1.3.1 Exogenous Additives

Some antifreeze agents, water retention agents, protease inhibitors, and cross-linking agents are often added to the surimi to improve the gel.

The myofibrillar proteins in frozen surimi often undergo degeneration during storage, which results in the weakening of the gel strength (Zhou et al., 2006). Stabilization of these proteins during frozen storage is key to producing adequate surimi gels. Therefore, antifreeze is added to maintain the functional attributes (e.g., gelation and water holding capacity) of myofibrillar proteins and to prevent structural changes in the surimi (Walayat et al., 2021). Sucrose and sorbitol are the most commonly used cryoprotectants individually and in combination with other agents such as polyphosphates, whey protein concentrate, and egg white protein (Walayat et al., 2022). Chen et al. (2020) found that the addition of sucrose and sorbitol into common carp surimi significantly reduced the loss of textural properties by inhibiting the oxidation and protein denaturation after five freeze-thaw cycles.

Polysaccharides are also often used to enhance the gel strength of fish surimi due to their good water retention. The polysaccharides commonly used in fish surimi production are starch and hydrocolloid. Starch can be used as a filler in surimi gel to improve its elasticity (Haimei Liu et al., 2014). During heating, the gelatinized starch is wrapped in the surimi gel network structure, which increases the attraction between the starch granules, making the network structure more compact and increasing the gel's elasticity strength. The improvement of the surimi gel depends mainly on the size of the starch molecules and the amylopectin content. Li et al. (2022) found that surimi with a high straight chain starch additive tended to form brittle gels, while highly branched starches tended to form sticky surimi gels. In addition, the strength of surimi gels with nano-starch is greater than that of surimi gels with added micro-starch (Peleg, 2019).

Hydrocolloids are also often used to improve the strength of surimi gels because of their good water retention. The hydrocolloids commonly used in the processing of surimi products include konjac gum, carrageenan, and xanthan gum (Walayat et al., 2022). Each hydrocolloid has its own different structure, resulting in different effects on the surimi gel strength. Suitable hydrocolloids should be selected according to the anticipated end product.

Chen et al. (2020) investigated the effect of adding various quantities of curdlan, xanthan gum, κ-carrageenan, and gelatin at various concentrations on the gel properties and protein conformation of surimi from silver carp. They found that the addition of curdlan, κ-carrageenan, or gelatin at a lower levels could significantly promote the gel strength, textural profiles, and water-holding capacity. Jianhua Liu et al. (2019) added konjac oligo-glucomannan to suppress the decrease in the gel strength of red gurnard

(*Aspitrigla cuculus*) surimi during frozen storage (−18 °C for 50 days).

The modori is an inevitable problem in surimi production. Non-muscle proteins such as bovine serum albumin, whey protein concentrate, pig serum albumin, soy protein isolate, and egg white have been used as inhibitors that can prevent the activity of cysteine and serine proteases in surimi. In addition, they improve gel properties of surimi by cross-linking with myofibrillar proteins and reduce myofibrillar protein degradation. Of these inhibitors, the best one is pig serum albumin which, through the "trap mechanism," inhibits the activity (Morrissey et al., 1993). In addition, soy protein isolates and egg white proteins have excellent gel properties, which can form a good network with myofibrillar protein during heating, thus enhancing the gel strength of surimi.

Transglutaminase (TGase) is often used as a cross-linking agent to improve the strength of surimi gels. This is because TGase can catalyze the reaction of the γ-carboxamide group with a primary amine. This reaction catalyzes the mutual cross-linking of myofibrillar protein and the formation of uniform dense three-dimensional network structure, which in turn improve gel strength (Dong et al., 2020).

Researchers investigated the effects of microbial TGase on the gel-forming properties of frozen-stored longtail southern cod surimi at different incubation temperatures (35 °C, 40 °C, 45 °C, 50 °C). They found that the gel strength of surimi supplemented with 300 U/kg TGase had the highest gel strength when incubated at 35 °C for 2 h (Yang et al., 2020; Zhang et al., 2021).

4.1.3.2 Improving Processing Methods

New processing techniques such as microwave and ohmic heating as well as 3D printing are being investigated to improve the gel properties of surimi products.

Microwave heating is now widely used to improve the gel strength of surimi products because microwaves can quickly cross the modori temperature range and inhibit cathepsin activity, thus reducing the degradation of myofibrillar by proteases (Cao et al., 2019, 2020). Cao et al. (2018) found that using microwave heating instead of a second water bath heating improved the gel strength of the fish surimi.

Ohmic heating, by passing an electric current through a conductive food, produces more even temperature distribution compared to traditional water bath or steam heating processes. This enables ohmic heating to achieve greater uniformity and the desired textural properties throughout the surimi (Fowler & Park, 2015). Park et al. (2014) found that ohmic heating rapidly denatured myofibrillar proteins, thus greatly improving the gel strength of pollock. Compared with water bath heating, ohmic heating can improve the elastic modulus and hardness of surimi products (Choi, 2006).

3D printing is a new intelligent molding technology that can be utilized to achieve products of special texture such as the filamentous structure of meat analogues (Kim et al., 2021). By changing the filling structure during 3D printing, we can manipulate the hardness, gel strength, and resistance to shear of surimi, thus enabling the development of special foods for the elderly, infants, and young children suffering from dysphagia to meet their special textural needs. Yu et al. (2022) studied the 3D printability of *Hypophthalmichthys molitrix*-sea cucumbers compound surimi gel. The results showed that κ-carrageenan could improve the quality and 3D printability of compound surimi gel.

4.2 Dried Fish Products

There are many types of dried fish products, the common types include stockfish (unsalted fish, dried by cold air and wind on wooden racks on the foreshore), clipfish (salted for 2-3 weeks, and then dried), karuvadu (sun-dried), and so on. Regardless of the type of dried fish generally have to go through the drying and dehydration process. Drying removes water from the food matrix. Drying is achieved by radiation, convective heating, conduction and other methods, and when a critical moisture level is reached, it inhibits the activity of enzymes and the growth of microorganisms, and also imparts unique textural properties to dried fish products (Zhang et al., 2017). The drying rate directly affects the texture of dried products. With rapid drying rate, the surface dries faster than the core, resulting in a hardened appearance and increased product hardness. An excessive drying rate can lead to dry cracking of the product (Gulati & Datta, 2015). The drying rate is influenced by transfer mechanisms, such as the vapor pressures of the food and the drying air, temperature and air velocity, moisture diffusion in the product, thickness, and surface exposed for drying (Guiné, 2018; Gulati & Datta, 2015). It has been found that case-hardening is particularly enhanced with higher drying temperatures, higher air velocities in the drying chamber, and lower relative humidity of the surrounding air.

4.2.1 Methods to Improve the Textural Properties of Dried Fish

The manufacturing process of dried fish products can be controlled by selecting suitable drying methods to control the vapor pressure, temperature, air velocity, and moisture diffusion in food and dry air, which in turn regulate the textural properties of the dried products (Guiné, 2018). Sun drying is the traditional way of drying fish products, but it is difficult to control the quality of sun-dried products because of the weather (Cheng et al., 2021). To improve drying efficiency and product quality, new drying methods such as freeze drying, microwave drying (Wang et al., 2013), infra-red drying, and multistage drying methods have been applied in the production of dried fish.

4.2.2 Freeze Drying

Freeze-dried fish products are made by removing water from prefrozen fish through the sublimation of ice crystals under high vacuum conditions. Because freeze-dried fish is frozen before dehydration, a stable solid skeleton is formed, which is maintained after dehydration, and a porous sponge-like structure can be formed, resulting in a crispy texture. In addition, because the material is frozen in advance, the original inorganic salt solute dissolved in water is fixed; therefore, the surface hardening phenomenon caused by solute migration does not occur during dehydration. In addition, the freeze-dried product also has a more elastic texture due to less damage to the muscle structure of the fish. However, the equipment used in freeze-drying is relatively expensive; therefore, freeze-drying technology is often limited to the drying of high-quality products.

4.2.3 Microwave Drying

Microwave drying is achieved by the evaporation of moisture from food products through the heat generated when the microwaves irradiate and penetrate food (Lenaerts et al., 2018). Heating during microwave drying occurs simultaneously throughout the food; therefore, surface hardening and uneven heating are avoided.

Compared to traditional convective drying, microwave drying has the advantages of volumetric heating and reduced processing time. While it may cause overheating of particles and the undesired degradation of bioactive compounds, its use in a vacuum significantly prevents quality degradation of heat-sensitive materials. However, microwave drying has the disadvantages of high-power consumption and high drying cost. In production, hot air drying and microwave drying can be combined to reduce costs and improve the quality of dried products.

4.2.4 Infrared Drying

When food absorbs infrared rays, atoms and molecules vibrate, generating heat which results in evaporation. During the infrared drying process, the temperature inside the food is higher than outside because the infrared rays penetrate the tissues, allowing heat to accumulate inside the food, while the moisture on the surface continues to evaporate and dissipate the heat. The result is that both water and heat migrate outward from the interior, accelerating the drying process without undesirable structural changes, which improves the product texture.

4.2.5 Multistage Drying

In recent years, multistage drying technologies such as hot air microwave drying and microwave-assisted freeze drying have gradually emerged.

Qin et al. (2020) compared the quality of grass carp fillets after microwave-hot air multistage drying with hot air drying. They found that this process produced better product than hot air drying alone.

In general, multistage drying methods can improve the texture of dried fish products, produce higher quality products than single-stage drying methods, and are more energy efficient.

4.3 Smoked Fish Products

Smoked fish is produced from fresh raw fish through a process of salt curing and smoking, which imparts flavor and increases temperature dehydration during the smoking process (Hagos, 2021). Divergent textural properties are related to the hardening of fish caused by smoke drying and the softening of fish caused by autolysis. Compared to fresh fish, heat-smoked fish is harder, and some studies have shown that smoked fish requires greater force to penetrate than fresh fish after freezing and thawing (Zotos et al., 1995).

4.3.1 Factors Influencing the Textural Properties of Smoked Fish

Understanding the factors affecting the texture properties of smoked fish products is important for regulating the quality of smoking fish products. The quality of smoked fish depends on the raw materials, pretreatment, and method of smoking (Belichovska et al., 2019).

4.3.1.1 Raw Materials

The quality of the raw fish is an important factor affecting the texture of smoked products. Smoked products prepared from frozen fish have poor (TPA) adhesion and cohesion, which can be attributed to the reduced water holding capacity of the fish and altered fish tissue due to ice crystals and protein denaturation occurring during freezing (Puke & Galoburda, 2020). In addition, the texture of smoked fish is related to the nutritional composition of the raw fish. It has been shown that the hardness of smoked fish is inversely proportional to the fat content of the raw fish. This may be due to the release of free fat during chewing, resulting in a reduction in the hardness of the smoked fish (Robb et al., 2002).

4.3.1.2 Pretreatment Methods

Curing the raw fish before smoking is usually done by brine soaking, which reduces the water activity and pH value of the raw fish to obtain smoked fish products with better sensory and texture properties. The hardness of smoked fish products increases after curing with 10% salt alone or in combination with 75% salt and 25% calcium chloride (Dhanapal et al., 2011). In addition, a reduction in pH during the curing process results in a softer texture of the smoked fish product, but too low a pH denatures the proteins, increasing the hardness, suggesting that soaking the fish in a 10% salt concentration for 60 min results in a better texture (Dhanapal et al., 2013; Jimenez Lugo et al., 2020).

4.3.1.3 Smoking Methods

The temperature of the smoking chamber classifies the process as cold, warm, or hot smoking. Liquid smoke is also used in the manufacture of smoked fish (Stołyhwo & Sikorski, 2005). Different smoking methods yield differently textured smoked fish products. Cod smoking, where the temperature range of the smokehouse is 12–25 °C, is a light preservation process that involves curing, drying, and smoking. Compared to hot-smoked fish, cold-smoked fish has a firmer texture and lower water content (Dhanapal et al., 2013). Salmon trout, herring, cod, and Okhotsk atka mackerel (*Pleurogrammus azonus*) are often processed into cold-smoked products.

For warm smoking, the temperature range of the smokehouse is relatively high, ranging from 30 to 50 °C. At these temperatures, fat melts and is lost while some proteins coagulate due to the heat, and the resulting texture of smoked products is slightly hard. Warm smoking methods are mainly suitable for salmon, trout, swordfish, and sardines, etc. For hot smoking, the temperature range of the smoke chamber is up to 120–140 °C. The high smoking temperature coagulates almost all of the protein, and the surface hardness of the product is high. However, the product contains more water inside resulting in an elastic product.

Liquid smoking of fish involves immersing the fish in a liquid smoking fluid for a period of time, followed by drying. Drying usually facilitates the formation of slightly hardened surface; however, the high internal water content results in an elastic product.

4.3.2 Methods to Improve the Textural Properties of Smoked Fish

Each of the smoking methods has its own advantages and limitations. At present, the use of a combination of smoking methods to improve the texture of smoked fish has gradually received people's attention. Researchers found that the use of heat steaming combined with smoking reduces the excessive hardness of the smoked fish (Tirtawijaya et al., 2020). One study found that smoked fish produced at 160 °C had the softest and least acceptable texture, while smoked fish products produced using a combination of cold and hot smoking processes had higher sensory scores for appearance and texture (Deng et al., 1974). It has also been shown that adding sugar for dry curing before immersion in liquid smoke reduces the hardness and elasticity of smoked fish products (Sampels, 2015).

4.4 Fermented Fish Products

Fermented fish products are made from fish after curing, microbial fermentation, and other steps. The products include liquid fermented products (such as fish sauce), whole fish fermented products (such as enzymatic spiced fish), and fermented fish surimi products (such as fermented fish sausage).

TPA parameters (hardness, cohesiveness, chewiness, and so on) and gel strength are often used to evaluate fermented fish products' texture (Xu et al., 2021). The formation of the texture of fermented fish products is a very complex process. During the fermentation process, the muscle is taut due to salt infiltration and water loss, which increases the hardness of the product. Endogenous protease and collagenase can hydrolyze myofibrillar protein, leading to a decrease in the products' hardness. Salt infiltration, water loss, salt content, and the balance of fermented juice control the speed of the cohesiveness of fermented fish products. Fermentation results in the degradation of myofibrillar protein, which increases the hydrophilic groups and water-holding capacity leading to an increase in the adhesion strength of fermented fish products (Xu et al., 2021; Yang et al., 2017).

Gel formation often occurs during the fermentation of fish products, which increases the hardness, elasticity and cohesiveness of muscle proteins through denaturation (Riebroy et al., 2008a, Visessanguan et al., 2004). Gel formation is mainly caused by microbial fermentation producing weak acids (Xu et al., 2021). Lower pH causes continuous conformational changes in the protein, which, together with charge changes, are sufficient to form a network. The progression of fermentation results in a Surimi gel network due to hydrophobic interactions, disulphide bonds and non-disulphide covalent bonds. Hydrophobic interactions are particularly important in the early stages of gel formation. In later stages, many disulfide bonds are formed, which strengthen the gel network. The heavy chain of myosin is the major protein component of fermented surimi gels, but actin and other low molecular weight proteins (produced by proteolysis) are also involved in the formation of the gel network.

4.4.1 Factors Influencing Textural Properties of Fermented Fish Products

The factors influencing the texture of fermented fish products include the microorganisms, fermentation temperature, ionic strength, and endogenous enzyme activity. During fermentation, microorganisms have the main influence on the texture (Xu et al., 2021). Under the action of microorganisms, the pH value of fish muscle decreases, which affects the activity of endogenous and microbial enzymes. In fermented fish products, structural changes in proteins (denaturation and aggregation) affect the elasticity, cohesiveness, and hardness (Riebroy et al., 2008b).

Inoculation and natural fermentation have different effects on the texture of fermented fish products. For example, compared with naturally fermented fish products, inoculated fermented fish products present more obvious sensory fermentation characteristics and the meat is softer and more palatable (Gallart-Jornet et al., 2007). In addition, the texture of fermented fish products depends on the inoculum, for example, the surimi inoculated with lactic acid bacteria has increased the cohesion and better hardness, while yeast inoculation results in greater chewiness and springiness (Wang et al., 2013).

The fermentation temperature also has a great influence on the texture of fermented fish products. Higher fermentation temperature results in intense protein degradation, thereby softening and improving the texture of fish which had previously been dried (Cao et al., 2019). While a high temperature can shorten the fermentation time, it is necessary to add lot of salt which can result in a poorly controlled process. Moreover, it can give rise to a product with red flesh, high salt content, poor flavor, and heavy odor. Consequently, lower temperature fermentation is preferred.

The ionic strength is an important factor affecting the textural properties of fermented fish. The ionic strength has a significant effect on acid-induced structural changes, aggregation, and the gelation properties of fish myofibrils. Increasing the ionic strength can increase the partial unfolding of the protein, resulting in more active groups on the protein surface. This conformational change promotes the interaction of protein molecules during acidification.

The endogenous enzymes also have an important effect on the quality of fermented fish products. Highly active endogenous TGase catalyzes the formation of ε-(γ-glutamine)-lysine bonds, which can increase the gel strength of fish products. In contrast, endogenous cysteine proteases such as cathepsins B, L and H and aspartic proteases affect gel strength during gelation because they can cleave hydrophobic amino residues, reducing hydrophobic interactions (Fang Yang et al., 2016).

4.5 Canned Fish Products

Canned fish is a ready-to-eat product made from fresh or frozen fish after processing, filling in can, adding oil, water or brine (to aid heat transfer) and seasonings, sealing, and sterilisation. The shelf life of canned fish is extended by preventing contamination and oxidation by exhaust sealing (Horner, 1997). The fish generally has a softer texture as it is exposed to two heating processes (precooking and sterilization). Moreover, the high-pressure heating causes a decrease in the hardness of fish bone matrix (Wijayanti et al., 2021). Therefore, fish used in canning requires dense organization and moderate hardness, so that texture of the final product can reflect the quality of the canned product (Littleton, 2010). The pretreatment of the raw materials and sterilization can both influence the texture of the canned fish.

Most canned fish products are produced from frozen fish, which needs to be thawed before processing. The thawing methods can affect the texture of the fish. If the thawing time is too long, it will cause the growth and reproduction of microorganisms, accelerate the oxidation and decomposition through the action of proteases, and cause a softening of canned fish. Short thawing time will cause high drip with associated loss of nutrients, affecting the freshness and palatability of fish. In general, air or water thawing is used, with the method and degree of thawing depending on raw material characteristics, process requirements and other factors (Cai et al., 2020). In addition, the curing process also has an important effect on the texture properties of canned fish. During salting, the hardness of the fish tissue increases due to the osmotic dehydration of the brine, which benefits the preheating process and canning (Wijayanti et al., 2021).

Preheating can be undertaken by streaming, firing, or smoking (after salting), which can affect the texture of canned fish. Preheating removes some of the water, denatures the protein, compacts the muscle tissue, and gives the product a certain hardness. Because canned products can be stored for a long time and require high moisture control of raw materials, the pretreatment of raw fish is particularly important. TPA elasticity, cohesiveness, chewiness, and recovery of the products obtained by the superheated steam dehydration were significantly higher than those obtained by deep-frying. In addition, adding some additives to the fish during the preheating process can improve the texture properties of the canned product. Jung et al. (2020) found that the addition of corn to the canned surimi reduced the hardness and cohesiveness. It has been shown that the addition of peas to canned tuna will improve the hardness, chewiness, elasticity, and sensory properties (Mohan et al., 2013). Tangke et al. (2021) found that increasing the tuna bone meal ratio resulted in a stronger and thicker texture for canned tuna porridge.

To ensure that canned products have a long shelf-life, thermal processing must be carried out correctly. Fish are rich in protein, fat, and other nutrients which during heat sterilization will degrade, affecting the textural properties of canned fish. Currently, the main sterilization methods for canned foods are traditional steam sterilization and pressure-assisted thermal sterilization. The higher temperature and longer heating time of steam sterilisation is beneficial for inactivating microorganisms, but can result in overcooked fish products, resulting in a soft product texture. Pressure-assisted thermal processing kills micro-organisms, can pasteurise starches and can denature proteins to form gels. Moreover, it changes the flavor and texture compared to thermal sterilization. Therefore, there is a need to select suitable sterilization conditions according to the product characteristics during the canned fish production process (Balasubramaniam, 2021).

4.6 Other Products

4.6.1 Easy-to-Eat Fish Products

Easy-to-eat fish products are an important food source for people with swallowing difficulties, such as the elderly, infants, and post-surgical patients (Sukkar et al., 2018). Easy-to-eat fish products require texture modification to control changes in the state of food during swallowing; adjust the viscosity of liquid food; and eliminate heterogeneous, oversized, and reduced fibrous food to avoid the risk of choking (Sungsinchai et al., 2019). Colloid mills apply intense shearing forces, which can reduce the particle size of products to the micrometer range (Li et al., 2016; Vishwanathan et al., 2011). Subjecting steamed fish to a colloid mill created pastes that met the requirements of the level 4 of the International Dysphagia Diet Standardisation Initiative framework (Xie et al., 2021).

Similarly, the reduced particle size achieved by homogenization allowed particle-particle interactions and promoted protein cross-linking, forming a cod protein gel of much lower strength than those of ordinary surimi products (Xie et al., 2022). In addition, the 3D printing not only increased the hedonic value of sturgeon paste (improve appearance) but also created the textural characteristics of layer-by-layer stacking.

4.6.2 Fish Snack Products

Snack foods are a category of fast-moving consumer goods which people eat during leisure and rest. The current fish snack foods include fish fillets, fried fish skin, and fish crackers. The variety of texture properties, taste, and flavor of these snack foods creates a strong market.

The fish fillet is made by cutting the fish body, removing the skin and bones for further processing. This food comes in a variety of forms, including frozen, marinated, and dried fish fillets. Joshy et al. (2020) used air frying technology to improve the fish fillet creation process. The hardness of fish fillets increased with the increase of frying time, decreased with the increase of frying temperature, and the elasticity increased with the frying time. The fried fish skin is a snack with a strong Asian flavor. Fang et al. (2021) adopted lower frying temperatures and a longer frying period to obtain good product texture for fried fish skin.

Recently, researchers combined fish with accessories and side dishes to develop fish crackers that are easy to chew and digest, which are deeply loved by the elderly and children. The hardness and fracture ability of biscuits decreased as the proportion of sturgeon fillet powder increased and slightly decreased compared to the control biscuit (Abraha et al., 2018). However, the addition of Bombay duck fishmeal to extruded biscuits increased their hardness (Chakraborty et al., 2020).

5 Conclusion

Texture measurement and evaluations for fish and fish products are significant factors in freshness quality control and assurance, as well as product development in the seafood industry. The formation mechanisms and influencing factors on the texture properties related to fish and fish products are reviewed in this chapter, and methods to improve the texture properties of fish products are proposed. This study can be used to improve the regulation of texture properties during the raw fish circulation and the processing of fish products.

Both sensory and instrumental methods can be used to measure fish texture. Although fish texture can be measured and evaluated through sensory and instrumental methods, it is difficult to agree on which is the best method, and there is no single method universally accepted and applied in the fish and fish product industry. Computer vision and spectroscopy are potential innovative methods for nondestructive and online measurements of fish texture and structure.

This chapter describes in detail the textural characteristics of raw fish and the factors affecting them. It also discusses the control of processing and storage and distribution conditions of raw fish to regulate its texture and make it more palatable for consumption through further processing. However, due to the uncertainty of fishing and the difficulty of controlling the environment of breeding waters, it is very difficult to control the quality and texture of raw fish consistently. We can only reduce the fluctuation in the texture of raw fish by choosing the appropriate treatment and storage methods.

This chapter also provides a better understanding of the basic scientific principles underlying the formation of the various textures of different processed fish products and the factors that have an impact on those textures, providing a solid foundation for further texture research and the regulation of fish products. Despite the vast amount of knowledge associated with the production of fish products, it is still not possible to guarantee high quality fish products. In fact, the texture of a quality fish product lies in the control of the ingredients and processing methods used to produce that fish product, with a complex range of potential influences.

Several techniques for the texture modification of fish products have emerged in the past decades to enhance the texture properties of fish products, reinforce the special texture properties of fish products, and meet the needs of those consumers who have difficulty consuming normal foods. This area has attracted much attention currently from both academic and industrial researchers due to its relevance to the fundamental understanding of formation mechanism and the influencing factors resulting in fish's special texture and the growing requirements of industrial applications. However, many improved technologies (such as 3D printing, ohmic heating, infrared, microwave, and other technologies) are currently in the laboratory research stage, and their application and promotion still require the efforts of researchers and enterprises.

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Texture of Dairy Products

Mike Lewis

1 Introduction

This chapter aims to provide an overview and practical guide for both measuring and using data related to the rheology and texture of milk and milk products. Worldwide, well over 500 billion litres of cow milk is produced every year, as well as lesser but significant amounts of milk from other species, the main ones being buffalo, goat and sheep.

In the UK, almost 50% of raw milk produced is consumed as liquid milk, about 30% goes into cheese production, 10% into milk powder and the remaining 10 % into a wide range of other products. These products have very different rheological properties to liquid milk.

This breakdown will be different in every country. For example, Ireland and New Zealand consume about 10% and 2% of their total milk production as liquid milk and are well known as large exporters of dairy products. Also in the UK, milk production is about the same all year round, but in Ireland and New Zealand, where seasonal calving is practiced, the amounts produced are very different from month to month. Some of the largest users of milk may actually be short of milk, for example China and India.

Strictly speaking, food texture is a sensory characteristic and as such be evaluated by individuals rather than by instruments. Sensory analysis can be time-consuming and instrumental measurements will reduce the time taken and are thus widely used for routine texture evaluation of dairy products. Furthermore, there are good correlations between instrumental and sensory perception of viscosity, for example, see Conti-Silva et al. (2018).

Consumers have expectations about the foods they eat. For example, milk should be rich and creamy, butter should be smooth and melt steadily (Sect. 2.5.2), and every individual cheese will have its own texture and flavour characteristics (Sect. 2.5). Skim milk is seen by many to be a healthier option, but it is watery; however, skim milk products are now available which have a creamier mouthfeel. Semi-skim milk has increased in popularity and the process of homogenisation helps to increase perceived creaminess. Cheese whey is green, watery and unappealing as a product, yet the protein can be concentrated by ultrafiltration and microparticulation and can be used to replace fat. Manufacturers of dairy products have to understand what the consumer requires and produce products that consistently match these kinds of expectations.

There are some important challenges faced by the milk producer and processor which may impinge on obtaining the rheological and textural characteristics that are required. The first

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challenge is that raw milk is perishable and should be processed as soon as possible after milking. Freshly expressed milk is sterile and warm and is usually chilled as quickly as possible and kept chilled until processed further. However, this is not always possible; for example, in warm climates the lactoperoxidase system (FAO, 2005) can be activated to prolong keeping quality. The impact of the lactoperoxidase system on the texture of milk products has not been investigated.

The second challenge arises from the complex chemical composition of milk and its biological variability. Food composition tables are useful, but they report average values and ignore the fact that every batch of milk will be different. There are wide variations in both fat content and protein content, which are likely to have the greatest impact on rheological properties. For example, through 2022, milk fat in UK milk ranged between 4.05% and 4.38% and milk protein between 3.29 and 3.47%, reaching record highs in November and December. To appreciate the chemical complexity of milk, the database and detailed tables provided by Foroutan et al. (2019) should be consulted. The mineral content is important, as is the important role of Ca and P in terms of holding the casein micelle together.

The third challenge comes from a need to produce a uniform end-product that matches the consumers requirements. In textural terms, we are talking about achieving a uniform mouthfeel, texture profile as well as understanding and controlling the rheological properties that affect product texture.

Additionally, milk also has a diverse microbiological flora and there are 60 indigenous enzymes. Some of these and especially proteases will breakdown milk protein which will again affect its rheology.

Other challenges come from the environmental lobby in terms of the perceived negative environmental issues associated with milk production and processing. Issues such as reducing greenhouse gas emissions, water utilisation and energy and waste are being addressed in a very positive manner (Dairy Road Map, 2018). The reality of the situation is that milk provides excellent value in terms of its carbon footprint as probably the most nutritiously dense food type that contains all the nutrients needed to sustain life. No plant-based food can make this claim. Table 1 shows an overview of the milk products discussed in this chapter.

1.1 Introduction to Rheological Properties of Milk

Rheology is the study of the deformation of materials, subjected to applied forces. A thorough understanding of rheology as a quality attribute is essential to the development of dairy products. Texture is a leading factor in consumer preference and is directly related to the rheological properties and microstructure of the product.

We would recognise milk as a low viscosity fluid, but it can be used to make products which embrace the entire rheological spectra, from fluid to solid. Milk products are also produced in powder form.

In addition to the impact of milk viscosity on mouthfeel, practical applications of viscosity measurement include pressure drop calculations, determining whether flow is streamline or turbulent, pump selection when transporting such fluids and for predicting heat transfer rates and residence time distributions. Such data can be used for monitoring certain production processes. As we move into a more digital era, many of the processes will be monitored on-line and in real time.

For quality assurance, measuring rheological properties of dairy products is important for evaluation of texture. For many products the aim is to produce certain rheological properties which fall between defined limits, outside which may lead to the consumer finding the product unacceptable. Examples will be given throughout the text.

1.2 Milk Viscosity

SI units have now become common; however, viscosity values are still often recorded as centipoise (cP), where 1 cP = 1 mPa.s. Water has a viscosity of 1.002 mPa.s at 20 °C.

Table 1 Overview of milk products

Product	Variants	Textural defects	How rheology is assessed
Milk	Whole milk or standardised to different fat and protein contents	Watery; those related to fat separation, e.g. cream plug graininess or sediment	Best measured with a capillary flow viscometer
Cream	From 12% to over 50% fat and clotted cream	Too thick or too thin	Rotational viscometers
Butter and dairy spreads	Fat typically about 85%; low fat spreads, down to 40% fat	Spreadability and those related to emulsion stability	Penetrometers, extruders and viscoelastic methods
Milk concentrates	Up to 60% total solids	Excessive viscosity, gelation, crystallisation	Rotational viscometers
Cheeses	Ranging from mature hard cheeses through soft	Various, for example too pasty to too soft Slicability is very important	Extruders, texture analysers, viscoelastic methods
Yoghurt and other cultured products	Set or stirred	Not firm enough, susceptible to syneresis	Empirical testing Viscoelasticity
Milk and whey powders	Milk, whey and infant formulations	Free flowing, not sticky easy to wet and dissolve	Brookfield rheometer PFT powder flow tester
Frozen dairy products	Ice cream, sorbets, yogurts	Icey, watery, too hard when frozen	Viscoelasticity; serrated detecting elements to prevent wall slip
Aerated products	Ice cream, foams, whipped cream	Poor stability – too firm or runny; too hard	Controlled stress rheometers
Dairy/plant hybrid products	This is an expanding niche area	Similar to milk product	Capillary flow viscometers

Kinematic viscosity can be measured directly with a capillary flow viscometer, where kinematic viscosity is defined as:

$$\text{Kinematic viscosity} = \frac{\text{Dynamic viscosity}}{\text{Density}} \quad (1)$$

with SI units of m^2s^{-1} and cgs units of centistokes (cSt), where 1 cSt = 10^{-6} m^2s^{-1}.

Milk has about twice the viscosity of water, i.e. ~2 cp. Some representative values at 20 °C are as follows: 5% lactose solution, 1.15 mPa.s; rennet whey, 1.25 mPa.s; skim milk, 1.79 mPa.s and whole milk, 2.127 mPa.s. Of course, these are average values. Milk (skim, semi-skim and full cream), cheese whey and ultrafiltration permeate are relatively low in total solids and have a low viscosity. The cheapest and probably most accurate instrument for measuring the viscosity of these fluids is a capillary flow viscometer, which measures the kinematic viscosity.

Chen et al. (2014) reported the viscosity values of bulk milk collected on 25 occasions over a complete year to be in the range 1.53–2.36 mPa.s, with an average value of 1.93 and standard deviation of 0.21 mPa.s. For most engineering calculations, milk and other fluids described above can be considered to be Newtonian fluids. However, milk below 40 °C has been observed to follow shear thinning behaviour occasionally, which was attributed to cold agglutination of the fat globules (McCarthy & Singh, 2009).

The viscosity of all fluids decreases as temperature increases. When measuring viscosity, the temperature should always be recorded. Data for viscosity of fluids is scarce above 100 °C, as the fluid must be pressurised whilst its viscosity is being measured. Such data would be useful, as milk products are sterilised in containers at temperatures of about 120 °C and ultra high temperature (UHT) treated at temperatures of 140 °C. Kessler (1981) illustrated how the viscosity of some dairy

Table 2 Some viscosity values at various temperatures (mPa.s or cp)

Temperature (°C)	20	50	80
Whole milk	2.12	1.07	0.68
Skim milk	1.74	0.84	0.53
Cheese whey	1.26	0.70	0.42

Taken from Kessler (1981)

fluids changes with temperature and Table 2 shows some of those values.

From this it can be seen that these products change viscosity by about 2% for each degree Celsius increase in temperature. A linear relationship has been observed between the logarithm of viscosity and reciprocal of absolute temperature ($1/T$). If this holds, then it could be useful for estimating viscosities above 100 °C.

Where accurate measurement is required, temperature should be controlled to ±0.1 °C and for more routine quality assurance work to ±1 °C. Bertsch and Cerf (1983) used a capillary viscometer to measure the viscosity of a variety of milk products in the range 70–135 °C; fat contents ranged from 0.03% to 15% and some milks were homogenised. Some equations for estimating the viscosity of Newtonian milk products at different temperatures and compositions have been compiled by McCarthy and Singh (2009) and Lewis (2022b).

During pasteurisation or sterilisation, viscosity will decrease substantially during the heating period and increase substantially during the cooling period. Heat treatment of milk containing starch is more challenging, for example milk custards. These will initially have a low viscosity but this increases substantially as the starch gelatinises and there will be a further increase during cooling. This could cause problems in the cooling section of a plate heat exchanger, where gaskets have been blown due to excessive viscosities at that location in the process. Tubular heat exchangers are more suited for such products.

A more academic and semi-empirical approach for predicting the viscosity of dispersions is outlined by Walstra and Jenness (1984). It assumes that the increase in viscosity results from hydrodynamic interactions only and is governed by the following equation:

$$\mu = \mu_0 \left(1 + \left(\frac{1.25\varphi}{1 - \dfrac{\varphi}{\varphi_{\max}}} \right) \right)^2 \qquad (2)$$

where μ represents viscosity of the suspension (milk) and μ_0 represents viscosity of solvent (water). φ represents volume fraction of the dispersed particles; $\varphi_{\max}$ is the hypothetical volume fraction giving close packing, which is 0.9 for fluid milk products, but it may be somewhat higher for evaporated milk and somewhat lower for high fat cream.

Thus the total volume fraction is given by:

$$\varphi = \varphi_c + \varphi_{wp} + \varphi_l + \varphi_f \qquad (3)$$

φ_c = hydrodynamic volume of casein (3.9 ml/g)
φ_{wp} = hydrodynamic volume of whey protein (1.5 ml/g)
φ_l = hydrodynamic volume of lactose (1.0 ml/g)
φ_f = hydrodynamic volume of fat (1.11 ml/g)

Thus milk containing 2.9% casein, 4% fat, 5% lactose and 0.6% whey protein (w/v) would give a viscosity of 1.68 mPa.s (Lewis, 2022a).

Inspection of this equation shows that the amount of casein is the most influential factor affecting the viscosity. An example of a calculation is provided by Lewis (2022a). This may appear to be a rather convoluted calculation but it allows one to look at how milk composition affects viscosity and to account for biological variability. The simplest solution may be to measure the viscosity using a U tube viscometer at the temperature of interest. In principle, this equation could be used for creams and more concentrated products.

Commercial heat treatment processes may slightly increase milk viscosity but changes are usually small.

1.3 Newtonian and Non-Newtonian Fluids

For most practical applications, milk can be assumed to be a near-Newtonian fluid. However, this situation changes as total solids are increased.

As mentioned, protein and fat will contribute toward most to the measured viscosity at any shear rate and its non-Newtonian behaviour.

Fluids flowing through tubes are subject to a shear rate, whereby the shear rate is approximately equal to 8 v/D, where *v* is the average velocity and *D* is the pipe diameter. In mixing equipment, the shear rate is proportional to the rotational speed of the mixer. Some shear rates encountered in pumping liquids through pipes are 1 to 1000 s^{-1} and for mixing and stirring applications, between 10 and 1000 s^{-1}, while shear rates encountered for other unit processes are given by Figura and Teixeira (2007) and Lewis (2022b). In terms of shear rate exerted in the mouth, Shama and Sherman (1973) show that this depends on the viscosity of the food, but is typically between 6 and 1000 s^{-1}.

Cream and concentrated milk products may show non-Newtonian behaviour, as will ice cream mixes and fermented products such as yogurt and other soft cheeses. The most common is time-independent pseudoplastic behaviour. When measuring viscosity of a non-Newtonian fluid, one consideration is to measure it at a shear rate close to those it is likely to experience during oral processing. There are a number of rotational viscometers available for measuring fluid viscosity with different measuring systems, such as concentric cylinder or cone and plate (see chapter "Rheometry and Rheological Characterisation" for further details). For those on a low budget, the Brookfield viscometer with simple spindle attachments for low and high viscosity fluids has been widely used for quality assurance purposes in the dairy processing sector. For research and development and for looking at more fundamental aspects, you could expect to pay 5–10 times more for your instrument. Netzsch, Anton Paar and Haake rotational viscometers are widely used by researchers.

1.4 Rheology of Creams and Other High Fat Products

The starting point for cream and butter production is separation of raw milk. The predominant phase is the skim milk, but we will focus on the cream, which may leave the separator at up to 50% fat content. After that, it will be standardised, by adding amounts of skim milk determined by performing a mass balance (Lewis, 2022b). It will also be homogenised, depending upon its fat content. This will affect both its viscosity and non-Newtonian behaviour!! Factors such as rate of cooling, milk fat composition and its fatty acid profile will also influence the viscosity.

Some observations on high fat-containing products will be helpful in understanding their rheological behaviour. When fats are cooled, crystallisation will occur, and they will undergo a liquid-to-solid transformation to form primary crystals with characteristic polymorphism. These primary crystals then aggregate to form clusters, which further interact, resulting in the formation of a continuous three-dimensional network. The macroscopic rheological properties of networks formed by lipids are of great importance in food products that contain significant amounts of fats. Such dairy products include cream, butter and a large variety of cheeses, as well as products containing dairy products such as chocolate and ice cream. Important sensory characteristics, such as spreadability, hardness, appearance and mouthfeel, are dependent on the mechanical strength of the underlying fat crystal network.

Martini and Marangoni (2007) state

> in order to truly understand, and eventually predict, the macroscopic properties of soft materials, it is necessary to characterise and define the different levels of structure present in the material and their respective relationship to a macroscopic property.

Knowledge of the relationships between molecular composition and phase behaviour, solid-state structure, growth mode, static structure and macroscopic properties will eventually allow for the rational design of specific macroscopic properties.

This network can be visualised as being built from aggregates rather than from straight chains of fat particles and can be thought of as a colloidal aggregate, analogous to a protein gel. Each of the fat particles is, in turn, composed of several aggregated fat crystals. The quantitative description of such a complex and 'random' system is difficult. Recently, fractal geometry has proven to be extremely helpful in the characterisation of these fractal objects.

Marangoni and Rousseau (1996) have developed two methods for characterising macrostructure in fat systems. These methods include small deformation rheology and microscopy techniques, employing a fractal approach.

The formation of a fat crystal network is of key importance in the manufacture of plastic fats, because it provides firmness or solid-like properties (viscoelasticity). Aspects of viscoelasticity appropriate to dairy products are discussed in the next section.

1.5 Viscoelasticity in Dairy Products

Viscoelastic behaviour is found where a product exhibits both viscous and elastic properties at the same time. Dairy products such as butter, yoghurt spreads and cheese exhibit viscoealsticity. There are four major approaches to analysing this more complex behaviour, which are discussed in more detail by Lewis (2022b). This section will focus on oscillatory methods, which are now widely used and provide fundamental information on the degree of viscousness and elasticity. Oscillatory rheometers are capable of generating a considerable amount of data. Two different approaches are widely used Lewis (2022b).

It is common practice to undertake an amplitude sweep prior to further characterisation. An *amplitude sweep,* at constant frequency, looks at the behaviour of samples in the non-destructive deformation range and to determine the upper limit of this range. It may also be worthwhile to characterise behaviour, with increasing deformation if this upper limit is exceeded, where the internal structure gets softer, starts to flow or breaks down in a brittle way.

The amplitude sweep enables us to identify the linear viscoelastic region, a *frequency sweep,* within this region helps to describe the time-dependent behaviour of a sample in the non-destructive deformation range. The range is usually 0.01–1 Hz. High frequencies will simulate fast motion on short times scales, whereas low frequencies simulate slow motion on longer time scales or even when the product is at rest. Using frequency sweeps, the oscillation frequency is increased or decreased step-wise from one measuring point to the next while keeping the amplitude constant.

There are also different ways to present the results. The loss factor, tan δ, can be plotted in addition to the curves of G' and G''; this is very useful when there is a phase transition in the sample, for example a sol/gel transition or simply a point of gelation. Usually, for practical applications, a liquid is called ideally viscous if tan $\delta > 100$, while a solid material is called ideally elastic if tan $\delta < 0.01$.

Therefore, when inspecting literature data on G' and G'' values, one should establish the frequency range, the temperature and the amplitude used. In conclusion, G' and G'' values can provide some very useful insights into the behaviour of a range of dairy products and changes in that behaviour induced by different processing conditions.

Two additional research methods are monitoring the gelation processes (and how quickly it proceeds) and measuring the final strength of the gel.

2 Dairy Products

2.1 Cream Viscosity – Practical Aspects

Milk is typically separated cold at 10 °C (lower or higher temperatures of up to 50 °C can also be used). One important difference is where the agglutinin proteins will reside. Above 40 °C, they are predominantly in the skim milk, but at low temperatures, they will remain in the cream. Agglutinins are claimed to promote aggregation of fat globules and are said to account for why raw milk or raw cream separates more quickly than might be expected. However, they are inactivated at higher temperatures, such as during pasteurisation and in heat treated creams may play no further part in fat globule coalescence. Because hot milk is less viscous than cold milk, it can pass faster through the cream separator, enabling higher throughput, and is often preferred for industrial processing for this reason. Separators working on hot milk are typically integrated with a milk pasteuriser, enabling cream separation, in- line fat content standardization and pasteurisation in a single integrated process. Nevertheless, cold milk separation has some benefits. It may, for example, allowing longer production run times by avoiding heat-induced fouling. It also reduces the potential growth of thermoduric bacteria that are capable of surviving at high temperatures.

Commercial cream products may range from 12 to over 50% fat. Common types of cream are single cream at 18% fat, whipping cream at 35% fat and double cream at 48% fat. A cream manufacturer will wish to make each product to a constant consistency to match the expectation of the consumer. Although the fat content of these creams is very different, the composition of the aqueous phase does not differ much. For each cream type, there may be demand for a product which can be poured easily or for one which is thick and spoonable. Some typical values for the kinematic viscosity (m^2s^{-1}) of cream at 20 °C are given by Kessler (1981): 20% fat = 6.2×10^{-6}; 35% fat = 14.5×10^{-6} and 45% fat = 35×10^{-6}. However, these values can be changed considerably by other factors discussed.

Cream can show rheological characteristics across the whole range, from Newtonian, shear thinning behaviour to shear thinning with a yield stress. They may also exhibit time-dependency when they are measured and show further age-thickening during storage. As the fat content increases, the rheological properties will be much influenced by the size and nature of the fat globule and that will include not only the total amount of fat, how much is crystallised at the relevant temperature, but also which of the crystalline forms are produced. Most creams are also homogenised to reduce fat separation during storage, and homogenisation also has a pronounced effect on viscosity. To summarise, there are many factors that affect cream viscosity, the main ones being cream separation temperature, fat content, fat globule size and distribution, the way of heating and cooling, and temperature. Cream cooled quickly sometimes shows dilatant behaviour, but this may change during storage to shear thinning. Warming cream from 5 °C to 20–25 °C and then cooling it down again will increase the viscosity and is known as rebodying. UHT cream may have a shelf life of 6–12 months, and it is important that no changes occur during storage, such as fat separation. Some of the more fundamental aspects affecting viscosity of creams has been discussed by Walstra and Jenness (1984), and McCarthy and Singh (2009).

2.2 Butter and Spreads

Butter is produced by churning cream. Cream can be whipped, and a phase inversion process eventually results in butter and buttermilk. You may have unintentionally produced butter at home if you whip cream for too long. Initially air is incorporated into the cream and a foam is produced. Further whisking begins to destabilise the foam and more fat globules coalesce with each other into ever coarser clumps of butterfat, at which point, air and liquid that were held together inside the pockets of fat begin to weep; the fat loses volume, and the cream becomes granular (in kitchen parlance, it is 'split'). Further whipping causes the emulsion to be inverted; the fat globule membranes are broken down, forcing the fat to clump tighter together and forcing the air and water out. Thus, butter is made.

Butter is a premium product which many margarine manufacturers try to emulate, especially its creamy flavour. Butter is a water in oil emulsion with a milk fat content of ~85%, and its rheological behaviour is dictated largely by its fat phase. According to Wilbey (2009), the texture of the butter should be smooth, with a steady melt on the palate. The consistency should be neither crumbly, indicative of under-working (as found with some batch-produced butters), nor gummy as a result of over-working. Graininess may be the result of slow cooling or temperature cycling, while grittiness is usually attributable to poorly dispersed salt crystals.

One drawback for butter is its poor spreadability straight from the refrigerator. This results from the high percentage of crystalline solid in the fat phase at refrigeration temperatures. Hardness and spreadability are most influenced by the melting characteristic of the fat or its solid to liquid fat ratio. Classically, this is evaluated by dilatometry, but now by NMR solid:liquid fat analyser. While not a rheological measurement, the solid:liquid fat ratio for a butter or a spread will strongly influence its spreadability. This ratio is largely dictated by the percentage of saturated fat in the fat phase of the product. For example, butter fat contains 62% saturates, rapeseed about 6% (the lowest of the vegetable oils), compared to sunflower at 10%, corn oil at 13% and olive oil at 14%. At 10 °C, butterfat contains 56% solid fat, whereas sunflower oil is close to zero.

There are a number of ways to improve the spreadability of butter. The most complex but fundamental approach is to alter fatty acid profile of milk by altering the cow's diet. This has been shown to work but is not conducive to producing suitable milk on a large scale. A second and more widely used option is by blending in vegetable oils before the product is churned. Many spreadable butters now contain an undeclared proportion of vegetable oil to reduce their overall solid:liquid fat ratio. Some examples of this include brand names such as Anchor and Lurpac. It is interesting that butter is not mentioned on the labelling. A non-branded variant (British spreadable) is cheaper, but possibly too soft.

Currently, a lot of work has focused on the production of low-fat spreads. Butter and margarine typically contained 85% fat and are made from cream and vegetable oil, respectively. Lower fat spreads were considered to be healthier options, and over a period of time, spreads have been developed, with fat contents reduced to below 40%. Ideally, these would have similar rheological and spreadability as the full-fat variants. These have been discussed in more detail by Mortensen (2009).

Traditionally butter rheology involved measurement using a FIRA extruder, an empirical device which measures both the force required to extrude the product through an orifice and the frictional force as the plug of butter is driven through the cylinder. Another instrument is the cone penetrometer. This has been found useful for determining the yield stress for butter, margarines and other spreads (IDF, 1981). Both these instruments are described in more detail by Lewis (2022b). More recently viscoelasticity measuring techniques have been used. Of course, spreadability can also be measured by sensory assessors.

2.3 Dairy Foams

The two main dairy foams are those produced by milk, for example in cappuccino and those produced when whipping cream.

The amount of air incorporated is given by the overrun, which is the increase in volume compared to the original volume, expressed as a percentage. Traditionally conventional cream whipping may have overruns of 100%, but aerosol creams, using nitrous oxide as the propellant, may give overrun values of 400–500%. These produce much larger volumes of whipped cream, but only with shorter-term stability.

Considerable milk is now used by the coffee industry for making products such as cappuccino. There are various methods available to produce a milk foam: by aeration and agitation, heating and agitation, and agitation and steam injection heating (Huppertz, 2010; Ho et al., 2019). The design and engineering aspects of foaming devices are important to get the best foam from any milk sample, which would entail producing a large volume of foam that has good stability in a short time period. Links between injector design, steam pressure and milk foam quality were reported by Jimenez-Junca et al. (2015) for steam injection systems, whereas Ho et al. (2019) compared different types of devices for milk foaming. Huppertz (2010) comprehensively reviewed the foaming properties of milk.

The foaming properties of milk have become more apparent recently, as increasing amounts of milk are used by coffee producers for their specialty beverages and the popularity of kitchen-scale milk frothing devices. However, the rheological and textural attributes of these foams have received much less attention.

A second important dairy foam is whipped cream. Unlike egg whites, where fat inhibits the whipping, when cream is to be whipped, a minimum 30–35% fat content must be present to form a foam. Additionally, cream with a higher fat content, for example UK double cream at 48% fat, will actually whip faster while forming a stiffer, denser and less voluminous foam.

Ice cream is frozen foam which contains dairy products (Sect. 2.7.1).

2.4 Concentrated Milk

Some notable viscosity changes occur during milk concentration, for example in evaporation, reverse osmosis and ultrafiltration. Many of these concentrates will subsequently be spray dried. The concentration process prior to drying should remove as much water as possible to increase drier capacity, to reduce energy costs and to increase the bulk density of the powder. The extent of concentration that can be achieved may be limited by viscosity or solubility limits of components (e.g. lactose). Drying a concentrate produces a powder with a higher bulk density that will be less compressible, more free-flowing and easy to handle (See Sect. 2.6).

Concentrates with lower total solids may exhibit near-Newtonian behaviour, but this may change to non-Newtonian at some point during the concentration process. The following are some general points.

Concentrates produced by heat and reverse osmosis will be similar in terms of their rheological properties, but those produced by ultrafiltration will be different, as will be their fat contents. So, a wide range of rheological behaviour may be encountered. Non-Newtonian behaviour manifests at lower total solids in ultrafiltration concentrates than in evaporated milk, because the proportion of protein is higher and lactose lower.

Near-Newtonian behaviour was found to persist to higher total solids at elevated temperatures. Since viscosities (at a specified shear rate) are more related to compositional factors, equation 2 can be used to predict the viscosity of milk concentrates. One modification was that the voluminosity factor for denatured whey protein was 1.07 for native whey protein but was 3.09 for denatured whey protein.

Changes from near-Newtonian to non-Newtonian behaviour were observed for whole milk. Concentrates showed Newtonian behavior up to 20% total solids, obeying the power law equation from 20% to 34% solids and the Herschel Buckley equation (plastic behaviour) at higher total solids. The precise ranges over which these different behaviours are found depend upon numerous factors such as dry solids content, temperature, shear rate pre-treatment of milk prior to evaporation and the evaporation method and conditions. Generally, the power law constant k increases, while the power law index (n) decreases as total solids rise.

Evaporated milk is an interesting product to manufacture. The milk is forewarmed and total solids are increased to about 25–30%. The final stage of production involves addition of a stabiliser and sterilisation of the product. In this situation, the viscosity increases substantially as a result of the sterilisation process, typically at 115–120 °C for 10 to 20 min. If the process is not properly controlled the evaporated milk may become extremely viscous or even coagulate. The aim is usually to prevent excessive thickening and especially coagulation during the sterilisation process. This is facilitated by an intensive forewarming process and by addition of stabilisers such as disodium hydrogen phosphate (DSHP) which is generally the stabiliser of choice. Trisodium citrate (TSC) is also effective but may give rise to the formation of calcium citrate crystals during storage (Deysher & Webb, 1952). This may impart a gritty mouthfeel and may block nozzles in some coffee machines.

Chen (2014) measured seven commercial evaporated milk samples and found their total solids ranged from 27.5% to 27.9% and the kinematic viscosity from 27.6 to 46.1 cSt. Evaporated milk can also be made by reconstituting milk powder, but it is important to select milk powder with a good heat stability, otherwise the same principles apply in terms of stabiliser addition. Some fluid dairy products are kept for a substantial time before consumption and further viscosity changes may occur, one example being gelation during storage of UHT milk.

Other concentration processes are as follows:

Reverse osmosis is similar to evaporation, but without heat. Reverse osmosis can comfortably concentrate milk up to 25% total solids. It is cheaper in terms of both capital and running costs and may be installed to increase the overall evaporation capacity. Ultrafiltration is the most interesting membrane process, as it concentrates both protein and fat, so the rheological properties of the concentrates would be more complex than those produced by RO.

Fermentation of ultrafiltration concentrates is described in the next section.

2.5 Milk Fermentation

Fermentation is involved in the production of yogurt, other cultured products and most cheeses. The main change is the conversion of lactose to lactic acid, which is monitored by measuring pH and/or titratable acidity. The resulting fall in pH will result in an increase in minerals in the soluble phase and an increasing loss from the curd itself. As all cheese-making processes are different, the amount of minerals retained in the curd will be different and will decrease as the ultimate pH of the cheese decrease. This would be expected to affect the final texture of the product.

Manufacturing soft cheeses or quarg by ultrafiltration is interesting (Puhan & Gallmann, 1980). Throughout the process, a permeate containing calcium (Ca) and phosphorus (P) is being continuously removed. It is not clear whether casein micelles differ considerably in their mineral composition compared to the original milk or whether any significant casein dissociation takes place as a result of ultrafiltration. The process involves concentrating skim milk by about four times followed by fermentation with a lactic acid culture. Doing the fermentation first does not make sense, yet experience has shown that too much mineral retention results in an unpleasant off-flavour, described as bitter or metallic (Winwood, 1983) as well as becoming smeary, gluey and shiny in appearance. Puhan and Gallmann (1980) reported that a higher calcium content is responsible for these unwanted defects which can be avoided by fermenting first, followed by the ultrafiltration process.

The mineral content will most likely affect the rheological properties of the final product and hence its texture, so using ultrafiltration technology to produce fermented milk products is a challenging task (Tamime & Robinson, 1999). Thus, if texture or flavour problems are encountered when using membrane technology for making fermented products, it would be worthwhile looking at their mineral content.

2.5.1 Yoghurt

Yoghurt is one example where a range of rheological approaches can be used. Its manufacture involves the fermentation of milk under controlled conditions and is described in excellent detail by Tamine and Robinson (1999).

The main processing parameters influencing the texture of yoghurt are the materials used and their fortification level, fat content and homogenisation conditions, starter culture, incubation temperature, pH at breaking, cooling conditions and any additional handling of the product after manufacture.

Milk for yoghurt is typically heated above 90 °C to improve product consistency. Stabilisers may be added. Starter cultures should be carefully selected, as they vary in the amount of acid, volatile components and polysaccharides they produce. Where skim milk is used, it is usually fortified to about 14–16% solids, but full-fat varieties are also produced. The two main types of yogurt are set yogurts and stirred yoghurts.

It is not surprising that yogurt can exhibit a variety of non-Newtonian effects, such as shear-thinning, yield stress, viscoelasticity and time-dependency. Yoghurt texture is one of its important quality characteristics. For quality assurance, the main interest would be to ensure a product of consistent quality, so the method of measurement could include penetrometers, falling sphere viscometers or a very simple protocol with a rotational viscometer, depending upon availability in the factory. Most yogurts show shear thinning behaviour and some time-dependency. Controlled stress rheometry would most likely be used in a research environment to understand some of the more fundamental aspects of the gelation process. In this case, values of G' and G'' and frequency sweeps would be more appropriate. Such methods might also be more appropriate for troubleshooting operations, for example looking at cases where product consistency is poor or samples show syneresis, where a clear liquid forms on the surface as the gel shrinks during storage. Some examples are shown in Lucey (2016).

2.5.2 Cheese Products

2.5.2.1 Introduction

Cheese-making is a partitioning process and the two products formed are cheese and whey. It is advisable to make the best use of both streams. The partitioning process itself has been described recently in more detail by Lewis (2022a).

Rheological methods can be used both for monitoring the cheese-making process and for evaluating the final product. During cheese manufacture, this can involve monitoring the formation of the curd and evaluating the best time to cut the curd. From that time point onwards, rheological measurements can be used to evaluate the progression of the curd, from the point where it is separated from the whey to its point of consumption. Time from curd cutting to consumption may range from one week to over two years. One major problem is the prevention of mould growth during cheese storage.

Ten kilogram of starting milk produces approximately 1 kg of hard cheese or 2 kg of soft cheese. About 75–80% of the milk protein will end up in the curd in conventional cheese-making. Ultrafiltration processing can increase this up to 100% (Sect. 2.5)

There are a wide range of cheese products available; some general descriptions are soft/hard; high fat/low fat; renneted/acidic, to name a few.

Cheese is produced from a wide variety of milking animals. The most common is bovine milk, but goat and sheep milk cheese are also available. Cheese may be made from raw milk or heat-treated (pasteurised) milk. UHT milk should not be used to make a renetted cheese. Ricotta cheese is made by heating cheese whey to coagulate the whey proteins.

It is important to know the recoveries of protein, fat and calcium in the cheese. This will affect both the economics of the process and the texture and nutritional value of the cheese. Other issues are how contaminants such as heavy metals, pesticides and radionucleotides partition into cheese and whey.

Values for calcium (mg Ca per g protein) in a range of varieties are as follows: Cheddar cheese, 28.2; Edam cheese, 29.6; Feta cheese, 23.0; and cottage cheese, 5. The values for the starting milk is about 36 mg Ca per g protein, based on total protein and about 46 based on casein protein. So, not only does the cheese-making process partition casein and whey proteins, but it also has a drastic effect on the amount of total calcium that is retained in the cheese.

The second partitioning issue is perhaps more subtle and concerns mineral partitioning within the cheese matrix itself, i.e. casein bound or dissolved in the cheese aqueous phase (Cooke & McSweeney, 2017). The pH at whey drainage during cheese-making not only has a huge effect on calcium retained in the curd but it also has a major effect on texture. High pH at drainage (e.g. Emmental) gives an elastic texture, while low pH at drainage (e.g. Cheshire) gives a crumbly, short texture (Cooke & McSweeney, 2017).

During ripening, calcium migration will take place from the curd into the aqueous phase and this can influence the texture of the cheese (Cooke & McSweeney, 2017).

Whey processing is an important industry, with the production of protein concentrates and isolates for functionality and health (Deeth & Bansal, 2018). An exciting process is microparticulation of whey proteins to produce products with improved textural attributes (Ipsen, 2017). Microparticulated whey proteins can be used in high protein beverages or as fat replacers. This ability they have to mimic both the casein micelle and the fat globule in terms of their contributions to product texture is fascinating.

2.5.2.2 Cheese Grading and Cheese Rheology

Cheese grading is the process of evaluating cheese to assess texture, body and flavour. Grading is done by trained experts and gives an objective description of the product during the maturation process. It is used to select which market the cheese is sold into – retail, wholesale or export.

Grading evaluates body, texture and flavour. A grading iron is used to take a plug from the cheese. 'This plug shall be firm and appear solid, smooth, compact, close and should be translucent, although it may have a few small mechanical openings. It may possess limited sweet holes in accordance with the degree of curing but free from other gas holes' (USDA.gov, 1956). The cheese grader regularly grades cheese to ensure that it meets the criteria that have been set in terms of taste, texture and flavour profile of each particular cheese. This ensures a consistency in the quality and range of cheese that is available to the customer. Cheddar is sold at various stages of maturation. The taste develops as the cheese matures, from young creamy taste of mild cheddar to complex nutty flavours of mature cheddar. The taste is also dependent on the time of year the cheese was made, the grass the animal was grazing on or the animal feed used.

Below are some of the requirements that you should know for being a cheese grader (Ukstandards.org, undated):

- The organisational sampling requirements for cheese grading and why it is important to adhere to them
- The importance of aroma, texture, flavour and colour to cheese grading
- The organisational cheese grading specification
- How to apply the organisational cheese grading specification to cheese grading
- The organisational recording and reporting requirements for cheese grading
- The common characteristics that may cause down-graded cheese
- The organisational procedures for dealing with cheese that does not meet the minimum grade

More detailed information about cheese grading and sensory profiling is provided by Muir (2010).

Cheese rheology covers two main areas: hard and semi-hard cheeses, which have predominantly a solid characteristic, and soft cheeses, which are viscoelastic in nature. Its rheological properties will affect the texture of the cheese.

Cheese texture may be defined as a 'composite sensory attribute' resulting from a combination of physical properties that are perceived by the senses of touch (including kinaesthesis and mouth-feel), sight and hearing. It can be measured directly using a trained sensory panel; however, owing to the difficulty and cost in assembling sensory panels, they are not routinely used for gauging cheese texture. Instead, cheese texture is generally measured indirectly using rheological techniques.

Guinee and O'Callaghan (2010) summarise testing methods. Early empirical test equipment included compressors, penetrometers and curd tension meters, which were used in such a way that experimental variables were not consistent and, therefore, results were not comparable between laboratories. Measuring viscoelastic properties will eliminate this problem. The amplitude of the test must be small enough that the material is unaltered by the applied force, which means that the test is conducted in the linear viscoelastic range. Configurations include the concentric cylinder, parallel plate, and cone and plate.

A much-used procedure for assessing the rheology of soft or semi-hard cheese is by compressing a cylindrical or cubic cheese sample between two parallel plates of a texture analyser using compression in one or two cycles. Analysis of the resulting force–displacement or stress–strain relationship is often referred to as texture profile analysis. This enables the determination of a number of rheological parameters, e.g. fracture stress, fracture strain, firmness and springiness, which are related to sensory textural characteristics such as brittleness, hardness and chewiness.

If force is increased until the sample ruptures, a yield stress can be measured, or if force is applied repeatedly, sample response can mimic first bite–second bite deformation of the food (texture profile analysis) (Tunich, 2000). Torsion gelometry involves the application of large strain shear forces to a capstan-shaped sample and has been used to discriminate between various types of hard cheese.

The rheology of cheese (Tunich, 2000; Lucey et al., 2003) has been measured most extensively at all stages of production. Both penetrometers and oscillatory rheometers have been used for determining the viscosity of soft fresh cheeses and for showing the influence of the various processing steps, e.g. heat treatment, homogenisation, cooling, on textural properties. A problem-solving approach to cheese-making has been edited by McSweeney (2007). Almost 200 cheese-related problems have been posed and each is answered by an appropriate expert and many of these relate to cheese texture faults.

One cheese in high demand is mozarella cheese for pizza manufacture, and its important textural attribute is its strechability. Gunasekaran and Ak (2002) have provided a comprehensive chapter on measuring stretchability. Some typical textural requirements of cheeses as a food ingredient in different types of application are as follows: crumbles when rubbed, good shredability, sliceability, stetchability and free flowability when shaken (Gunasekaran & Ak, 2002).

2.6 Milk Powders

2.6.1 Introduction

Milk can be converted into a range of powders. Powders are usually reconstituted before being consumed, so their textural attributes may not be thought to be of interest. However, powder rheology is important in both how easily they are transported and stored and their reconstitution properties. Hayes (1987) has described a system for characterising a wide range of food powders based on density, size, flowability, abrasiveness, and a range of other properties as well as hazards such as flammability, explosiveness and corrosive nature. Many of these properties will be influenced by the chemical composition of the powder as well as by its moisture content and compressibility.

The conditions prevailing at the surface of the powder are also important as this affects how particles interact and how easy they will flow. Differences in flowability can simply be observed by pouring different powders out of a container. Other simple tests are slide angle and angle of repose. Slide angle is measured by placing powder samples on a flat smooth horizontal surface, which is slowly inclined until the powder begins to move and this slide angle is noted.

Angle of repose is also useful in the design of powder handling systems. Its value depends upon the method of determination which is normally by allowing the powder to form a heap. Other methods involve a bed rupture method or a rotating drum method. Its magnitude is affected by frictional forces and interparticle attractive forces, which become dominant in cohesive powders. According to Carr (1976), angles up to 35° indicate free flowability; 35–45° indicates some cohesiveness while 45–55° indicates cohesiveness with a loss of free flowability. Angles >55° indicate very high cohesiveness with limited or zero flow. These parameters are empirical in nature and often results are not applicable when conditions are changed (Peleg, 1977).

Small particles adhere much more closely to each other than large particles. For powders that are cohesive, the ratio of the interparticle force to the particles own weight is large. The more cohesive a powder is, the more difficult it is to handle. Schubert (1987a, b) states that the most food powders are non-cohesive (and hence free-flowing) when their particle size exceeds 100 microns and explains why agglomeration is now widely used. Increasing the powder moisture content makes powders more cohesive and increases the particle size at which the transition from cohesive to non-cohesive takes place.

2.6.2 Powder Compression and Selection of the Best Powder

Powders are compressed when they are filled into hoppers or when sacks of powder are piled on top of each other. This may have an adverse effect on their flowability, which also tends to improve with increasing particle size and decreasing moisture content. Data obtained from a Jenicke flow cell can be used to describe the unconfined yield stress F_c and the major consolidation stress (σ_1) (Peleg, 1977; Schubert, 1987a; Lewis, 2022b: The ratio (σ_1/F_c) is termed the Jenike flow function. Its value corresponds to the following characteristics:

<2	very cohesive, non-flowing
2–4	cohesive
4–10	easy flowing
>10	free flowing

Measuring these properties will help to determine whether a powder will be hard to transport and store. Hopefully, this understanding will soon lead to being able to produce powders that are always easy to handle. Crowley et al. (2014) describe the methodology and present some data for milk protein concentrates ranging from 35% to 95 % protein (dwb). These powders not only had different protein contents but also had different surface area to volume ratios.

One instrument for measuring rheological properties of powders is the Brookfield flow tester. It can measure flow function, wall friction and compression, to ascertain whether there will be flow-related problems. Another instrument is the PFT Powder Flow Tester, which can deliver quick and easy analysis of how powder will flow in industrial processing equipment.

Dairy powders come in many forms: whole milk powder (WMP), skim milk powder (SMP), caseins, whey protein concentrates and isolates, lactose and mineral fractions, buttermilk and cheese, yoghurt and cream powders. SMP and WMP are the main powders produced and SMP is used in condensed (evaporated) milk, reconstituted UHT milk, ice cream, cultured dairy products, bakery, cheese and other products. SMP is available in four categories, according to the severity of heat treatment; low heat, medium heat, high heat and high heat, high stability powder, based on extent of whey protein denaturation brought about during its preparation. For producing evaporated milk by reconstituting SMP, a high heat powder should be used, along with suitable stabilisers to ensure that the product does not coagulate or become too viscous during the final sterilisation (Deeth & Lewis, 2017). SMP is used to fortify skim milk in the range 1 to 6% for yoghurt manufacture and a medium heat variant is recommended. Too much powder addition may lead to a powdery texture (Tamime & Robinson, 1999). They also cited work where yoghurt texture was found to differ considerably for different grades of milk powder. Also a different type of powder might be needed for set and stirred yoghurts. In summary, care should be taken when using dairy powders to ensure that the best choice is being made to achieve the desired product texture and other desired sensory characteristics. My view is that more research would be worthwhile in this area.

2.7 Products Containing Dairy Ingredients

2.7.1 Freezing and Frozen Desserts

Freezing of milk is a complex process. Lewis (2022b) presents an enthalpy-composition chart, showing the amount of water that is frozen at different values of temperatures and total milk solids. According to this chart, the percentage of frozen water in milk at 12% TS at different temperatures is as follows: −1 °C, 40%; −2 °C, 68%; −5 °C, 86%; −10 °C, 92% and −20 °C, 95%. Thus, most of transition from water to ice takes place over the temperature range −1 to −5 °C in milk. If stored at a constant temperature, e.g., −20 °C, the amount of frozen water remains constant, but if storage temperature fluctuates, some water melts and refreezes.

The most common frozen dessert is ice cream; again, its rheology is important. Ice cream is another example of a foam, and ice cream is aerated and frozen simultaneously. Increasing the overrun will make an ice cream with a softer texture. Again, the consumer has expectations about the texture of ice cream, for example a creamy texture with no icy or other unpleasant mouthfeel attributes. Other textural defects listed by Marshall et al. (2003) are those of body, such as crumbly, gummy, shrunken or heavy, and defects of texture such as buttery, coarse and sandy. The desired body is described as firm with a substantial feeling of solid matter within the foam. The desired texture is smooth, creamy and homogenous.

Ice cream rheology is very temperature dependent. Ice cream leaving the freezer must be pumpable and is defined as soft ice cream, at about −5 to −7° C, yet it is hardened at −18° C. Any ice cream stored in a domestic freezer will also be at this latter temperature. There is consumer demand for ice cream that is easier to scoop when taken straight from the freezer. In this case, this can be achieved by control of the amount of frozen water, usually by using sugars which depress freezing point more than sucrose, which will have the desired effect. One major challenge in rheological assessment of ice cream is temperature control.

2.7.2 Chocolate Rheology

The ingredients for milk chocolate are cocoa solids, milk solids, sugar and cocoa butter. When mixed together, the resulting product has a coarse texture which shows little resemblance to smooth pourable chocolate. To produce a finer dispersion, it is sheared for several hours by conching. Lecithin may be added and the end product will be a flowable, pourable chocolate. The aim of the manufacturer will be to produce chocolate of constant consistency. The length of the conching period distinguishes chocolate of high quality. Conching also contributes toward the flavour of the chocolate.

The rheology of chocolate is very important for several reasons. Firstly, it contributes toward the mouthfeel characteristics of the finished product, which is one of its main selling points. Secondly, it influences its pumping characteristics. This is important in procedures such as enrobing, where chocolate is poured over nuts or caramel, for example in the production of individual chocolates or chocolate-coated biscuits. If the viscosity is too thick, excessive chocolate will be deposited, but if it is too thin, then it will run off. Obtaining a uniform thickness of chocolate is essential and depends upon controlling the rheology of the chocolate prior to the enrobing process. In this application, it is best measured using rotational viscometers or by controlled stress viscometry, and a temperature of 40 °C is commonly used. A standardised procedure has been suggested by Wolf (2011). Chocolate viscosity under these conditions is modelled as a Casson fluid.

Liquid chocolate at 40 °C is also very different to the chocolate that we purchase. To achieve a its final smooth consistency, it needs to be cooled under controlled conditions to obtain its correct crystalline configuration. This tempering process and the crystalline forms that chocolate can take are described in more detail in chapter "Candy Texture (Sugar Confectionery)". A chocolate bar will be evaluated using very different tests to those used on the pourable chocolate at 40 °C. Thus, there are two different products to characterise, one is the pumpable chocolate and the other is the final finished product. A variety of the instruments can be used for the finished product, depending upon the circumstances, for example a penetrometer with universal texting machine would be appropriate.

Milk chocolate will contain a substantial amount of milk solids. As a "milk man" myself, I have often wondered about the exact role of milk and the impact of milk quality on the overall quality of the chocolate. I have not seen much written about this. One well known advertising campaign made great use of the slogan "a glass and a half of milk in every bar." Would chocolate be different in texture if its milk solids were provided from milk powder or fresh milk?

3 Conclusions

The milk secretory cell is a wonder of nature and produces a highly nutritious product from a wide variety of plant sources. Both milk and all dairy products will vary in composition from day to day and this will affect their rheology, mouthfeel and textural attributes.

The texture of dairy products covers the complete spectrum of rheological behaviours found in foods. There are a variety of instruments that look at empirical factors as well as fundamental properties.

The three main groups interested in dairy products are producers, consumers and research scientists. The producer of dairy products wishes to produce a product with consistent rheological properties and texture. The consumer of dairy products has expectations of the texture of the products they have purchased and use their senses to see whether products match those expectations. The research scientist strives to understand the underlying principles of producing the best chocolate and the components and processing steps that will produce the perfect texture.

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Candy Texture (Sugar Confectionery)

Meredith Cohen and Richard Hartel

1 Introduction

1.1 Overview

Oxford Languages defines “candy” (another word for “confectionery”) as “a sweet food made with sugar or other sweeteners, typically formed in small, shaped pieces and flavored with chocolate, fruit, or nuts.” As this definition states, confectionery’s main differentiating factor is sugar or sweetener’s presence. Most confectionery starts from a basis of sucrose, glucose syrup (glucose polymers from a starch source), and water. This mixture can then be blended and/or heated, and other components may be added: dairy (e.g., cream in caramel), hydrocolloids (e.g., gelatin in gummy bears), or inclusions (e.g., nuts in nougat). These ingredients, along with the processing methods used, form the basis for the determination of the microstructure of the confection. This microstructure in turn influences both the mechanical and the sensory properties of the final product.

Confections come in many forms—traditional, sugar-free, vegan, allergy-friendly, and so on—but all share one critical component: water. Water is able to form hydrogen bonds with candy ingredients, affecting material properties such as water activity and boiling point, which in turn impact the processing methods and the final product. Water content is important to graining in candies, as crystallization occurs when a supersaturated sugar solution is cooled. Water content is also vital to most confections since it plays a major role in texture. Candy thermometers typically show the stages of candy making listed as a function of temperature, as shown in Table 1, based on viscosity of the sugar syrup as water is removed.

Besides water, one of the most significant factors affecting the texture of confections is the amount of sugar that is crystallized, as opposed to in amorphous form. The crystallinity is primarily governed by water content and the ratio of sugar to glucose syrup in the original formulation, although processing conditions can also influence crystallization. Cooking the mixture allows water to boil off, causing supersaturation and eventually crystallization, otherwise known as graining, of the sucrose. However, the glucose syrup acts as a “doctoring” agent to moderate crystallization. Glucose syrup decreases the solubility of sucrose slightly and impedes sucrose lattice formation, thus inhibiting crystallization. Partially grained confections like fondant and fudge are intentionally formulated and produced in a way that causes crystallization, creating a “short” texture. Ungrained confections such as salt water taffy or hard candy are designed to remain in amorphous (uncrystallized) form.

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Table 1 Candy thermometer classifications correlated to approximate water content

Boiling temperature	Water content (%)	Description
106–112 °C (223–234 °F)	17.5–27.5	Thread: forms fine, thin threads that quickly dissipate into cold water
112–116 °C (234–240 °F)	14–17.5	Soft ball: forms a soft ball that does not hold its shape
118–120 °C (244–248 °F)	11–12.5	Firm ball: forms a ball that is firm enough to hold its shape, but is sticky and easily deformed
121–130 °C (250–266 °F)	7.5–11	Hard ball: forms a ball that is hard and holds its shape, yet is still slightly pliable
132–143 °C (270–290 °F)	4–7	Soft crack: forms hard, but not brittle threads that can be stretched between fingers
146–154 °C (295–310 °F)	2–3	Hard crack: forms brittle threads that snap when bent between fingers

Reproduced with permission from Hartel et al. (2018)
Descriptions refer to state of sugar syrups cooled quickly by dropping into cold water

Among other properties, moisture content has a significant effect on graining of confections, although the effects are complicated because water affects both the supersaturation driving force for crystallization and the mobility of water molecules (Ergun et al., 2010). The range of moisture content and approximate crystallinity in various confections can be seen in Fig. 1. General relationships between crystallinity and texture of a variety of confections are given in Table 2.

The type of glucose syrup used can alter properties as well. Glucose syrups are typically characterized by "dextrose equivalents" (DE), a measurement of the quantity of reducing sugars in proportion to the amount of dextrose (also known as glucose) present in the syrup, on a dry weight basis. A higher DE glucose syrup will have a higher amount of dextrose, a monosaccharide, relative to the total amount of mono-, di-, and polysaccharides present. Lower DE syrups have more longer-chained sugars, which provide more viscosity and body to a product.

Processing methods for confections—encompassing everything from cook time and temperature to mixing and addition of other ingredients afterward—also can have a significant impact on texture. Agitation can influence texture, since crystallization of a supersaturated solution is promoted by intense mixing. In confections like fondant, intense agitation is used to promote uniform crystallization in order to form many small crystals. In amorphous or glassy candies, like hard candy, the goal is to maintain an entirely amorphous (non-crystalline) structure, so agitation is avoided. Aeration is designed to incorporate air into confections like marshmallows, lowering the density and changing the mouthfeel.

1.2 Texture

As emphasized by Szczesniak (2002), texture should be considered a sensory property. To evaluate texture in confectionery, data is collected both from sensory assessment and from simulatory tests conducted with tools such as a texture analyzer. Other instrumental measurements have been undertaken, namely with rheometers, but those results generally do not correlate well with the consumer's perception of the candy's texture because the forces applied are very different from those seen during oral processing. Further, the role of saliva in oral processing is also vital to texture perception, as pointed out by Boehm et al. (2019); however, integration of saliva into instrumental measurement is challenging.

1.2.1 Sensory Assessment

Sensory tests of confections are done in a similar manner to those of other foods. Because of the wide range of textures among confectionery products, there is no single attribute that is most important, with each candy having its own unique characteristics. Having said that, hardness and stickiness are generally the most broadly applicable and are vital to the perception of anything from toffee (hard and ideally not too sticky) to extruded marshmallow (soft and very sticky). Toothpacking is important for some confections, like caramel, but less relevant for others, like bubblegum. "Shortness" is another term frequently applied to candy. Shortness is the

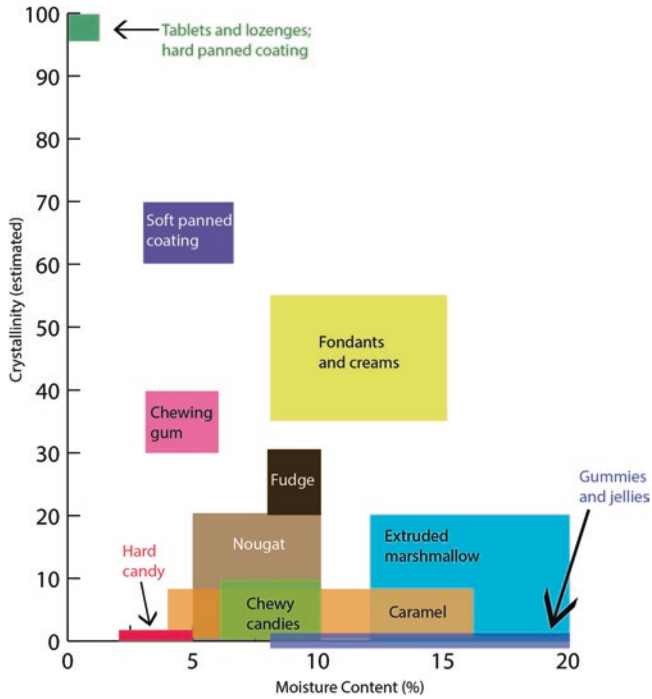

Fig. 1 Crystallinity vs moisture content in various confections. (Adapted from Ergun et al., 2010 and Bussiere and Serpelloni, 1985)

Table 2 Relationship of texture to crystal content of confections

Category	Examples	Texture
Non-crystalline	Syrup candies	Viscous liquid
Liquid	Gummies and jellies	Chewy; solid-like structure due to hydrocolloids
Amorphous	Ungrained caramel; chewy nougat; marshmallow	Chewy
Glassy	Cotton candy hard candy; brittles	Floss Hard and brittle
Crystalline	Rock candy Candy powders Tablets or lozenges (wafers)	Hard crystals Free-flowing powder Compacted or fused powder
Partially crystalline	Grained (after dinner) mints; fondants and creams; grained caramel, fudge, nougat, and marshmallow; hard and soft panned shell candy	Variable texture depending on crystal content, with increasing "short" texture as crystal content increases

Reproduced with permission from Ergun et al. (2009) and Hartel et al. (2011)

opposite of stringiness and refers to the degree to which a candy breaks immediately when pulled apart, rather than forming strings. For example, grained nougat is typically very short, while ungrained caramel is typically very long, or stringy. Other attributes (sensory cohesiveness, chewiness, etc.) are important in other candies.

Some studies attempt to bridge the gap between sensory and instrumental measurements by focusing on quantifying parameters related to oral processing. For example, Foster et al. (2006) recorded muscle and jaw activity as study participants chewed gummy candies with a range of hardness in order to compare the results with mechanical texture analysis. Wagoner et al. (2016) examined caramel via similar methods. These studies, among others, illustrate the complexity of human oral processing of confectionery and the difficulty of mimicking it with machines.

1.2.2 Texture Analyzer

In general, the properties of confections that are most typically examined via a texture analyzer are hardness and stickiness, although tensile tests are also sometimes used. Hardness in particular has been shown to correlate well with sensory panel results and therefore is useful for manufacturers in assessing the standards of a product (Szczesniak, 2002). In studies on confections, hardness has often been measured via a full texture profile analysis (TPA), as the TPA also provides other relevant mechanical data. Instrumentally measured stickiness or the related property adhesiveness in candies is determined via a variety of creative methods, including the peel test (Wang & Hartel, 2021), tack force (force required to pull the probe off of the sample) on a texture analyzer (Steiner et al., 2003), and adhesiveness as measured in a TPA (Kurt et al., 2022) or penetration test (Mendenhall & Hartel, 2016).

1.2.3 Other Instruments

Other instruments, especially the rheometer, are sometimes employed to approximate how the texture of a candy would be perceived by a consumer, as well as to determine fundamental parameters for comparison. However, since the force application of a rheometer differs significantly from human oral processing, rheometers are of limited use in comparison to sensory data. Nevertheless, rheological properties are frequently mentioned in the literature about confectionery science, as they are still important for understanding the broader mechanics of candies.

2 Hard Candy

"Hard candy" in this chapter refers to a candy containing sugar, glucose syrup, and water (along with flavor, color, and other minor ingredients) that has been cooked to high temperatures and cooled such that it forms a glass—an amorphous state of matter that is technically considered an extremely viscous liquid rather than a true solid. Hard candy comes in forms ranging from lollipops to carbonated candy to cough drops.

2.1 Ingredients and Manufacturing

Hard candy is made by cooking the sugar syrup to the hard crack stage (146–154 °C). At this point, the water content is very low (1–3%) and consequently the mixture will be very viscous. After cooking, volatile components like acids, flavors, and colors are added, and the candy is shaped and cooled. Shaping can be done by depositing a hot liquid into a mold, such as for lollipops, or by physical manipulation of a cooled pliable mass, such as for "cut rock" (hand manipulation) or drops (mechanical roller).

2.2 Structure

The key microstructural element of hard candy is the glassy state, characterized by the glass transition temperature (Tg). Tg is defined as the point where the viscosity of a fluid exceeds about 10^{12} Pa-s and the material becomes solid like. Hard candy is a metastable, highly supersaturated solution in the glassy state that does not crystallize because of the limited molecular mobility. When kept below Tg, the candy does not undergo cold flow due to its glassy state—molecular mobility is reduced enough that movement cannot occur. If the storage temperature is too high, the candy can begin to flow and even become fluid again. Tg is dictated by a combination of water content and saccharide distribution in the formulation, with low water content and high molecular weight saccharides giving a higher Tg. Hard candy is very hygroscopic, meaning that it has a high tendency to absorb water from the air. If water is absorbed, it dissolves some of the sucrose on the exterior of the candy, which can then lead to crystallization (an undesirable occurrence for many hard candy products). Hard candies can sometimes be aerated, such as in candy cane production; the air can be incorporated physically or chemically and serves to change both color and texture of the final product.

2.3 Rheology and Texture

The main factors affecting texture of hard candy are Tg, water content, and the molecular weights of the saccharides present in the formulation. Hardness is generally correlated with Tg, with a higher Tg corresponding to a candy that is harder and less chewy (Hartel, 2012; Nowakowski et al., 2015). Much of the differences in texture between varieties of hard candy comes from moisture content, whether within the formulation or absorbed from the air. As illustrated in Fig. 2, hard candy has a J-shaped (type III) moisture sorption isotherm, meaning that equilibration with a high-relative-humidity environment will cause the candies to take up moisture at an exponential rate (Netramai et al., 2018).

This moisture uptake can cause stickiness and potentially graining if the glucose syrup-to-sucrose ratio is low. The stickiness comes from the fact that moisture sorption into hard candy reduces its Tg; a lower Tg means that the product will regain fluid properties at a lower temperature, resulting in stickiness (Nowakowski & Hartel, 2002). Adding a higher proportion of glucose syrup to the formulation assists in preventing graining, as it inhibits crystallization, but it also increases stickiness (Nowakowski & Hartel, 2002). Similarly, a higher DE corn syrup will contribute more lower molecular weight sugars, lowering Tg, and increasing stickiness.

3 Fondants and Creams

Fondant, a highly crystallized sugar matrix, is typically found as filling for chocolate-coated candies or a basis for cake icing, and is also used as a seed crystal source for confections like fudge. Creams are usually a mixture of fondant and frappé, an aerated sugar solution, making them less dense than fondant. Creams can be found as fillings of chocolate-enrobed confections.

3.1 Ingredients and Manufacturing

To make fondant, a mixture of sucrose and up to 15% glucose syrup is heated so that any sucrose crystals are entirely dissolved. Then, the mixture is boiled down to approximately 10–12% moisture, and finally cooled statically to optimal beating temperature (40–50 °C) before being intensely agitated in order to promote rapid, almost instantaneous, crystallization to maximize nucleation rate and minimize crystal growth.

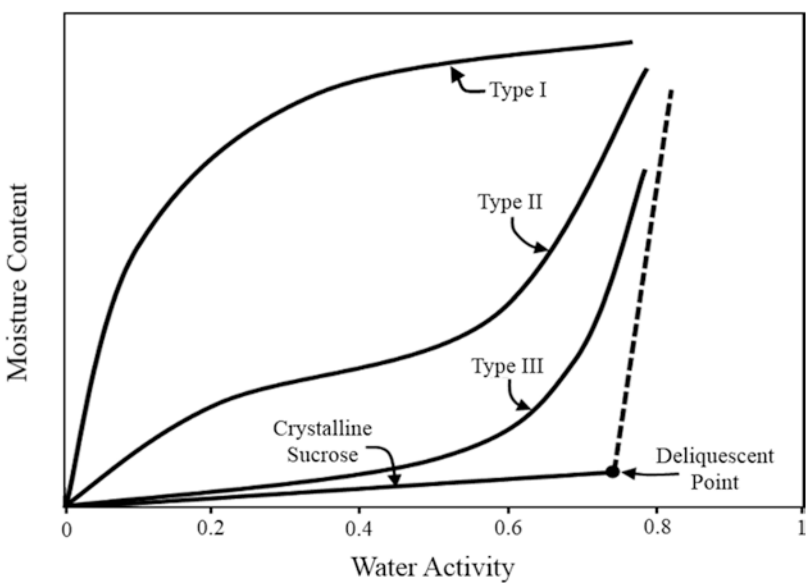

Fig. 2 Common moisture sorption isotherms (from Hartel et al., 2018). Hard candy has a type III isotherm (Netramai et al., 2018)

This agitation allows production of a large number of small (<20 µm) sugar crystals. Deposited creams use fresh fondant combined with bob syrup, a mixture of sucrose and glucose syrup at approximately the same proportions as the continuous phase of fondant, in order to thin the fondant enough for depositing. Extruded creams use a powdered version of fondant as a basis, with water added to reach the right consistency. Colors and flavors are added to creams to provide unique tastes. Creams also can include invertase, an enzyme that softens the cream over time by hydrolyzing sucrose (Hartel et al., 2018).

3.2 Structure

Both fondants and creams are highly crystallized, with air content being the major structural difference between the two—creams are more aerated in order to reduce density. Fondants can be considered a dispersion of sugar crystals in a sugar syrup continuous phase, which consists of all the water, all the glucose syrup and sucrose to saturation. Creams are similar, but with numerous small air bubbles from the frappé dispersed throughout the continuous phase. Fondants are 45–60% crystalline on a mass basis, with the higher crystal content yielding a firmer fondant. The size of the crystals is generally intended to be below the consumer's detection threshold, which is approximately 15–20 µm. The crystallization amount and size are controlled by many factors, including degree of supersaturation, beating temperature and intensity, and ratio of ingredients that inhibit crystallization (corn syrup, invert sugar, etc.).

3.3 Rheology and Texture

Textural properties of fondants and creams are dependent on crystal content, composition of the liquid phase (primarily affecting continuous phase viscosity), and density. Fondant with a lower water content is firmer because more of the sucrose is in crystalline form rather than in solution. Beyond hardness, the texture of fondant is dependent on crystal size, with crystals that are too large being detectable as coarseness by the consumer. Thus, controlling crystal size by beating the fondant at the optimum temperature for that formulation is necessary (Hartel, 2001). Preventing crystallization before beating has begun is also important for optimizing the balance between crystal nucleation and growth.

Low molecular weight humectants like glycerol and invert sugar soften texture by reducing continuous phase viscosity. Invert sugar may be added directly to a formulation or created via the addition of invertase or acid to the sucrose mixture before cooking. Invert sugar also softens texture by limiting sucrose crystallization. The addition of invertase to fondants and creams was demonstrated to decrease hardness along with the loss and storage moduli (i.e., made the fondants softer and more fluid) and received higher sensory scores from a 10-person panel (Ozcan et al., 2019). The hardness of creams is also decreased by addition of frappé to reduce density. Small air bubbles dispersed throughout the sugar matrix allow fracture points upon compression, meaning that less force is needed to break the product.

4 Gummies and Jellies

The differentiating factor between gummies, jellies, and other confections is the presence of a hydrocolloid, which forms a network around an aqueous sugar solution. The term "gummies" technically refers solely to candies made with gelatin, while the term "jellies" refers to every hydrocolloid except gelatin (pectin, carrageenan, starch, agar-agar, etc.). The term "gummies" is now sometimes used colloquially to encompass all hydrocolloid-based candies.

4.1 Ingredients and Manufacturing

These candies are made by combining and cooking sugar, glucose syrup, water, and flavor/acid/color with a (typically pre-hydrated) hydrocolloid and letting the mixture set as it cools. Details such as cook temperature and time, as well as when the hydrocolloid is added, are dependent on the type of hydrocolloid used. After cooking is complete, the mixture can be deposited into molds, either starch or starchless, poured as a slab to be cut, or extruded into ropes or other shapes.

4.2 Structure

The definition of "gels" is somewhat ambiguous. Bagal-Kestwal et al. (2019) define them as "non-fluid colloidal networks or polymer networks that are expanded throughout their whole volume by a fluid," while Glicksman (1982) defines them more specifically as "the association or cross-linking of long polymer chains to form a three-dimensional continuous network which traps and immobilizes the liquid within it to form a firm, rigid structure that is resistant to flow under pressure." The key point in both these definitions is that gels are essentially liquids held in place by a network of hydrocolloids. "Hydrocolloids" are similarly loosely defined, being described as "a range of polysaccharides and proteins derived from various sources including trees, plants, seaweeds, microorganisms, and animals" by the Handbook of Hydrocolloids (Williams & Phillips, 2021).

The most common types of hydrocolloids used in confections (excluding licorice, which will be discussed in its own section) are gelatin, starch, and pectin. Each has a different gelation mechanism based on the intrinsic chemistry and the operating conditions.

4.2.1 Gelatin

Gelatin is a protein derived from collagen, itself a protein found in animal bones, skin, and connective tissue. Collagen-containing animal parts—usually bovine hide or pig skin—are chemically treated and heated in order to break covalent and hydrogen bonds in the collagen, forming gelatin (Dille et al., 2021). Gelatin gels are uniquely thermoreversible at a temperature near that of the human body and are formed as the hydrated gelatin molecules cool and form a cross-linked network of triple helices (Dille et al., 2021). These cross-links are what provide gelatin gummies with their characteristic elasticity and distinct texture. Gelatin is most typically classified by bloom strength, which is a measure of the hardness of a gel under standardized conditions. For more information on gelatin, see chapter "Hydrocolloids as Texture Modifiers".

4.2.2 Starch

Starch granules consist of densely packed amylose and amylopectin molecules. In the granule, the amylose is amorphous, while the amylopectin molecules are partially crystalline. Once heated in the presence of sufficient water, the granules absorb water and swell, allowing amylose molecules to leach out from within the granule. Likewise, given enough heat and water, the amylopectin molecules lose their crystallinity and become part of the aqueous solution. When cooling begins, the amylose molecules interact to form a gel network, which is perceived as chewy when eaten (the more the amylose present, the firmer the gel). For more information on starch, see chapter "Starch, Modified Starch and Extruded Foods".

4.2.3 Pectin

Pectin, a polysaccharide made of galacturonic acid units and extracted from citrus rinds and other fruit skins, has two main types, high and low methoxyl, depending on the number of methoxyl groups attached to the chain. High methoxyl (HM) pectin (>50% methoxylated) sets when the pH of the solution is low enough. Acidic solutions deionize the carboxyl groups attached to the molecular backbone, leading to attraction and formation of junction zones. Having the correct sugar content is also necessary for gelation to occur, as the sugar competes with the pectin molecules for water and thus enables cross-linking. Low methoxyl (LM) pectin sets when there are enough calcium or similar ions present in the solution, generally regardless of pH or sugar content. HM pectin gels are softer and shorter than LM pectin gels, which are more on the rubbery side. Pectin that is low on both methoxylation and amidation coagulates into a jam-like texture but will not form a full gel. In confections, LM pectin is not frequently used. For more details on pectin, see chapters "Texture of Vegetables and Fruit" and "Hydrocolloids as Texture Modifiers".

4.2.4 Mixed Hydrocolloids

Mixing different hydrocolloids together leads to a wide range of properties, many of which have not yet been fully explored in the scientific world or found their way into the confectionery industry. Whenever hydrocolloids are mixed, there is potential for phase separation, which can affect texture and shelf life of these products.

4.3 Rheology and Texture

The textures of gummies and jellies depend significantly on the water content and the type of corn syrup used, which dictate the viscosity of the continuous phase, as well as on the amount and type of hydrocolloid used in the formulation. In general, adding more of a hydrocolloid will lead to the formation of more cross-linked junction zones, which in turn increases gel rigidity (Saha & Bhattacharya, 2010). Table 3 shows the typical textures of confections made with the different hydrocolloids.

Confectionery gels are differentiated from standard hydrogels by the addition of sucrose or another sweetener. Adding sugar to a gelatin gel, for example, increases the gelation and melting temperatures while decreasing the strength of the gel system, implying a disruption of the internal gel structure (Wang & Hartel, 2022a). The higher solids content that comes from the sugar increases cross-linking in gelatin gel systems, though it inhibits cross-linking in starch-based systems (Burey et al., 2009). Acids, which are also often added to confectionery gelatin gels to enhance flavor, have less of an effect on the hardness (Wang & Hartel, 2022b).

Table 3 Textures and appearances of the three main hydrocolloids in gummies and jellies

Hydrocolloid	Gelatin	Starch	High methoxyl pectin
Texture and appearance	Elastic; firm; translucent	Chewy; soft or firm; opaque	Short; tender; clear

Adapted from Carr et al. (1995)

The elastic texture of gelatin gummies varies depending on the amount and type of gelatin used. Adjusting the concentration and bloom strength of the gelatin may yield gummies with the same hardness, but other textural properties may vary. For example, gummies made with higher bloom gelatin yield a shorter and firmer texture. The elastic properties of gelatin are unique, imparting a unique texture to gummy candies that is difficult to match with any other hydrocolloid or combination of hydrocolloids. Pectin jellies are more tender and have a shorter texture than gelatin gels, while starches provide more chewiness with a range of firmness (Carr et al., 1995).

Mixing multiple hydrocolloids in one system frequently leads to phase separation, particularly when a protein and a polysaccharide are present together. However, some combinations can be beneficial when creating new candies. For example, confectionery gels made with gelatin and HM pectin were smoother, more brittle, and less chewy than gels made without the pectin (DeMars & Ziegler, 2001). Gummies made with kappa-carrageenan, a seaweed derivative, were more brittle and less elastic than gelatin gummies (Song et al., 2022). Upon addition of carboxymethylcellulose, though, water mobility became more restricted, leading to a decrease in syneresis and a consequent increase in elasticity (Song et al., 2022). In this study, texture was evaluated via both texture profile analysis (TPA) performed by a texture analyzer and quantitative descriptive analysis (QDA) performed by a sensory panel. They concluded that the TPA measurements of hardness, adhesiveness, cohesiveness, gumminess, and chewiness can be used as predictors of the sensory product evaluations. Kappa-carrageenan also works synergistically with konjac, a hydrocolloid gum derived from tubers (Utomo et al., 2014). This study showed that adding konjac to kappa-carrageenan in jelly candies gave the candies sensory attributes closer to a gelatin-based commercial candy than kappa-carrageenan alone. Together, these studies provide a few examples of synergistic hydrocolloid combinations, with many options still unexplored.

5 Licorice

Licorice can be considered a subset of gummies and jellies—one that uses flour as the gelling agent. It is argued that true licorice must contain licorice and/or anise extract; however, many sorts of flour-based fruit-flavored twists are commonly referred to as licorice, particularly in countries where "licorice" lacks a Standard of Identity.

5.1 Ingredients and Manufacturing

Wheat is the most typical flour found in licorice, at around 20–35% of the total formulation. Sweetness is provided by glucose syrup, molasses, and/or sugar, as well as glycyrrhizin, the sweetener component of licorice extract; oil may be added for lubrication. The ingredients are combined in a kettle, boiled, and cooked under pressure until the starch is gelatinized to the proper extent. After cooking, acids, color, and flavors may be added, and the candy is extruded to form the desired shape. Licorice must be extruded at a very specific temperature in order to maintain flow of the candy while also ensuring that it will set in the proper form.

5.2 Structure

As with regular starch jellies, the gelatinized starch from the flour in licorice creates a matrix surrounding an aqueous sugar solution. Gelatinizing the starch to the correct degree, where some starch granules are fractured and others are swollen but intact, is critical to develop the correct structure. In commercial licorice, some granules remain intact, with the birefringence retained.

Water content and cooking temperature are critical parameters to control in order to avoid either complete or insufficient gelatinization. The addition of sugar also impacts texture by raising the gelatinization temperature, along with raising boiling point of the sugar mass. Thus, cooking parameters such as time and temperature must be precise.

5.3 Rheology and Texture

Licorice texture is primarily influenced by water content, starch content and gelatinization level, humectant presence, and sometimes fat presence. Traditionally produced (batch/kettle-cooked) licorice often has a shorter texture than commercially produced (continuously processed) licorice, but both are typically dense and chewy. Flour type also affects texture, as different flours can differ in amylose and amylopectin levels—a higher amylose content will generally lead to a stronger gel structure. The degree of gelatinization of the starch in the flour, which depends primarily on cook time and temperature as they relate to water content, can cause undesirable textures—over-gelatinization of starch results in a chewy, elastic product, while insufficient gelatinization results in one that is dry and spongy. Furthermore, the longer-chained molecules present in molasses and glucose syrup provide more softness than the smaller sucrose molecules, so controlling ingredient proportions is important to texture control (Cottam, 2013).

Starch retrogradation refers to the concept of starch molecules rearranging themselves and crystallizing, either immediately upon cooling (amylose molecules) or after several days (amylopectin molecules). In licorice-type sweets, retrogradation occurred more rapidly in harder products, suggesting a correlation between the two properties (Díaz et al., 2010). Hardness, which increased with the amount of acetylated corn starch added, was measured with both a Warner-Bratzler shear cell on a texture analyzer and a sensory panel.

6 Marshmallow

Marshmallows are airy confections that can be eaten plain, enrobed in chocolate, roasted over a fire, or used as a hot chocolate topping. They can be grained (e.g., circus peanuts) or ungrained (e.g., extruded marshmallows). The term "marshmallow" refers to the origin of the confection, which was originally made from the root of the marsh-mallow plant (*Althea* sp.). Marshmallow crème, a variation of marshmallow with a more spreadable texture than the extruded types, can be used as a spread or an ingredient in fudge.

6.1 Ingredients and Manufacturing

Contemporary commercial marshmallows are similar in formulation to gelatin gummies, with the basic recipe consisting of sugar, glucose syrup, water, and gelatin. Once the sugar and glucose syrup are cooked and cooled a bit, hydrated gelatin is added, and the product is whipped or otherwise aerated until the proper density is achieved (approximately 0.3 g/mL for extruded marshmallows). The cooling step is important in order to prevent denaturation or degradation of the gelatin, which would decrease its whipping abilities. Aeration methods for marshmallows include planetary mixers, pressure mixers, and continuous pressure beaters. After whipping, the marshmallow mixture is then extruded or deposited, with deposited marshmallows typically being slightly denser than the extruded type.

6.2 Structure

A standard marshmallow consists of air whipped into an aqueous sugar phase. As in other grained confections, grained marshmallows also have small sugar crystals distributed within the continuous aqueous phase. The process of aeration requires two steps: introduction of air and then stabilization to prevent coalescence of the bubbles. The bubbles are stabilized by the gelatin, which forms a gel at the air interface with the aqueous phase. The bubbles are distributed within the aqueous phase, decreasing the density of the product while increasing viscosity.

6.3 Rheology and Texture

Air (and therefore density) and water content are the most critical factors influencing marshmallow texture. A large number of small bubbles generally provides the characteristic smoothness. The air bubbles can act in a similar (albeit less dramatic) manner to sugar crystals, creating a shorter texture by disrupting the aqueous continuous phase. Grained marshmallows contain sugar crystals in addition to air bubbles, making the texture even shorter.

Marshmallows frequently harden under lengthy or suboptimal storage conditions, primarily due to moisture loss. The effects of moisture loss were more significant than those of sucrose crystallization, with higher DE glucose syrups allowing the marshmallow to retain more moisture (Lim et al., 2006). The increase in hardness as measured with a texture analyzer correlated with an increase in Tg, indicating that a higher Tg is the reason for the increased hardness. Lim et al. (2006) also determined via optical microscope images that longer whipping times led to smaller and more uniformly sized air bubbles, which had a higher degree of structural stability but allowed for more moisture loss (and thus a harder product after storage) than larger and less uniformly sized bubbles.

Beyond hardness, texture of marshmallows can be assessed via compression cycles in a texture analyzer (Kaletunc et al., 1992). In addition to standard texture analysis, the texture of marshmallow-style confections can be evaluated acoustically by using a sensor and amplifier to assess acoustic emissions upon deformation. Mechanical (texture analysis) as well as acoustic properties were shown to be affected by the whipping time of an agar-stabilized fructose solution (Herremans et al., 2013). Longer whipping time correlated with lower compression work along with a larger number of acoustic events, indicating a softer foam with a larger number of smaller-sized air bubbles.

7 Chewy Candies

Chewy confections, ranging from fruit chews to saltwater taffy to nougat, are lightly aerated. Aeration impacts texture significantly, as well as affecting other sensory and physical properties.

7.1 Ingredients and Manufacturing

As with other confections, the main ingredients in chewy candies are sugar and glucose syrup. Supplementary ingredients can be added to alter various properties, like humectants (to improve shelf life), fats and emulsifiers (to increase lubricity), starch (to reduce cold flow and increase shortness), and inclusions such as nuts. Hydrocolloids are also typically added in order to stabilize the air bubble structure, prevent coalescence and cold flow once the product has been aerated, and provide texture and chew. Aeration is a key part of the chewy candy manufacturing process and occurs after mixing and cooking to the desired water content. Aeration can be accomplished via incorporation of a frappé (a pre-aerated foam), air injection, pulling, or whisking.

7.2 Structure

Chewy candies typically consist of an amorphous sugar phase with a hydrocolloid, sometimes along with some fat and/or graining. Aeration method has a significant effect on the size, shape, and number of air bubbles present in the finished candy. For example, taffy is typically aerated via pulling, which leads to larger, irregularly shaped air bubbles. Some confections may have fat added, primarily to mitigate stickiness; however, fat must be added carefully so as not to interfere with the air bubble interface, leading to less aeration. Many chewy candies are slightly grained, in which case they will have small sugar crystals within the continuous aqueous phase. Grained chewy candies are generally less than 10% crystalline, as compared to fondant (45–60%).

7.3 Rheology and Texture

The texture of chewy candies is most notably affected by water content, Tg, and graining. Tg and water content are important for ensuring the correct hardness level—since chewy candies are typically intended to be soft, Tg must be low, with a water content of approximately 6–11% (McGill & Hartel, 2020). Viscosity of the continuous phase through choice of glucose syrup and/or humectant also affects texture, with more humectant giving softer texture. As with other grained candies, grained chewy candies will have a shorter texture than ungrained versions due to the interruption of the matrix by sucrose crystals. Starch addition can also provide some shortness, as well as decreasing cold flow.

Based on small amplitude oscillatory shear measurements performed on a rheometer, grained fat-containing chewy candies were found to have more of an elastic character than ungrained candies, which were more viscous (Schmidt et al., 2018). The graining led to lower stickiness, as well as a shorter texture, due to the grained crystals providing failure points amid the amorphous phase. Hardness was not significantly affected by graining; however, both types of candies were significantly softer at elevated temperatures due to the fat melting. Hardness and stickiness were measured with a cyclic penetration experiment on a texture analyzer, while shortness was evaluated using a tensile test.

8 Caramel, Fudge, and Toffee

Caramel, fudge, and toffee are distinguished from other confections by the inclusion of dairy (or a product equivalent to dairy for confections for those with dietary restrictions). Fudge is considered to be a highly grained caramel, being approximately 25–30% crystalline. “Toffee” is a term with different meanings depending on location, but in the United States, it refers to a candy made with primarily sugar and butter (no glucose syrup).

8.1 Ingredients and Manufacturing

Caramelization, a type of non-enzymatic browning, occurs when the sugar in a product is heated and releases caramel-flavored volatiles. Maillard browning, another type of non-enzymatic browning, also can play a role in the production of caramel, fudge, and toffee as a reaction between the milk proteins and reducing sugars (glucose and lactose). The influence of caramelization and Maillard browning on a product's flavor depends on formulation and processing.

8.1.1 Caramel

Caramels generally consist of water, sucrose, glucose syrup, and some form of dairy product (cream, butter, sweetened condensed milk, etc.). There are two approaches to caramel production: the first method favors Maillard browning and consists of mixing all the ingredients and then cooking to the desired temperature (which corresponds with water content); the other method favors caramelization and involves melting sugar and then adding the other ingredients. Due to the presence of fat, homogenization is important in manufacturing in order to maintain a consistent fat globule size. Hydrocolloids are also sometimes added to caramels to adjust texture properties.

8.1.2 Fudge

Fudge is made in the same manner as the first caramel production method, in which ingredients are mixed and then heated. To create the characteristic short texture, graining is promoted either by agitating the cooked candy as is done with fondant or by just seeding it with pre-made fondant.

8.1.3 Toffee

English toffee, as this confection is known in the United States, traditionally uses solely sucrose as the sweetener (i.e., no glucose syrup). Some of the sucrose inverts upon heating, preventing graining in a similar manner to glucose syrup. Regulating the fat content and including an emulsifier such as lecithin are also particularly important for toffee, as it does not contain much protein and thus has less fat globule stability.

8.2 Structure

On a basic level, caramel is an aqueous solution containing dissolved sugars and salt and dispersed protein aggregates and fat globules. The protein aggregates consist of partially denatured whey proteins complexed with casein micelles; they help prevent cold flow by raising viscosity. Caramel can be either grained or ungrained depending on whether there are sugar crystals present. Fudge is essentially a highly grained version of caramel, with sugar crystals disrupting the protein-and-carbohydrate network. Caramel can also be cooked to extremely low water content, in which case it would form a glassy matrix in a similar manner to hard candy. Somewhat similarly, toffee is a glassy emulsion that has small, partially crystalline butterfat globules dispersed throughout the sugar matrix. These globules are emulsified enough to provide good flavor release without leaving the consumer with a greasy mouthfeel (Lewis, 2007).

8.3 Rheology and Texture

As mentioned previously, caramel can have a wide range of textures depending on formulation and processing; the textures depend on water, protein, and fat contents, along with graining and hydrocolloid choice. Caramels are generally more viscous than elastic ($G'' > G'$), with liquid-like behavior at higher temperatures (Ahmed et al., 2006). Water content affects hardness, with lower water content leading to a harder candy. A higher degree of protein aggregation can also create a harder candy. Fat content can change the texture: not enough fat creates stickiness, while too much can lead to greasiness. Graining controls shortness—the high level of graining in fudge results in a much shorter texture than stretchy, ungrained caramels. Further, choice of hydrocolloid can have significant textural effects, with pectin and gelatin providing chewiness, starch providing shortness, and egg albumin foam providing lightness.

In an evaluation of ungrained caramel with varied corn syrup types and quantities of a fixed ratio of sweetened condensed milk to palm kernel oil, texture measurements from a sensory panel were directly compared with data from a rheometer and a texture analyzer (Steiner et al., 2003). Increasing the fat content by raising the amount of sweetened condensed milk and palm kernel oil decreased stickiness, as did using lower DE corn syrup. Panelists were most able to differentiate between samples based on hardness, stickiness, and toothpacking, with cohesiveness being the property least conducive to distinguishing the different samples. Storage modulus and viscosity as measured by the rheometer correlated with sensory hardness, cohesiveness, and number of chews; tack force as measured by the texture analyzer correlated with the perceived stickiness. The tack-stickiness correlation was observed by other researchers as well (Wagoner et al., 2016).

Aggregation of the milk proteins can also affect the hardness of a caramel, with larger aggregates creating a harder product by disrupting the continuous sugar syrup phase (Mendenhall & Hartel, 2016). Ingredient selection also plays a role in stickiness, where addition of mono- and diglycerides reduced stickiness by reducing the adhesive energy of the caramel (Wang & Hartel, 2021).

Oral processing measurements also can give context for the texture of a food. By using electromyography to measure jaw and facial muscle movement, hardness was shown to be the primary mechanical property correlating with oral processing (Wagoner et al., 2016). This study also varied ingredients, noting that caramels containing agar were perceived as harder and less sticky than those containing gelatin or not containing any hydrocolloid. Decreases in hardness correlated with increases in adhesiveness, as shown by changes in jaw movement as different caramels were tasted.

9 Tablets and Lozenges

Tablets and lozenges are more typically seen in the pharmaceutical industry, but they also represent an important segment of confectionery. Tablets and lozenges generally consist of a powder blend held together by either compaction or a binding ingredient.

9.1 Ingredients and Manufacturing

To make a tablet, sweetener particles are compacted in a tablet press. Magnesium stearate is frequently used as a lubricant to ensure smooth passing of the powders through the tablet press. Prior to compaction, the crystals sometimes need to undergo granulation treatment to ensure they will compact properly. This granulation can be either wet, meaning that a paste is made from the binder and particles and is subsequently dried and ground, or dry, meaning that pellets will be made rather than a paste. Lozenges, on the other hand, are not compacted; instead, a wet granulation paste is made by mixing sweetener powder with a liquid binder (glucose syrup and hydrocolloid) that is then shaped and dried.

9.2 Structure

In a lozenge, the base particles are held together by solid bridges and capillary forces from the liquid binder; the solid bridges form between sucrose particles due to recrystallization after water removal during drying. In a wet granulated tablet, capillary forces from the binder hold particle aggregates together within granules, and the granules are bonded together to form the larger tablet. For directly compacted tablets, particulate fracturing and rearrangement occurs, providing interparticle forces that strengthen the candy.

9.3 Rheology and Texture

The main sensory attribute perceived in a tablet is its hardness, which is affected by interparticle forces and water content. The high compaction pressure and the solid bridges formed between particles in a wet granulated tablet generate enough interparticle force to create a very hard product. Likewise, the fragmentation of the particles in direct compaction creates similar levels of interparticle force. Lozenge hardness depends on the initial water content of the dough—higher water content means more bridges are able to form, producing a harder candy. Excessive use of lubricant in a tablet can detract from hardness, as can lower compression force.

Unlike most other candies, tablets and lozenges do not rely on crystallization during production; instead, the importance of crystallization comes from the starting particle size (Vink, 1996). Particle sizes for wet granulation typically range from 20 to 60 mesh (250–840 μm), with size differences allowing smaller particles to fit in the interstitial sites between larger ones. Similarly, the fragmented particles in directly compacted tablets can fit between and bind with the unfragmented ones.

10 Gum

Versions of gum have existed since ancient times, though it only started being commercialized in the mid-1800s (Fritz, 2008). Modern gum is typically separated into two categories: chewing gum and bubble gum. Gum comes in myriad forms, ranging from tabs to blowpops to gumballs.

10.1 Ingredients and Manufacturing

Gum has many components, most notably gum base, which is a collection of natural and/or synthetic polymers with functional additives like plasticizers or antioxidants. Composition of the gum base plays a major role in the textural properties of gum. Bubble gum base contains a higher proportion of rosin esters and butadiene styrene, a polymer, while chewing gum base contains more wax and polyvinyl acetate (both resins) and polyisobutylene/butyl (another polymer) (Fritz, 2008). Beyond the base, the main component is powdered sweetener, which can be either sugar or a range of other nutritive and non-nutritive sweeteners. Softeners, acids, flavors, colors, and occasionally more specialized or functional components make up a smaller fraction of the mass of the gum. Once the ingredients have all been thoroughly mixed, the gum is shaped and/or cut into its final form.

10.2 Structure

Gum is unique in that it is not designed to be consumed in the same fashion as other confectionery; rather, it is intended to be retained in the mouth for an extended period of time. As such, there are two separate stages of gum microstructure that must be considered.

The first stage is the gum before chewing has begun. The base itself is primarily an amorphous matrix, but the overall gum piece is mostly constituted of the sweetener particles and semi-crystalline wax or lipid dispersed in this matrix. The sweetener particles provide bulk in addition to sweetness, and the crystalline particles are meant to prevent cold flow so that the gum retains its shape before it is chewed.

The second stage is during and after chewing has begun. Once the gum begins interacting with the saliva in the mouth, the sweeteners dissolve, releasing the flavor from the now-hydrated gum base. The gum base at this stage still contains encapsulated flavors, acids, and/or high-intensity sweeteners, which will be released gradually as mastication continues.

10.3 Rheology and Texture

The texture of chewing and bubble gums primarily revolves around composition. The synthetic rubbers in the gum base provide the characteristic viscoelasticity of chewing gum.

Because gum is not intended to be extremely elastic, the rubbers are not cross-linked so as to provide more plasticity. Softness of gum can be adjusted by changing the type and amount of polymers in the gum base, with higher molecular weight polymers producing a stiffer gum, or by adding plasticizers with a lower glass transition temperature. Adding too much or too coarse a variety of texturizer can lead to a feeling of coarseness as the gum is pressed between the tongue and the roof of the mouth (the method by which gum testers typically define texture) (Fritz, 2008).

Since "gum" is loosely defined, the goal of one study was to define "gum" based on the rheological properties of items that are typically considered to be gums (Martinetti et al., 2014). Their conclusion was that all chewing and bubble gums have classic (power law-fitted) critical gel behavior in the linear regime and "dramatic" strain extension. In other words, all studied gums meet the rheological criteria of a critical gel (the viscosity approaches infinity under steady shear and the equilibrium modulus is zero) while within a strain range that does not cause permanent deformation, and all gums are very stretchy (Chambon & Winter, 1987). This characterization is claimed to be distinct from other similar materials, which may meet one of the criteria but not both. The study also examined the rheological distinction between bubble and chewing gum, determining that bubble gums undergo more strain hardening (i.e., upon reaching a certain strain, they will become more resistant to deformation) and are harder to break/begin chewing initially than chewing gums. Addition of more glucose syrup provides a softening effect—a study found that decreasing the proportion of gum base with respect to glucose syrup decreased hardness (Palabiyik et al., 2020). Comparison of texture analyzer and sensory results allowed the authors to define maxima for acceptable chewiness and hardness levels, with hardness playing the most important role in consumer acceptance.

11 Sugar Panned Candies

Panning is itself not a type of candy, but rather a method of coating other items (candies, nuts, or anything small). There are three kinds of panning: soft panning, as is used for jelly beans; hard panning, as is used for coating chocolate lentils; and chocolate panning, as is used for chocolate-covered almonds. Techniques can be combined, such as for a Jordan almond, which are first chocolate panned and then hard panned. This section will cover soft and hard panning.

11.1 Ingredients and Manufacturing

As might be expected, panning is traditionally performed in a rotating pan, although larger continuous operations use a panning drum. Layers of sugar ("engrossing") syrup are applied to build up the desired level of coating. Particularly for irregularly shaped or lipid-containing centers, a pre-coating layer is applied first in order to maximize adherence of the sugar to the center. Pre-coating material differs depending on the type of center, but is typically a thin layer of a protein, gum, or long-chained carbohydrate. The sugar syrup is then applied in a number of doses as the pre-coated centers tumble in the pan. Generally, soft panning syrup is considered to be non-crystallizing, with a high proportion of glucose syrup to sugar; the addition of a layer of syrup is followed by a dry powder charge, usually starting with the larger particle size and ending with very fine sugar. Engrossing syrup for hard panning is intended to crystallize and thus has a high degree of supersaturation. It does not require a dry powder, as it hardens as it dries, and the sugar crystallizes out of solution. Usually, many layers (4–5 for soft panning and up to about 30 for hard panning) are needed to build appropriate shell thickness. After the sugar layers are complete, polish and glaze (usually wax, gum, starch, carbohydrate, protein, or shellac) are applied to finish the process and provide a glossy appearance.

11.2 Structure

11.2.1 Soft Panning

Soft panned candies have large crystals (25–100 µm) bound by the engrossing syrup. The force exerted on the crystals by other candies tumbling in the pan as well as the wall of the pan itself packs them tightly enough to hold together. A small amount of bridging among the crystals can occur due to temperature or water content changes.

11.2.2 Hard Panning

Unlike soft panning, the crystals in a hard panned shell are very small (about 1 µm or less). Once engrossing syrup is applied, the processes of crystallization and drying begin. Since drying leads to a higher solids content in the syrup (water is being removed from solution) and crystallization has the opposite effect (sugar is being removed from solution), both must be carefully controlled in order to optimize crystallization speed. Significant bridging among hard panned crystals likely occurs as well to produce the hard shell.

11.3 Rheology and Texture

Particle bridges, in conjunction with crystal size, dictate the texture of a soft or hard panned shell. The larger crystals of soft panned candies lead to a more easily broken shell due to the formation of fewer and weaker junction points; similarly, using more finely ground sugar for the dry charge additions leads to a firmer and smoother texture. By contrast, the bridges between the tiny crystals of hard panned candies result in a harder shell.

The water activity of the center can have an effect on final texture, particularly in soft panned candies. If water activity of the center is lower than the coating, moisture will migrate from the coating to the center until equilibrium is reached, resulting in a softer center and a harder coating than the original (Boutin et al., 2004). Equilibration with the surrounding environment also occurs, which can lead to excessive hardness in products like jelly beans (Troutman et al., 2001; Ergun et al., 2010). Water content can also affect hard-panned confections—if the water in the engrossing syrup is not allowed to completely evaporate, the moisture can be trapped between layers and cause shell failure (Bogusz, 2004).

12 Chocolate

Chocolate is one of the most complex types of confectionery, in terms of both components and manufacturing. It takes a variety of forms, but is most notably seen in chips, bars, or candy coatings. Compound coatings, which are made from fats other than or in addition to cocoa butter, don't meet the Standard of Identity in the United States, but are used to reduce costs and better control properties in many instances.

12.1 Ingredients and Manufacturing

The main ingredients in chocolate are chocolate liquor, sugar, cocoa butter, and sometimes milk powder. Chocolate liquor is also known as cocoa mass and consists of cocoa nibs that have been fermented, dried, roasted, and finally ground. The ingredients are mixed and refined to generate small sucrose and cocoa powder particles, then conched to release moisture and volatiles. Milk chocolate contains milk ingredients in addition to the sugar and cocoa ingredients, and white chocolate contains just cocoa butter, sugar, and milk solids, with no chocolate liquor present.

12.2 Structure

A chocolate bar has a continuous, partially crystalline cocoa butter phase with the cocoa solids and sugar particles dispersed within it. These particles range from 1 to 40 µm with an average of 10–20 µm. Cocoa butter takes several polymorphic crystal forms with differing degrees of stability and physical properties. Proper tempering and cooling of chocolate promote the development of the correct size, number, and polymorph of cocoa butter crystals. Because cocoa butters can be sourced from many different growing regions and types of beans, their lipid profiles might vary considerably, and therefore time and temperature must be adjusted to ensure successful temper.

12.3 Rheology and Texture

Chocolate is designed to melt in the mouth and, thus, the sensory properties of both solid and liquid chocolate are important to understanding the product as a whole. Particulate composition, fat content and characteristics, and tempering have significant effects on the texture of chocolate.

12.3.1 Liquid Chocolate/Rheology

Regardless of whether the chocolate is milk or dark, melted chocolate exhibits both thixotropic (time-dependent decreasing viscosity at constant shear) and shear-thinning (lower viscosity at higher shear) behaviors. Thixotropic behavior means that when melted chocolate is first stirred, particulate interactions that have built up over time cause the chocolate to be more viscous ($G' > G''$); continued stirring breaks down those interactions until the viscosity reaches a steady state ($G'' > G'$) (van der Vaart et al., 2013). The shear-thinning aspect means that since particles are able to interact more at lower shear rates, the viscosity will be higher than at a higher shear rate, when the particulate network is more disrupted. Increasing the cocoa butter (or other fat) content lowers viscosity of melted chocolate, since the fat increases the separation between cocoa and sugar particles and thus lessens their interactions. Emulsifiers like lecithin also decrease viscosity by altering the contact angle between sugar crystals and cocoa butter (Caparosa & Hartel, 2020). This property allows manufacturers to use less cocoa butter (and thus save money) while maintaining the same viscosity (Minifie, 1989). Understanding rheological properties of chocolate is critical because different chocolate applications (drops, molded bars, etc.) require different rheological properties.

12.3.2 Solid Chocolate/Mechanical

Dark and milk chocolates have different texture profiles, with dark chocolate being the harder of the two. Dark chocolate has a characteristic snap when broken, which comes from the tightly knit network of cocoa butter crystals surrounding the sugar and cocoa solids. Formation of the correct cocoa butter polymorph during tempering is crucial to ensuring this snap and also contributes to hardness (Afoakwa et al., 2007). Milk chocolate is softer due to the presence of milk fat, which causes a eutectic effect (lowers the melting point) and softens the texture (Afoakwa et al., 2007; Tscheuschner & Markov, 1989). The milk fat in milk chocolate also causes it to melt more quickly than dark chocolate (Tscheuschner & Markov, 1989).

The differences between the two types of solid chocolate are made clear in sensory tests, where milk chocolate is more cohesive and melts faster in the mouth, while dark chocolate is harder and packs the teeth more (Andrae-Nightingale et al., 2009). Andrae-Nightingale et al. (2009) also determined that hardness was the only sensory measurement taken that correlated significantly with instrumental data from a texture analyzer. However, Markov and Tscheuschner (1989) found reasonable correlations between sensory melting and instrumental melting height, as well as between smoothness (sensory) and maximum dispersed particle size (instrumental).

13 Summary

Confectionery products have a wide range of textures, both within and between categories. These textures are most notably affected by water content, choice and proportions of ingredients, glass transition temperature, and graining amount. Understanding the properties that dictate texture is critical to being able to develop candies that conform to consumer standards and desires.

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Starch, Modified Starch, and Extruded Foods

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1 Introduction

Quantitatively, starch is the second most abundant carbohydrate after cellulose. It is a major energy source for all living organisms, providing 60 to 80% of the calories consumed by humans globally. It is synthesized mostly by plants and some cyanobacteria and accumulates in specific tissues and organs like leaves (Arabidopsis), tubers (potato, cassava), grains (maize (corn), wheat, rice), fruit (green banana, apple), and stem (sago). Starch is stored in plants as discrete semi-crystalline particles, known as starch granules, varying in size (~1–100 μm in diameter), shape (polygonal, round, lenticular), association (simple, individual, or compound granule clusters), size distribution (uni- or bimodal), and composition (with different mineral, lipid, α-glucan, moisture, and protein contents) based on their botanical origin and growth environment.

The common sources of starch include maize, potato, wheat, cassava, and rice, whereas some less common sources include barley, oat, quinoa, sago, sorghum, yam, pulses, pea, and faba beans, among others. Starch is extracted from the mentioned plants using different extraction methods that involve separating starch granules from proteins and other plant tissues, washing to remove impurities, and then drying of starch which appears as a white/creamy powder.

Starch is of special interest in food and non-food industries as a versatile biomaterial due to its affordability, abundance, ease of modification, biodegradability, and non-toxic properties. It is used in the food industry as a source of energy and is added as an additive, thickener, stabilizer, gelling agent, binding agent, and moisture retention agent in many food products including bakery products, soups, noodles, sweeteners, beverages, sauces, coatings, and dairy and meat products. Another growing application of starch is the development of biodegradable packaging materials to reduce plastic packaging and their environmental impacts. Starch is also increasingly used in non-food industries such as adhesives, bioethanol and biofuel production, cardboard, leather, paper, textiles, and pharmaceuticals among other sectors.

This versatility of textural and functional properties of native starch largely depends on structural and compositional makeup of the granules, making its understanding fundamental for the optimal use of starch.

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2 Starch Granules and Composition

In nature, starch is deposited in plants in the form of granules in the amyloplast. Starch granules vary in size, shape, chemical composition, and interaction with other non-starch components depending on the plant source, plant maturity, and growth condition. The size of the granules varies from less than 1 micron to about 100 microns. Figure 1 shows the starch granules from different sources under the microscope. As depicted in the figure, rice starch granules are polygonal in shape and their diameter on average is usually <5 μm, and potato starch granules are elliptical in shape and are >75 μm in diameter. The granules may present simple or individually (e.g., rice starch) or as compound or cluster (e.g., wheat starch).

Starch granules contain growth rings comprising amorphous and crystalline domains formed by a complex network of amylose and amylopectin, organized in the form of alternating concentric shell-like structures of 120–400 nm thickness. Within the starch granules, starch molecules along with some minor components can be found as are described below.

2.1 Composition of Starch Granules

Starch is a polysaccharide, majorly (>97%) comprising two α [1 → 4] linked D-glucose polymers known as "amylose" and "amylopectin." Amylose is an essentially linear molecule with a few branches and forms a single helical structure in its native form, whereas amylopectin is a huge and highly branched molecule with a cluster structure of short chains linked together with α [1 → 6] branching links (Fig. 2). These are explained in more detail in the next section. In most common types of starches, relative weight percentages for amylopectin range between 72% and 82%, and between 18% and 33% for amylose. Certain genotypes, however, have up to 70% amylose (known as high amylose varieties), while other genotypes (waxy) have less than 1% amylose (Cornejo-Ramírez et al., 2018). The amylose and amylopectin content, their degree of polymerization (DP), and molecular weight vary with starch botanic sources, plant variety, maturity, and growth condition. The ratio of amylose to amylopectin has a significant effect on the physicochemical properties of starch. For example, firmness increases with increasing amylose content, thereby increasing the resistance of starch to take up water. Table 1 shows the amylose content and DP of some starches.

Apart from amylose and amylopectin, native granules contain some minor components including traces of protein, phosphorus-containing compounds, lipids, and minerals. The content of the minor compounds varies with the botanic source of starch, plant variety, growth condition, plant maturity, extraction methods, and chemical testing procedure (Table 2). Although minor components are low in quantity, they have great influence on the physicochemical and nutritional properties of starch. For example, it is well known that the complex between amylose and lipid reduces starch digestibility. In addition, starches with less impurities such as cassava starch produce gels with high clarity, while starches with more protein and fiber content such as cereal starches produce opaque gels.

2.2 Molecular Structure of Amylose and Amylopectin

Amylose, with a molecular weight range of 10^5–10^6 g/mol, has a corresponding degree of polymerization (DP) of 100 to 10,000 glucose units. Of these, less than 0.5% of the glucoses are in α[1 → 6] links, making it a relatively unbranched structure of 3–11 chains with about 200–700 glucose residues in each molecule. This low degree of branching facilitates the tendency to form semi-crystalline aggregates and colloidal suspensions upon dissolution.

Amylopectin is relatively larger with a molecular weight of about 10^8 g/mol and a DP that can exceed one million. About 5% of the glucose units in amylopectin are α [1 → 6] linkages, resulting in a highly branched, tree-like structure with a com-

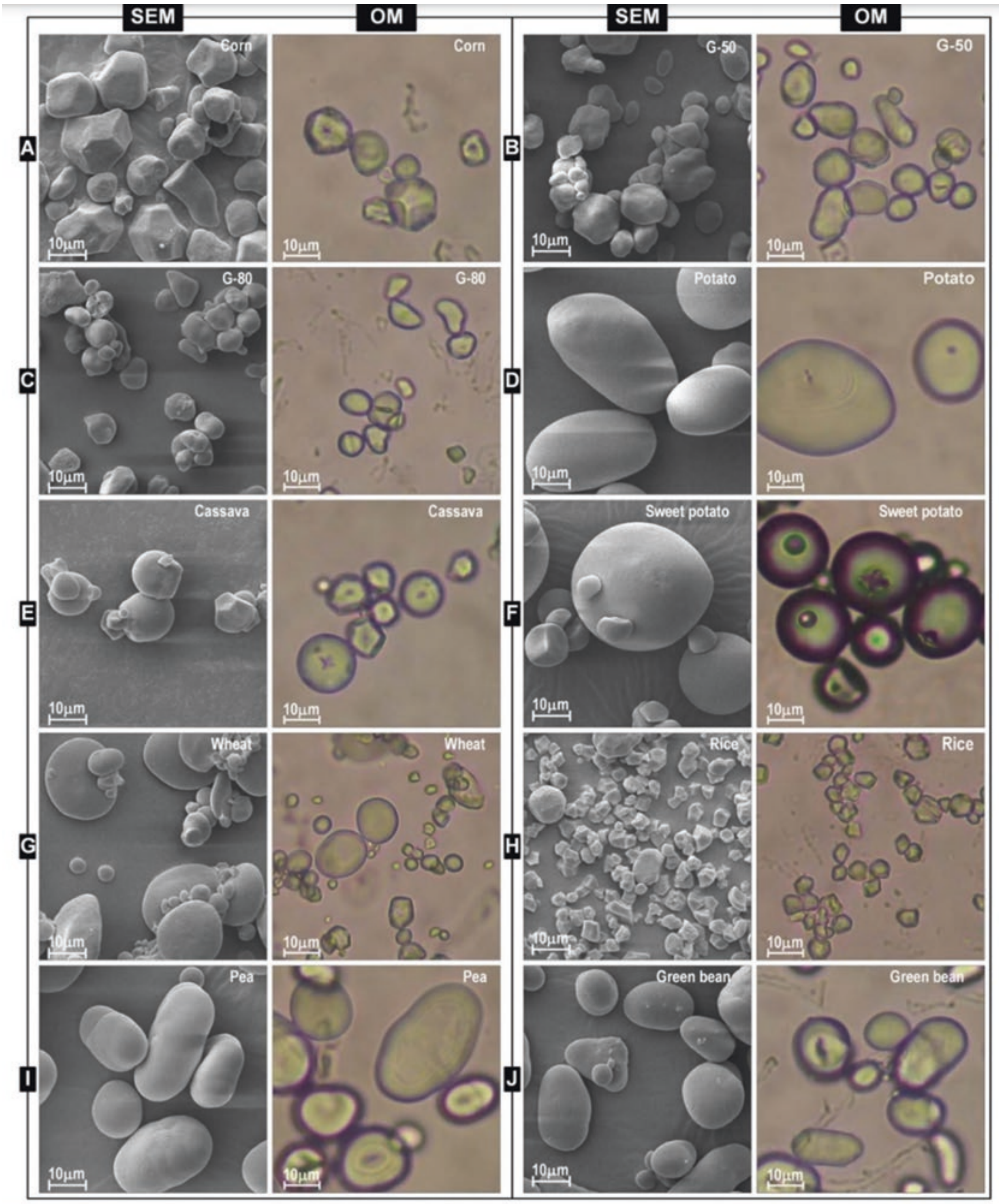

Fig. 1 SEM and optical microscopy images of starch granules from different botanical sources (Khalid et al., 2017)

plex molecular architecture that varies with the placement and length of branches (Bertoft, 2017). Amylopectin branches are classified according to their pattern of substitution: unsubstituted A-chains which have reducing ends that link covalently to B- or C- chains, but do not carry other chains, B- chains that link to other B- or C- chains and may also carry other A- or B-chains and a single C chain (per amylopectin molecule) that contains the only reducing end of the macromolecule (Fig. 3). The vicinal A-chains form double helices and are more thermostable.

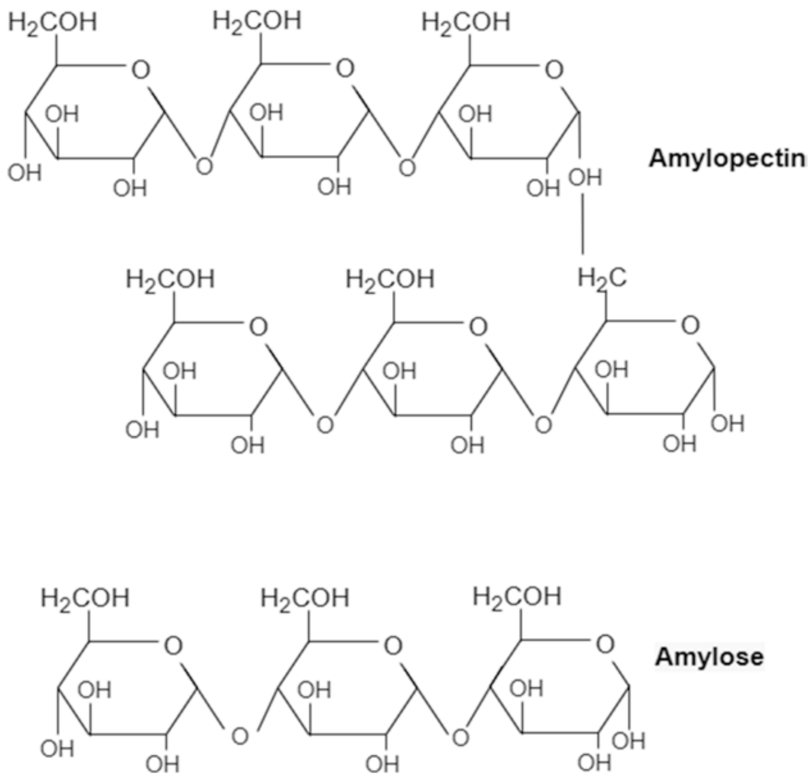

Fig. 2 Molecular structure of amylopectin and amylose

Table 1 Amylose content and degree of polymerization of common starches

Source	Amylose (%)	DP
Wheat	17–34	980–1570
Rice	17–29	230–370
Maize	20–28	960–830
Potato	25–31	4920–6340
Barley	22–27	1220–1680
Sweet potato	19–20	3280

Adapted from Bertoft (2017)

The arrangement of these double helices forms the crystalline lamellae which alternate with the amorphous lamellae formed by the clusters of the branch points (Fig. 4a). The thickness of such a repeat is maintained among starches of different botanical sources at around 9 nm. These sequential repeats of amorphous and crystalline lamellae form semi-crystalline zones which are limited by amorphous zones. Both zones are visible under the microscope and are called "growth rings" (Fig. 4b). The arrangement of amylose and amylopectin in the growth rings and the lamellar organization of the crystalline layers within these rings is still ambiguous (Vamadevan & Bertoft, 2015).

3 Morphological Properties of Starch Granules

Understanding the morphological properties of starch granules can provide us with valuable information about their origin (source of starch); granules type (e.g., A and B type granules in wheat starch); the presence of damaged starch granules caused by some severe food processing methods such as milling, sonication, and extrusion' granules water uptake and swelling as a result of starch gelatinization (e.g., during cooking of starchy foods); and the interactions between starch granules and other food compounds such as proteins (e.g., in bread crumb).

Table 2 Proximate composition of minor components in common starch sources

Source	Ash (%)	Protein (%)	Lipid (%)	Phosphorus (%)	References
Cassava	0.2	0.1	0.1	0.01	Beuninger et al. (2009)
Potato	0.4	0.1	0.1	0.08	Breuninger et al. (2009)
Corn	0.1	0.4	0.7	0.02	Breuninger et al. (2009)
Wheat	0.2	0.4	0.8	0.06	Breuninger et al. (2009)
Rice	0.2	0.3	0.9	n.a.	Yoo and Chang (2018)

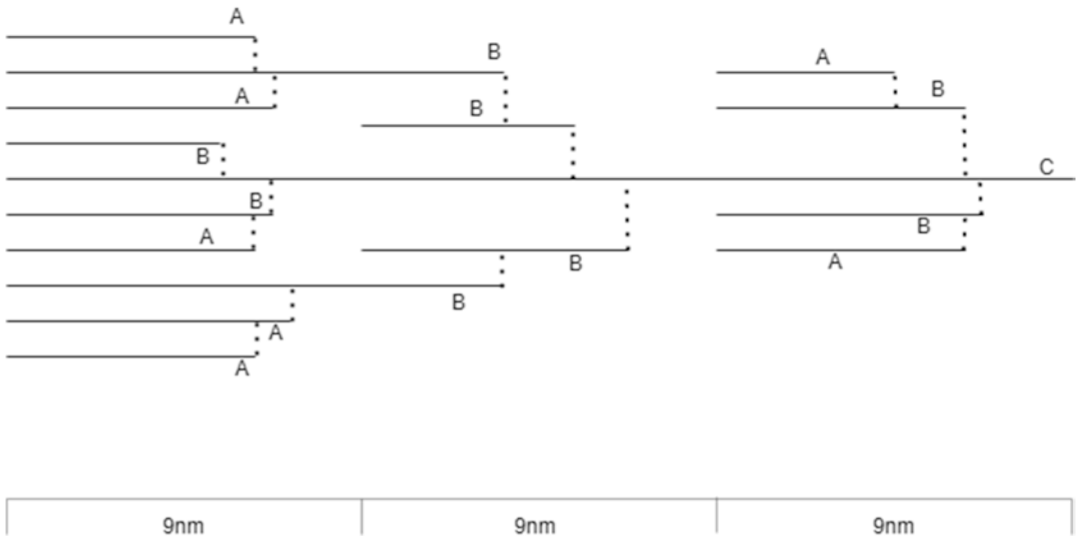

Fig. 3 Schematic representation of an amylopectin section depicting the branching pattern of (1 → 4)-α-chains

To study the morphological properties of starch granules, different types of microscopic methods are commonly used providing different levels of information and details as described below.

3.1 Light Microscopy

Optical microscopy is the fastest and most intuitive way to help distinguish starch molecules (Zhang et al., 2013). It is used to observe the morphology of starch granules with limited details about the granular shape and appearance, growth rings (specially on large starch granules), the presence of large cracks or fissures due to processing, and also gelatinized starch granules (Fig. 5a). To study more details about starch granules, more advanced microscopes are used as discussed below.

3.2 Polarized Light Microscopy

The unique arrangement of amylose and amylopectin within the granules forms a semi-crystalline structure in the form of concentric growth rings comprising crystalline and amorphous lamellae. Amylopectin double helices fall within the crystalline lamellae, while single helices of amylose and the amylopectin branch points form the alternating amorphous regions. The ordered structure of starch molecules inside the granules appears as birefringence and Maltese cross. This structure can be observed under a polarized light microscope (Copeland et al., 2009; Pérez & Bertoft, 2010) (Fig. 5b). When the granules are heated in the presence of water, a gradual loss of the birefringence is observed, till it completely disappears upon disruption of the starch granule (Fig. 5c, d).

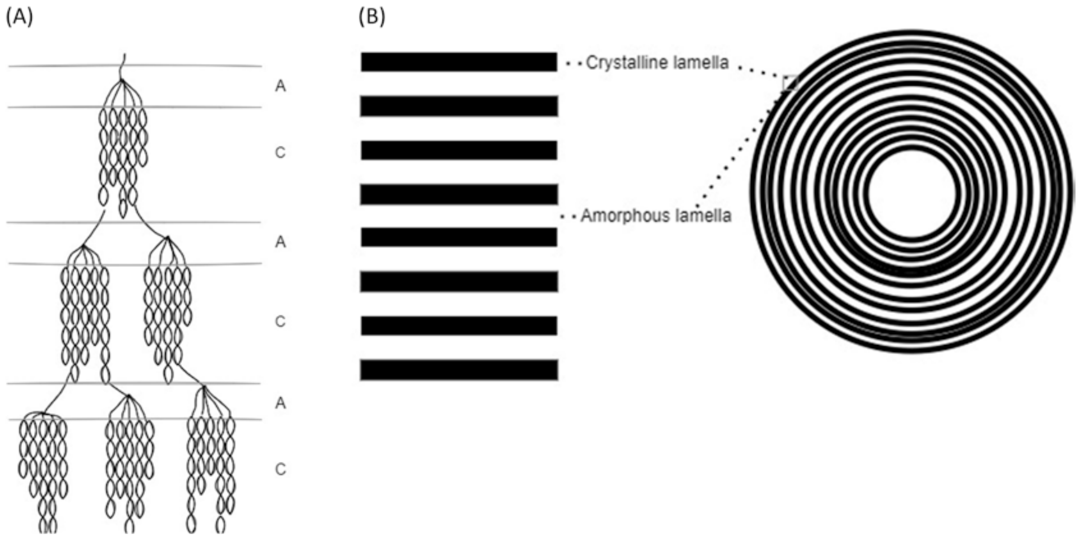

Fig. 4 Diagrammatic representation of the lamellar structure of starch granules. (**a**) Branching pattern of the double helices in amylopectin cluster. Amorphous and crystalline regions are denoted by "A" and "C," respectively, and (**b**) stacks of crystalline lamella

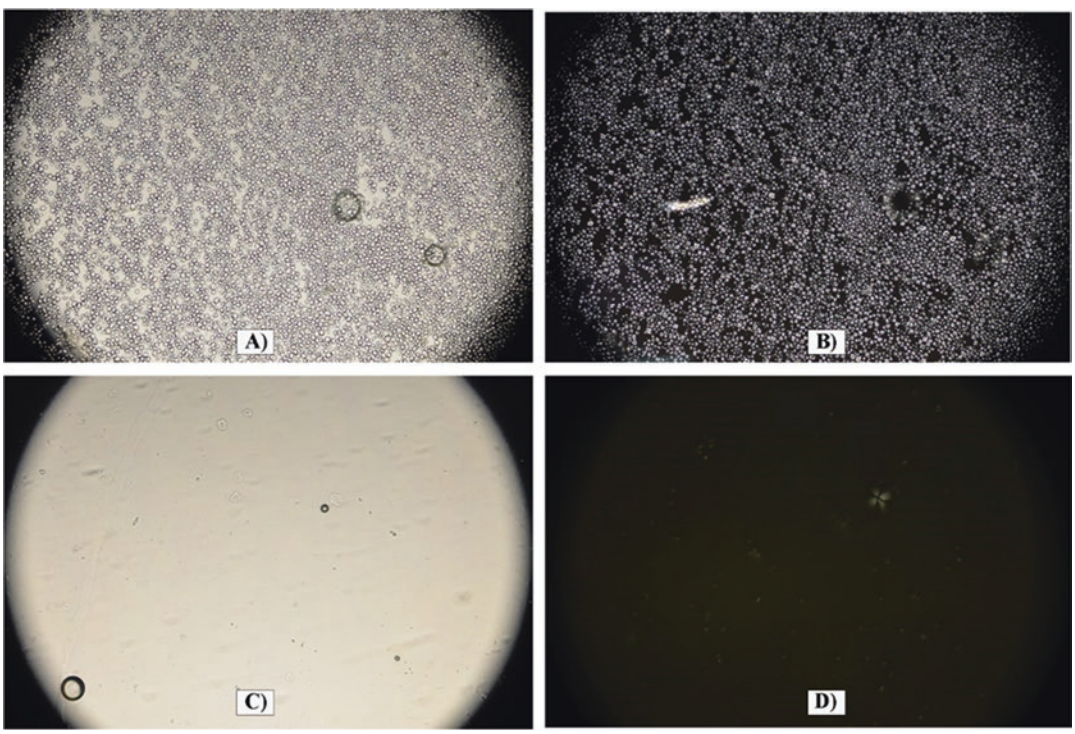

Fig. 5 Images of corn starch dispersion before (**a**, **b**) and after (**c**, **d**) gelatinization under optical (**a**, **c**) and polarized (**b**, **d**) light microscope at 10×

3.3 Scanning Electron Microscopy (SEM)

SEM produces high-resolution images as compared to other microscopic techniques by using a beam of electrons instead of light to scan the surface of the sample. Dehydrated samples are best suited for the SEM technique; however, for samples where water removal isn't possible or the sample matrix can be altered by drying, cryo-SEM imaging is carried out. Doing so, the sample is flash frozen to preserve and examine various phenomena such as water absorption, swelling power, amylose leaching, and retrogradation. The stability of emulsions and nano emulsions stabilized by starch can also be studied (Feng et al., 2022), along with surface characteristics (smooth or porous), shape, particle size, and modality of starch (Fig. 6).

Upon storage and dehydration, fractal-like networks forming a "cell-wall" structure with well-defined pores in starch gels have been observed under SEM. The matrix surrounding the pores appears thicker with prolonged storage time due to retrogradation (Wang et al., 2015). SEM micrographs can also be used to visualize the effect of storage temperature on the fractal microstructure of retrograded starch gels. At lower storage temperatures, smaller cavities were formed than at higher temperatures (Wu et al., 2012).

3.4 Confocal Scanning Laser Microscopy

Starch imaging using confocal scanning laser microscopy is used to obtain three-dimensional (3D) images of the granules from various botanical sources in their native form, during processing or modification, and in the final product (food). It allows for examination of the different cross-sections of starch without the use of any sectioning techniques.

3.5 Atomic Force Microscopy (AFM)

Atomic force microscopy or scanning force microscopy is a very-high-resolution type of scanning probe microscopy providing information at near-molecular resolution of the granule surfaces. AFM is preferred over the conventional microscopic techniques due to its much higher resolution (more than 1000 times higher resolu-

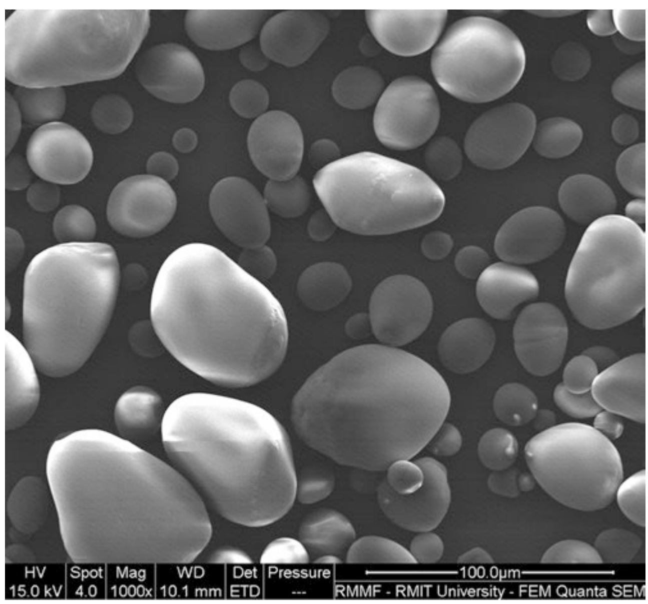

Fig. 6 SEM micrograph of potato starch granules under 1000x

tion than optical microscope); easy sample preparation; no need for metal coating, freezing, or drying the samples; and ability to scan the samples in aqueous or atmospheric conditions (Chang et al., 2012). It can be used to study native, processed, and modified starches by providing 3D images of the starch granules and information about the surface topography and sample elasticity.

4 Physiochemical Changes of Starch During Heating and Cooling

Thermal processing including cooking, baking, and extrusion is a common type of food processing method to produce a wide range of foods. Followed by heating, food is often cooled down for packaging and marketing. Both heating and cooling have substantial influence on the morphological and physicochemical properties of the starch granules and their constituents. The changes of starch during heating and cooling are described as starch gelatinization, pasting, and retrogradation which are described below.

4.1 Starch Gelatinization

Starch granules are highly robust and impermeable to water at ambient temperature and do not show any considerable viscosity. During the initial stages of thermal processing, at temperatures between 20 and 60 °C, water molecules are reversibly complexed with starch molecules, reducing the mobility of water molecules. At this "initial gelatinization temperature," the granular starch structure remains stable and granules still exhibit a typical birefringence under polarized light. However, when heated above 60 °C (approximately) in excess water (>60% water) the crystalline starch granules absorb water and swell, leading to a rapid increase in viscosity. When starch granules are hydrated and subjected to high temperatures, the hydrogen bonds between amylopectin and the amylose double helices are broken and replaced with water. Water first enters the amorphous growth rings, and after a certain degree of swelling the disruptive stress is transmitted to the crystalline regions. The amylose double helices become dissociated and amylose molecules leach out from the granules, though the granular structure is retained till further heating. The leaching of amylose increases the paste viscosity, and the viscosity reaches a maximum (peak viscosity) when the number of swollen intact granules is at a maximum. A higher swelling capacity of starch granules translates to a higher viscosity in granules and gel. In addition to the physicochemical characteristics of starch, the viscosity of a starch-water mixture depends on the concentration of starch in the dispersion and shear applied to it. Under static conditions, full gelatinization of starch requires >63% water (Liu et al., 2009). When water is limited, gelatinization is restricted and progressively (with reduced water) replaced by melting of crystalline granules (see chapter "Food Texture Diagrams and Maps").

The gelatinization temperature for most starches is between 60 and 80 °C, with a negative relationship between the amylose content and gelatinization temperature in general (Copeland et al., 2009). Crystalline amylopectin zone has a denser cluster structure, which increases its gelatinization temperature compared to the amorphous zone. It should be noted that the starch gelatinization temperature is different for different starch granules, for example the smaller granules of wheat starch (B-type) are gelatinized at higher temperatures than the larger granules (A-type).

4.2 Starch Pasting

At elevated temperatures (above the gelatinization temperature) and especially during mixing and shearing, the swollen starch granules burst, and the water and the starch molecules are released into the surrounding environment leading to a rapid reduction in viscosity. This phenomenon is called "pasting."

4.3 Starch Gelation

During cooling of the gelatinized/pasted starch to below the gelatinization temperature, starch molecules form a gel structure with water which is stabilized by the intra- and intermolecular interactions of amylose and amylopectin. As a result of starch gelation, the viscosity increases. Amylose molecules rapidly aggregate and the formation of amylose junction zones is said to be responsible for the setback viscosity (for more information on setback, see chapter "Rheometry and Rheological Characterisation", Sect. 3). Higher amylose content in starch results in a higher setback viscosity (Srichuwong & Jane, 2007). Amylose molecules are quite unstable and shrink due to a decrease in the kinetic energy and Brownian motion of the water and polymer molecules. This results in formation of new inter- and intramolecular hydrogen bonding (Tako et al., 2014). The physical properties of starch gels vary depending on the starch origin and the ratio of amylose: amylopectin and other constituents of the starch. In gels containing about 25% amylose, the molecules form a firm gel network as opposed to waxy starch gels, which are soft and contain aggregates but no network, exhibiting a less cohesive structure. Amylose network forms elastic gels that do not disintegrate easily, whereas waxy starch gels exhibit higher penetrability, stickiness, and adhesiveness (Tang & Copeland, 2007). Tuber starches such as potato and cassava starch produce soft, sticky, and transparent gels, while cereal starches produce hard and opaque gels (Fig. 7). Higher ratio of amylose: amylopectin makes stronger gels.

4.4 Starch Retrogradation

During storage (or aging) of the starch gel, the viscosity increases due to the starch molecular recrystallization and moisture loss. This process is known as "starch retrogradation." It is accompanied by a series of physical changes such as increase in paste viscosity, turbidity and crystallinity, gel formation, and exudation of water. Short-term retrogradation of starch is generally caused by the rearrangement of amylose, while the long-term retrogradation is caused by the crystallization of the outer branches of amylopectin. Amylose molecules gradually associate to form double helical crystallites of 40–70 glucose units. Hydrogen bonding between starch chains and hydrophobic interactions drives the formation of double helices. This increases the gel firmness and reduces the water-binding capacity, resulting in the quality deterioration of starch-containing foods. Further, intermolecular hydrogen bonding occurs between amylose and amylopectin. Two or more short side chains of amylopectin molecules may associate with an amylose molecule. When the intermolecular hydrogen bonding between amylose and amylo-

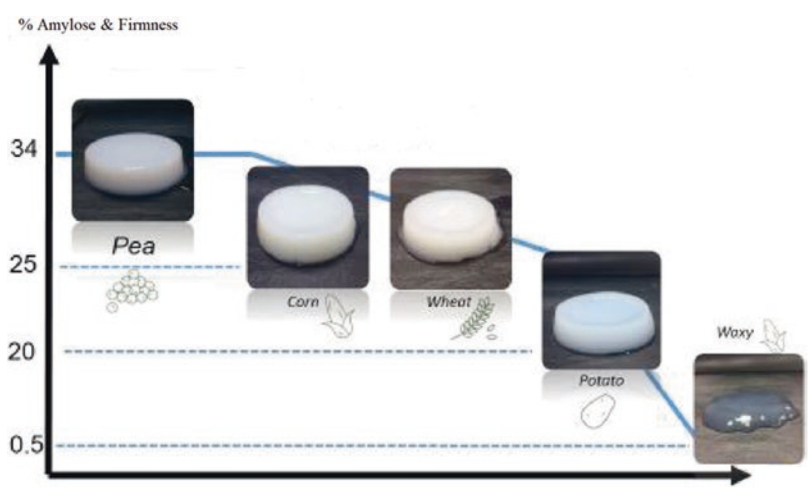

Fig. 7 Retrograded gels formed from starches of different botanical origins (Roquette, n.d.)

pectin molecules is saturated, the amylopectin molecules show an intermolecular binding. These double helices are then packed into crystals. Amylose retrogradation determines the initial hardness and stickiness of processed foods, while the long-term development of crystallinity and gel structure, as seen in staling of cakes and bread, leading to the toughened bread crumb, soggy crusts, and diminished flavor is due to amylopectin retrograding. Waxy starches tend to have less retrogradation than normal and high amylose starches. The water content and storage temperature have great influence on the rate and extent of retrogradation of starch gels. Lipids and surfactants can retard or interfere with the retrogradation.

Effects of retrogradation in food are generally undesirable. Susceptibility of legume starch gels to retrogradation and syneresis makes them unsuitable for products stored at low temperatures. However, in a few cases, retrogradation is promoted to modify organoleptic, mechanical, or structural properties, for e.g., in breakfast cereals and parboiled rice, as it results in reduced stickiness and hardening. Other examples include dehydrated mashed potatoes, noodles, and vermicelli (Karim et al., 2000). However, one of the positive effects of starch retrogradation is related to the formation of type 3 resistant starch which is resistant to the starch digestive enzymes. Accordingly, type 3 resistant starch is formed. Resistant starch has applications in the development of low calorie and low glycemic index (GI) foods.

5 Properties of Starches from Different Botanical Origins

When selecting starches for a specific purpose, it is important to consider the innate differences between starches of different botanical origins. Here, a brief comparison of the structural, functional, and textural properties of five main starches – maize, cassava, wheat, potato, and rice – are provided. Differences in properties among different starches are largely attributed to differences in the structure and content of amylose and amylopectin, granular size and organization, and the presence of other components such as minerals, proteins, and lipids (Waterschoot et al., 2015).

5.1 Morphological Properties

The starch granular shape varies between spherical, oval, and polygonal, while the size varies between 1 and 100 μm. Potato starch has the largest granular size, with the round or ovular granules measuring between 10 and 100 μm. Cassava starch has round or truncated granules, 3–32 μm in size, while maize starch has polygonal granules ranging between 5 and 20 μm. Wheat starch exhibits a bimodal distribution with large, lenticular granules, 20–32 μm in size and small, round granules 2–10 μm in size. Rice starch granules are very small (3–8 μm) and polygonal in shape. Potato starch has been reported to have a smoother surface than other starches (Singh et al., 2003).

5.2 Composition, Swelling, and Solubility

Dry weight of starch comprises 98–99% of amylose and amylopectin. The packing of these within the granules varies among the different origins of starch. Amylose content varies between 23–31% for potato, 24–30% for maize, 0–33% for rice, 16–21% for cassava, and 18–30% for wheat starch. Phosphorus is a minor constituent that has a significant impact on the functional property of starch. Phosphorous content in starches varies from 0.003% in waxy maize starch to 0.09% in potato starch (Thitisaksakul et al., 2012). Phosphorous occurs as phospholipids and phosphate monoesters in starches. Maize, cassava, and potato starches have lower phospholipids than wheat and rice starches and hence have a higher swelling power and solubility. Phosphate groups on adjacent chains repel each other, weakening the extent of bonding within the crystalline region thereby increasing hydration.

The presence of phospholipids, however, lowers the paste viscosities, while phosphate monoesters bound to amylopectin increases paste viscosity and water-binding capacity as seen in potato starch. Free fatty acids in rice and maize starches reduce retrogradation and increase transition temperatures due to amylose-lipid complexation. The morphological structure of the starch granules also impacts swelling and solubility. Large and irregular granules perhaps help immobilize the starch within the granules, lowering solubility (Vamadevan & Bertoft, 2015). Tuber and root starches have large granules and low protein and lipid content compared to cereal starches. They also have a bland taste which is beneficial for their use as an ingredient in formulating different food products.

5.3 Gelatinization Properties

The crystalline order in starch is the basic underlying factor that affects functional properties of starch. Collapse of the crystalline order results in irreversible changes such as granular swelling, loss of birefringence, uncoiling and dissociation of the double helices, pasting, and starch solubilization. The order-disorder transitions occurring in a starch suspension on heating can be studied using differential scanning calorimetery (Table 3). Varieties of starch with high crystallinity report higher transition temperatures. Enthalpy (Δ*H)* which denotes the amount of energy required to melt all the starch crystals is high for potato, while wheat and maize starches exhibit a lower *enthalpy*. Higher amounts of short amylopectin chains exhibit a lower crystalline order, which results in a lower gelatinization temperature, while longer chains of amylopectin stabilize the crystal structure resulting in a higher gelatinization temperature. Potato starch seems to be an exception to this probably due to the presence of phosphate monoesters and a more open crystal structure. The shape and the distribution of granules also affect gelatinization and enthalpy values. Large and irregular granules, potato starch for example, exhibit a lower transition temperature and higher enthalpy. The rigid granular structure and the phospholipids present result in higher transition temperatures. The presence of amylose lowers the gelatinization temperatures. Hence, waxy and normal starch varieties would have higher gelatinization temperature compared to high amylose varieties. Potato starch pastes are fluid, viscoelastic, cohesive, and stringy. Cassava pastes exhibit similar properties but are less stringy and less cohesive. Wheat and maize starch pastes are non-cohesive, soft, and heavy bodied (Fig. 7).

5.4 Retrogradation and Textural Properties

Potato starch gels are highly cohesive, gummy, and chewy, probably due to higher DP of amylose forming relatively weak gels. Maize starch gels are brittle, strong, adhesive, and springy (Tables 4 and 5). Cassava gels are comparatively less springy, chewy, and gummy and much softer (Waterschoot et al., 2015). Maize and wheat starches retrograde faster than cassava or potato starch due to higher amylose and lipid content, and the smaller molecular size of wheat and maize amylose molecules. Rice starch produces sticky gels. Enthalpy value of retrograded starch is the quantitative measure of energy transformation that occurs when the recrystallized amylo-

Table 3 Thermal properties of starches from different botanical sources

Sample	Δ*H* (J/g)	T_o (°C)	T_p (°C)	T_c (°C)	References
Cassava starch	2.4	63.0	68.0	74.0	Klein et al. (2013)
Corn starch	2.2 ± 0.0	63.9 ± 0.8	69.3 ± 0.2	77.2 ± 0.1	Own data
Wheat starch	2.2 ± 0.1	53.0 ± 0.5	60.0 ± 0.1	68.9 ± 0.2	Own data
Rice starch	2.0	70.3	76.2	80.2	Klein et al. (2013)
Potato starch	5.2 ± 0.2	56.2 ± 0.7	63.2 ± 0.3	73.1 ± 0.1	Own data

ΔH (J/g) gelatinization enthalpy, T_o onset temperature, T_p peak temperature, T_c conclusion temperature

Table 4 Pasting properties of starches from different botanical sources

	Pasting temperature (°C)	Peak viscosity (cP)	Trough viscosity (cP)	Final viscosity (cP)	Breakdown (BD)	Setback (SB)
Cassava starch	66.4 ± 0.1	32910 ± 178	1435 ± 63	2989 ± 62	1856 ± 53	1553 ± 39
Corn starch	77.5 ± 0.4	4819 ± 288	4084 ± 185	6379 ± 486	735 ± 106	2295 ± 304
Wheat starch	63.6 ± 1.3	3371 ± 13	2968 ± 29	4652 ± 37	803 ± 19	1685 ± 48
Rice starch	81.0 ± 0.6	2964 ± 10	2303 ± 12	3583 ± 10	662 ± 14	619 ± 2
Potato starch	67.6 ± 0.1	13707 ± 217	1371 ± 23	2738 ± 311	12336 ± 200	1367 ± 309

Table 5 Textural properties of starches from different botanical sources

	Maximum force	Cohesiveness	Gumminess	Springiness	References
Cassava starch	140 ± 7	0.93 ± 0.03	133 ± 3	1.00	Own data
Corn starch	234 ± 5	0.87 ± 0.05	204 ± 6	1.00	Own data
Wheat starch	185 ± 21	0.92 ± 0.02	170 ± 22	1.00	Own data
Rice starch	156 ± 3	0.63 ± 0.70	88 ± 10	1.00	Baxter et al. (2004)
Potato starch	265 ± 3	0.91 ± 0.02	159 ± 5	1.00	Own data

pectin melts. The enthalpies for starch retrogradation are about 60–80% lower than those during gelatinization as retrograded starches have lower/weaker crystallinity. As potato and cassava starches have a higher retrogradation tendency, the decrease in transition temperatures and enthalpy is lower than rice, maize, and wheat starches (Singh et al., 2003).

6 Limitations of Native Starch and the Case for Starch Modification

Starch is one of the most abundantly used raw materials in the manufacturing industry. However, its industrial applications (in the native state) are limited by its low solubility, poor freeze-thaw stability, low pressure, thermal and shear resistance, susceptibility to enzymatic hydrolysis, tendency toward syneresis, and retrogradation. For example, as native starch is insoluble at low temperatures and requires heat to form dispersions, its application in heat sensitive foods is restricted. Furthermore, the viscosity of cooked native starch (e.g., potato or cassava) is often too high imparting gummy, cohesive textures to foods thickened by them. Most native starches show a drop in viscosity and thickening power on cooking (or retorting), especially at low pH. Amylose containing starches (maize and wheat) tend to form rigid, opaque gels at low temperatures (i.e., they retrograde). When stored near or below their freezing points, native starch gels exhibit lack of clarity and are prone to syneresis.

In order to overcome these drawbacks and make starch suitable for commercial applications, native starch may be modified to tailor its properties and functionality. The term "starch modification" is any treatment that alters the structure and functionality of starch by debranching, crosslinking, modifying chain length, pre-gelatinizing, and disproportionation. Cross-linked starch was introduced in the 1940s and acetylated starch in 1950s to be used in salad dressings and pies. Hydroxypropylation of starch in 1970s greatly improved the stability of frozen foods and puddings. In the 1980s, starch was spray dried to enable swelling in cold water, thereby accelerating the production of cold processed and instant desserts. Nowadays, modified starches are used extensively as thickening and gelling agents, stabilizers, fat mimics; for edible coatings and encapsulation; and to increase the resistant starch content and dietary fiber.

Though chemical modification of starch was dominant in the early years, physical, genetic, and enzymatic methods or a combination of these are becoming increasingly popular. Physical and enzymatic methods of modification are considered environmentally friendly, as they do not use chemicals ingredients and hence products are considered "clean label ingredients" (Mhaske et al., 2022).

7 Physical Modification of Starch

Physical modification of starch entails the use of varied physical treatments such as heat with or without moisture, mechanical processing, and radiation to modify starch. These treatments aim at improving processability, texture, or structure of starch. Non-thermal methods use pressure, radiation, pulsed electric field, or ultrasound to alter the properties of starch. Thermal modification includes dry heat treatment, pregelatinization, and hydrothermal processing (heat moisture treatment and annealing). During pregelatinization, heating of starch results in depolymerization and fragmentation disrupting the granular structure of starch. Cold-water swelling starch, produced by spray drying, produces a more uniform and strong gel upon hydration compared to pregelatinized starch (produced by drum drying or extrusion) (Majzoobi & Farahnaky, 2021). During high moisture treatment and annealing, starch is heated in water, above the glass transition temperature and below the gelatinization temperature, thus preserving its granular structure. Thermal treatments are energy and water intensive. In comparison, the low-energy nonthermal techniques minimize the deterioration of taste, texture color, and heat-sensitive components. Physically modified starch, in general, is preferred by the food industry as it is clean label. The various physical modifications of starch are summarized in Table 6 and some applications in the food industry are listed below.

7.1 Applications of Physically Modified Starches in the Food Industry

Hydrothermally modified starches are used in canned and frozen food industry as they have a high thermal stability and low tendency to retrograde. They also find applications in various baked goods. Bourekoua et al. (2016) studied the effect of high moisture treatment of maize and rice flour on gluten-free bread. High moisture treatment of flours was carried out at 65 °C with a 5:1 powder-to-water ratio. They reported that the inclusion of modified flours improved the softness, chewiness, specific volume, and height/width ratio of the baked bread in comparison to the control. Cham and Suwannaporn (2010) hydrothermally treated rice flour to make rice noodles. It was observed that high moisture treatment was appropriate when producing semi-dry or dried noodles, which required a higher gel hardness and tensile strength, while annealing treatment was better suited for noodles with a soft texture. Post-hydrothermal treatment reduced the amylose content which resulted in less retrogradation.

Drum-dried pregelatinized starch exhibited low crystallinity, high water solubility, and cold-water viscosity. Majzoobi et al. (2011) suggest it was an excellent thickener or gelling agent in instant/frozen foods or heat-sensitive products such as baby foods, cold desserts, salad dressings, and bakery mixes. Pongjaruvat et al. (2014) studied the effect of adding pregelatinized cassava starch to a rice flour-based bread. The result was a batter-like dough (less susceptible to shear during processing), but with an improved loaf volume and crumb softness. When added to gluten-free pasta, pregelatinized cassava starch reportedly improved its sensory and textural properties. Sharma et al. (2016) studied the impact of substituting wheat flour with extruded wheat starch or gelatinized-retrograded starch on characteristics of muffins, cookies, and noodles. Resulting noodles made by incorporating modified starches had a shorter cooking time, reduced

Table 6 Different types of physical modifications of starch and their advantages and disadvantages

Technique	Principle	Advantages	Disadvantages	Influence on structure and properties	Application
Dry heating	Low-moisture starches are heated at high temperature (100–200 °C) for prolonged time	Low cost Relatively quick No chemicals used Simple operation	May damage starch granules	heat and shear stable starches	baking improver, 3D printed foods
Hydrothermal modification (heat moisture treatment, annealing)	Starches are heated in water at temperatures >T_g and <gelatinization temperature	No chemical residue Structural integrity preserved	Long reaction time	Affects pasting properties due to enhanced shear stability and reduced swelling power	Canned foods, baby food
Pregelatinization	Starches are cooked/pasted and dried in conditions that restrict molecular reassociation	Quick Affordable	High equipment cost (drum dryer, spray dryer, extruder, etc.)	Irregular laminal, granular structure, and birefringence lost Flaky structure Depolymerization of the molecules	Dry mixes, cake mixes, cream fillings, frostings, toppings, puddings
Micronization	Depolymerization of starch molecules. Damages B-type granules, resulting in decreased crystallinity and double helix content	Product quality preserved	Increase in temperature Some techniques are costly and have low yields	Aggregated granules with rough surfaces Lower swelling power (SP) and solubility Weaker shear thinning behavior	Fat replacers, gelling agent, texture improver
Plasma	Free radical-induced cross-linking. Reduced crystallinity as the active plasma induces depolymerization	No residue Minimal thermal impact on product quality Cost-efficient	Causes lipid oxidation	Crystalline type unaffected Visible cracks and holes on the granule surface SP, solubility, and water absorption index (WAI) increased Reduced viscosity with soft gel behavior	
High pressure	Pressure applied on granules causes melting of amylopectin crystals and loss of birefringence	Product quality preserved Nontoxic Short processing time	High setup cost	Granule morphology and crystalline structure destroyed at pressures greater than 600 MPa Drop in viscosity	Fat substitutes

Ultrasound	Ultrasound waves destroy the crystalline regions of the starch granules	Simple setup High yield No residue	Difficult to standardize and reproduce Causes slight increase in temperature	Granules deformed with visible cracks and pores on the surface Crystallinity maintained Increased solubility and SP Less viscous, elastic pastes	Emulsification
Pulsed electric field	Starch-water suspension processed in an electric field strength of about 50 kV	Short processing time Energy efficient No residue	Only used for liquid products	Visible fissures and cavities on granule surface Drop in paste viscosity	–
γ-Irradiation	Radiations cause breakage of amylopectin chains in the amorphous regions and decrease the amylopectin to amylose ratio	Easy operation High efficiency No heating No residue	May affect sensory and physicochemical properties	Granular shape and integrity maintained Visible fractures and cleavages on granule surface Increase in solubility	Food preservation and sterilization

water uptake, lower hardness, stickiness, and gruel solid loss, as well as a higher resistant starch content. Cookies had a higher spread ratio while the muffins had less height, gas cells, and specific volume. Both the cookies and the muffins had a lighter color and a higher resistant starch content. Incorporating modified waxy maize starch improves the dough handling during cutting and imparts a chewy texture to cookies. When extruded rice flour was incorporated in yellow alkaline gluten-free noodles, it improved the tensile strength and elongation (stretching) of the cooked noodles (Seetapan et al., 2019). Pregelatinized starch has been widely used in noodle production to improve cooking and textural properties like elasticity, hardness, and resilience. The noodles also showed a delayed retrogradation (Obadi & Xu, 2021). Pregelatinized maize-starch added to extruded or fried snack food gives a crunchier, crispy texture with a higher mouth melt.

High-pressure-treated starch has great potential to conserve energy in various food industries as it lowers the gelatinization temperature to ambient temperature or lower. Nasehi and Javaheri (2012) processed starch pastes at concentrations greater than 15% and produced a creamy textured paste that can be used to replace fat/oil in dairy products, desserts, mayonnaise, confectionery, and other low-fat products without heat treatment.

Pulsed electric field technology may be used to sterilize liquid foods that have a low electrical conductivity and low viscosity (e.g., fruit juices, soup, milk, and liquid egg). Recently, it was found that pulsed electric field–treated starches helped in the production of resistant starches, rapidly digestible starch, and slowly digestible starch.

Gamma irradiation generates free radicals which cause molecular changes and fragmentation of starch, resulting in physicochemical changes such as increased acidity, water solubility, and lowered viscosity. It is thus used in a number of cereal porridges to reduce the viscosity and increase the cereal content.

Cold water–soluble starches prepared by spray drying are used as instant starches that swell extensively in aqueous conditions at room temperature. These are widely used in the preparation of gum candy (chewing gum), as the starches are soluble in glucose or sucrose syrups and form gels when poured into molds and allowed to set. Generally during baking, particulates (e.g., chocolate chips, small berries, nuts) added to batters tend to sink to the bottom as the viscosity drops during initial heating. Cold water–soluble starch added to such batters increases viscosity and prevents settling of the particulates.

8 Chemical Modification of Starch

Chemical modification involves the use of chemicals to incorporate functional groups on the backbone of starch, change its polarity, degrade the native structure, and/or increase the degree of substitution. Some popular methods of chemical modification involve acid hydrolysis, acetylation /esterification, oxidation, cross-linking, grafting, and dual modification. These techniques use hypochlorides, acids, phosphates, acetates, etc., which generate high volumes of effluents that are detrimental to the environment and, hence, require treatment before disposal. This additional cost incurred along with the push for clean label processing of food has caused a decline in the popularity of chemically modified starch in the food industry (Wang et al., 2022). The different types of chemical modifications are summarized in Table 7, and a few examples of their applications in the food industry are given below.

8.1 Acid/Alkali Hydrolysis

Starch hydrolysis products with a low dextrose equivalent and good water-binding properties are more effective as fat replacers compared to high dextrose equivalent starch hydrolysis products. Hydrolysate of potato starch with a dextrose equivalent of 2–5 at 3–5% can be used as a fat replacer without any change in product taste (Mishra & Rai, 2006). Cassava/sweet potato

Table 7 Different types of chemical modifications of starch and their advantages and disadvantages

Chemical treatment	Type	Principle	Influence on structure and properties	Food application
Hydrolysis	Acid treatment		Lower hot paste viscosity Improved gel strength and textural properties	Gummies, jellies, pastilles
	Acid treatment (dextrinization)		Improved solubility, gel stability, and emulsifying properties Decreased viscosity	Flavor encapsulation, glazes, and coatings in bakery and confections, fat replacer in bakery and dairy products
	Alkali treatment		Increased viscosity	
Oxidation	–	An oxidizing agent is used to add a carbonyl or carboxyl group to native starch	results in depolymerization that retards recrystallization Low viscosity High paste clarity, adhesion Lower retrogradation of cooked starches	Used in batters and breading for coating different food items, as texturizers in dairy and as binders in confectionery
Esterification	Phosphorylation (starch phosphate, distarch phosphate)	Phosphate groups added on hydroxyl group of starch	Improved paste clarity, firmness, and viscosity Reduced freeze-thaw stability, retrogradation, and syneresis	Gravies, dips, sauces, puddings and pie fillings Frozen foods
	Succinylation (with succinic acid anhydride/OSA)	Starch is derivatized with alkenyl succinic anhydride or octenyl succinic anhydride	Increased paste viscosity, freeze-thaw stability, and emulsion stabilization Reduced tendency to form gels	In fried products to improve juiciness and flavor. Snacks, soups, non-gelling creams, beverage emulsions, and refrigerated/frozen products
	Acetylation	Hydroxyl group of polymeric starch reacts with an acetyl group	Retards recrystallization and retrogradation Increased emulsion, stabilization, and viscosity High paste clarity	Bulking agent in snack food, imparts smoothness and sheen to soups and sauces. Replacer for egg yolk, gum Arabic, and caseinate
	Treatment with adipic anhydride		Higher paste clarity, viscosity, and stability	As a thickener
Etherification	Carboxymethylation	Hydroxyl groups in starch substituted with carboxymethyl	Soluble in cold water	Sweets and candies
	Hydroxypropylation	Hydroxypropyl group added to the starch molecule	Better solubility, water-holding capacity, freeze-thaw stability, and paste clarity Lower pasting temperature	Ice cream, dairy products, salad dressings
Cross-linking	–	The molecules of starch are covalently bonded to specific functional groups	Slow gelatinization Stable viscosity at low pH Improved heat transfer	Viscofiers and texturizers in salad dressing, canned foods, baby foods, sauces, soups, gravies, fruit fillings, pudding, deep fried foods

starch hydrolyzates with an amylopectin/amylose ratio of 80–85:15–20 can be used to partially substitute oils and fats in butter and cream. Hydrolysates can mimic the textural and physical properties of milk fat due to their colloidal properties and mouthfeel. They can also be added as an emulsifier in the production of low-fat, high-moisture cheese. The increased setback viscosity, resulting in the formation of rigid gels makes these acid-thinned starches suitable for manufacturing jellies, gums, and pastilles. As they yield a low paste viscosity at high and low temperatures, they are perfect for refrigerated products like salad dressings and mayonnaise.

8.2 Oxidation

Oxidation imparts low viscosity, high clarity, and stability to starch pastes. It improves the film-forming and water-binding properties of starch and hence finds a widespread application in many industries. In the food industry, oxidized starches are popular in creamy products with a low gel strength such as whipped cream, cream puddings, puddings, and high-clarity tender gum confections. The low viscosity of the starch also enables its use as a substitute for natural gums, gum Arabic in particular. Owing to its powder-like consistency, oxidized starch is used for dusting foods such as chewing gums and marshmallows and in mixtures of dough powder (Pietrzyk et al., 2014). Oxidized starches are used in frozen foods to improve their storage stability and to improve the freezing resistance of cheeses, as well as reducing crumbling upon frying. Oxidized starches have improved breading properties and are used in batter coatings of various foods such as fish, meat, scallops, and chicken drumsticks. It results in a pleasant coating with a golden-brown color and a non-crumbling, firm texture.

8.3 Etherification

Hydroxypropylation and carboxymethylation improve the textural properties, clarity, shelf-life, freeze-thaw, and cold-storage stabilities (reduced syneresis and retrogradation). Hydroxypropylated starch is used in bakery products to substitute wheat flour in bread creating soft crumb that retains its texture during storage. These starches are used as thickeners in pie fillings, fruit preserves, toppings, and soups, producing a clear, glossy paste. As they can withstand high temperatures, they are also used in retortable foods and hot processed oil dressings. Aqueous dispersions of the starches can also be used for coating foods before deep frying to increase crispiness and prolong freshness on storage. For thick, firm UHT puddings and creamy desserts, hydroxypropylated maize starch is widely used, while hydroxyproylated cassava starch is better suited to smooth textured desserts. Carboxymethyl starch in quantities as low as 0.3% can be used in ice creams to improve the consistency, structure, color, appearance, taste, and aroma.

8.4 Esterification

Octenyl succinylated starch is an amphiphilic hydrocolloid obtained by esterifying starch with octenyl succinic anhydride (OSA). These starches are commonly used as emulsifiers due to their amphiphilic nature, encapsulating agents for flavors, salt and fatty acids and as clouding agents in drinks. Banana, maize, and rice starches treated with OSA have been used to stabilize oil-in-water emulsions, helping in the maintenance of uniform droplet size. The increase in emulsion viscosity retards droplet movement, delaying coalescence, creaming, and flocculation. Partial replacement of wheat flour with acetylated rice starch increased the water-holding capacity of donuts. The increased water content resulted in a raised product moisture content and lower oil uptake during frying (Shih et al., 2001). The heat stability of acetylated starches (specifically acetylated distarch adipate) is important in UHT dairy desserts and custards. Similarly acetylated cassava, potato, and waxy maize starches are popular in canned food as they maintain the viscosity after processing. Acetylated cassava or potato starch improves the shelf life and taste of noodles (Sajilata & Singhal, 2005).

8.5 Cross-Linking

Cross-linked starches are commonly used as thickeners in foods which require a stable, high viscosity. Cross-linking reduces the loss of granular structure, paste clarity, viscosity, and stability against cold storage, and results in the formation of a stringy paste during cooking. At a high degree of cross-linking, waxy maize starch yields a stringy, cohesive, and rubbery texture when cooked, while cross-linked wheat starch results in a paste-like texture that has good rheological properties suitable to be used as a thickener in food. Drum-dried cross-linked starches exhibit "pulpy" textures and can be used in fruit-based sauces. They can be used in acidic media to produce a viscous system such as cherry pie filling. Cross-linking controls the expansion of baked goods along with the tacky mouthfeel. Cross-linked starches with low amylose content improve cake volume, crumb softness, and quality. Cross-linked cassava starch has good cold-storage stability and is preferred for making instant puddings with smooth textures and heavy-body consistency.

8.6 Dual Modification

Wang et al. (2017) reported that completely debranching waxy maize and potato starches with isoamylase before esterification with OSA produced small droplet Pickering emulsions that remained stable after 2 months. Pregelatinized acetylated starches are used in dry mixed instant gravies and pie fillings. When cold milk is added, the starch dissolves and sets into a gel that has a smooth texture and good eating quality. Acid-thinned maltodextrin can be oxidized to yield a non-gelling starch with low viscosity that can be used as fillings in chocolate-filled confections. Cross-linked starches tend to lose their water-holding capacity and paste clarity on prolonged cold storage. By acetylating these starches, the benefits of cross-linking are retained while improving the cold aging stability. When paired with partial acid hydrolysis, annealed high amylose maize starch showed a 32% increase in resistant starch. This product is white and has a bland taste, facilitating its use in products without altering their taste or appearance. It has been successfully used as a fat mimic and to increase the resistant starch content of food (Jayakody & Hoover, 2008).

9 Enzymatic Modification of Starch

Enzymatic modification uses enzymes to degrade starch molecules into different oligosaccharides, thus improving the functional and nutritional value in a variety of products (Fig. 8). The enzymes target the amylopectin chains and the amylose-amylopectin ratio. Reactions of active enzymes are mild and specific and create high-quality pure products (with few by-products). Enzymatic modification allows good control of the final starch properties and are generally in expensive to make.

9.1 Enzymes Used for Modification

9.1.1 Amylase

Amylases are classified into two categories – endo- and exoamylases. Endoamylases cleave the α-(1,4) glycosidic bonds present in the inner parts of amylose and amylopectin chains forming oligosaccharides of varying chain lengths. α-Amylase is a popular endoamylase that randomly hydrolyzes any -(1,4)-linkage of starch, drastically reducing the molecular size and pasting viscosity of hydrolyzed starch. Exoamylases either exclusively cleave the α-(1,4) glycosidic bonds or cleave both α-(1,4) and α-(1,6) glycosidic bonds at the non-reducing ends of the starch chains. Exoamylases act on the external glucose residues, producing glucose, or maltose and

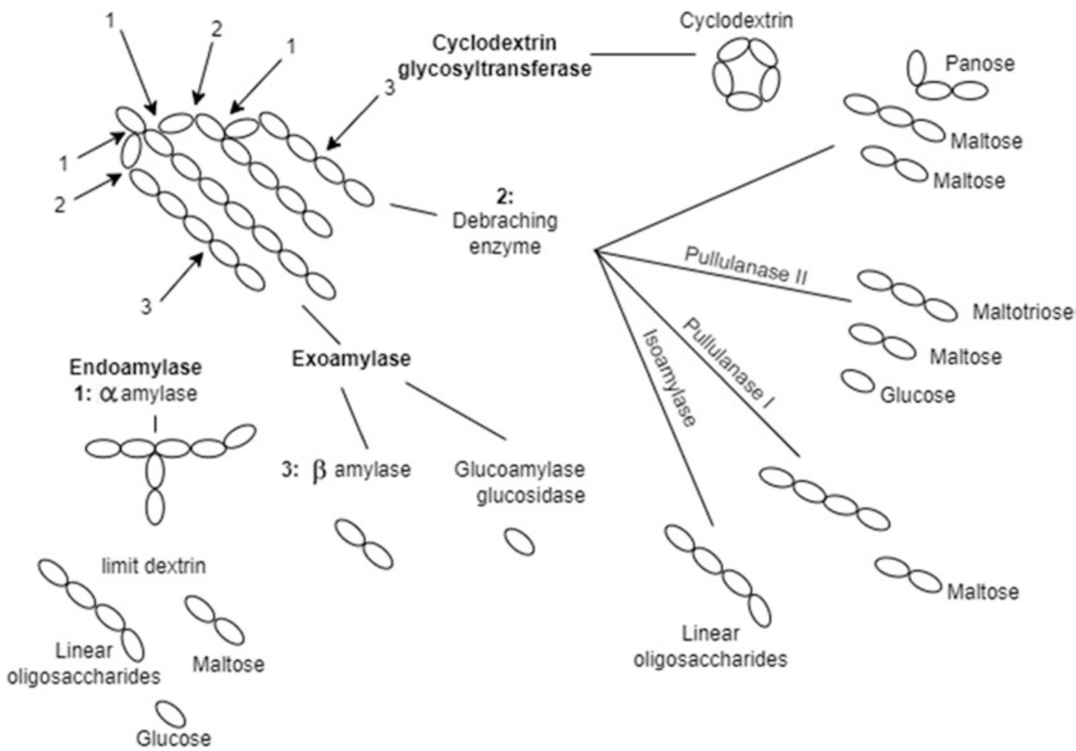

Fig. 8 Effect of various enzymes on starch

β-limit dextrin. Amyloglucosidase, glucoamylase, and α-glucosidase are commonly used exoamylases.

9.1.2 Debranching Enzymes

These enzymes act as a catalyst in the hydrolysis of α-(1,6) glycosidic linkages in amylopectin to produce linear glucans and dextrins. These are further classified as direct or indirect debranching enzymes based on their mode of action, i.e., directly hydrolyzing unmodified pectin or acting on amylopectin already modified by other enzymes. Pullulanase and isoamylaze are widely used debranching enzymes. Pullulanase is widely used for starch saccharification, as an antistaling agent, and products with slow digestion properties.

9.1.3 Starch Glycosyltransferase

Transferases cleave an α-(1,4) glycosidic bond of one starch molecule (donor) and transfer part of the molecule to another (acceptor) to form a new glycosidic bond. Amylomaltase and cyclodextrin glycosyltransferase are commonly used. These enzymes are very similar in the type of reaction, though they result in different structures, linear and cyclic, respectively.

9.2 Applications of Enzymatic Modified Starch in the Food Industry

Debranched starches form thermoreversible gels with a higher gel strength and fat-like mouthfeel and properties. They can be used to form creamy velvety textures and hence find applications in low-calorie foods and baked goods as fat replacers, as stabilizers in water-oil-water emulsions, and as vegan alternatives for gelatin in sugar confections (though gelatin is clearer than starch gels). In ice cream, α-amylase-modified starch can reduce the calorie content, raise the viscosity, enhancing the emulsification and foam stability, overrun and sensory score. In comparison to native starch, α-amylase-modified starches yield robust, hard, and brittle gels. Starches treated with amyloglucosidase created crisp coatings for bake-only chicken nuggets with improved sensory properties and mouthfeel. Luckett and Wang (2012) used isoamylase debranched maize starch to coat breakfast cereals, reporting a lower milk absorption while maintaining crunchiness after 3 minutes of soaking. Yoghurt creaminess can be enhanced with amylomaltase-treated potato starch. Combining two or three enzymes has been employed in a few studies, providing a synergistic effect. Woo et al. (2021), for example, used cyclodextrin, glucanotransferase, and a debranching enzyme to modify maize starch used to prepare frozen dough and bread. When a dough containing 5% modified starch was subjected to three freeze-thaw cycles, it exhibited a 19% reduction in water loss, while the bread was 37% softer and exhibited a 14% lower retrogradation peak. Aqueous dispersions of debranched starches yield varying fat like textures, from oily to creamy to waxy. Given they form high strength, thermo-reversible gels, they are used as fat replacers in coffee whiteners, low-fat spreads, ice cream, low-fat cheeses, baked goods, and breaded foods (Liu et al., 2017a, b).

4-α-GTase-treated starch is commercially available as Etenia™ and is used as a vegan alternative for gelatin in jelly-like confections and low-fat dairy products for enhanced creaminess and mouthfeel.

10 Common Techniques to Study the Physicochemical Properties of Starch

Several techniques are used to study the physiochemical properties of starch, and they are briefly described below.

10.1 Differential Scanning Calorimetry (DSC)

DSC measures changes in energy of materials subjected to controlled heating or cooling. The loss of starch granular structure, disruption of starch crystallinity, realignment of disrupted amylose and amylopectin molecules during recrystallization (retrogradation), and syneresis from starch gels can be observed by thermal analysis. Phase transitions (such as melting or crystallization) occur due to the absorption or release of heat or loss of mass. The transition temperatures (onset, T_o; peak, T_p; and conclusion, T_c) and change in enthalpy (ΔH) due to melting of crystallite (or double helical structure) (Fig. 9) or formation of ordered structures can be derived from DSC thermograms. Such thermograms can also provide transition temperatures and quantitative changes in enthalpy for the melting of recrystallized amylopectin in retrograded starch (Liu et al., 2009). In general, the temperature difference between the sample in a hermetically sealed pan and an empty pan (a reference) as a function of temperature are compared. A lower variation in between the onset and conclusion temperatures is indicative of a greater organization of the starch structure and less heterogeneity among its starch granules. Determination of the glass transition (T_g) is crucial in studying the gelling properties of starch, their stability, and changes in its mechanical properties during processing and storage (Clerici et al., 2019).

10.2 Texture Analysis

Texture analyzers (see chapter "Texture Analysers") have been widely adopted to study starch model systems and real food products. A particular test protocol, texture profile analysis (TPA), applies a double compression (two bites) to a sample of fixed dimensions. The compressive force is recorded as a function of distance or time. A generalized TPA curve is depicted in Fig. 10 and we can extract several characteristics from it. Fracturability is the force of the first shoulder or break point; hardness is the maximum force, occurring at the end of the first cycle; cohesiveness is the ratio of the work done to compress the sample on the second compression compared to that of the first. This is calculated from the area under the respective curves as A_2/

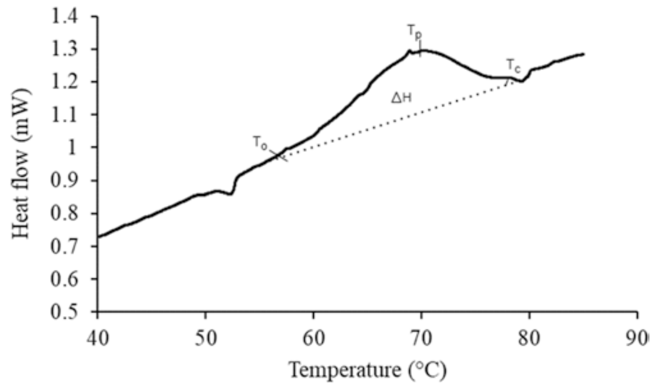

Fig. 9 DSC endotherm, transition temperatures (onset, T_o; peak, T_p; and conclusion, T_c), and change in enthalpy (ΔH) obtained while heating corn starch suspension from 40 to 80 °C

A_1. Springiness is calculated as distance D, while adhesiveness or stickiness of the product is given as the negative area 3. Gumminess (hardness × cohesiveness) and chewiness (springiness × cohesiveness) of the sample can also be calculated. The TPA test can be modified to suit the application by varying the sample size and shape, type of probe used, speed of deformation, extent of deformation, number of compressions, etc. While widely used, TPA has been criticized by a number of researchers (Peleg, 2019; Nishinari et al., 2019).

10.3 Rapid Visco Analyzer (RVA)

RVA is a heating and cooling viscometer that records the viscosity of a sample as it is stirred over a defined heating, holding, and cooling protocol. The process of pasting, or the process of gel formation due to the swelling and disruption of starch granules following gelatinization, is observed. An RVA profile (Fig. 11) provides insight into parameters such as the pasting temperature, the highest or peak viscosity of starch when heated, the minimum or trough viscosity, and the final viscosity of the sample when kept at a specific temperature. The difference between the final viscosity and the trough viscosity is known as the setback viscosity, which is generally correlated to the amylose content of the starch. Breakdown viscosity is the difference between the peak and trough viscosity. The RVA parameters can be correlated with the product quality and texture.

11 Extrusion Cooking of Starch

Food extrusion is a continuous mixing, cooking, and forming process during which raw ingredients (usually a flour mixture) undergo many transitions such as protein denaturation, starch melting/gelatinization, and lipid-amylose complexation before being shaped through a die. A food extruder can be considered a high-temperature short-time bioreactor (70–170 °C for 20–200 s) that combines several unit operations and applies heat, pressure, and high mechanical shear. The molecular transformations that convert the raw materials into a viscoelastic melt are influenced mainly by processing variables such as screw speed, temperature, moisture content, the geometry of the extruder (barrel and screws), and feed composition (e.g., amylose-amylopectin ratio, lipid level). Among all the components of the flour mixture, starches play a crucial role in starch-rich products (Camire, 2002).

11.1 Transformation of Starch During Extrusion

Water content along with temperature has a great impact on starch. Gelatinization temperature of starch is determined and reported under excess water condition. However, under limited moisture level, gelatinization temperature of starch increases as compared to the excess water condition. When the water content is in excess, the crystallites in starch can be pulled apart due to swelling, leaving no crystallites to be melted at higher temperatures. Breakfast cereals and

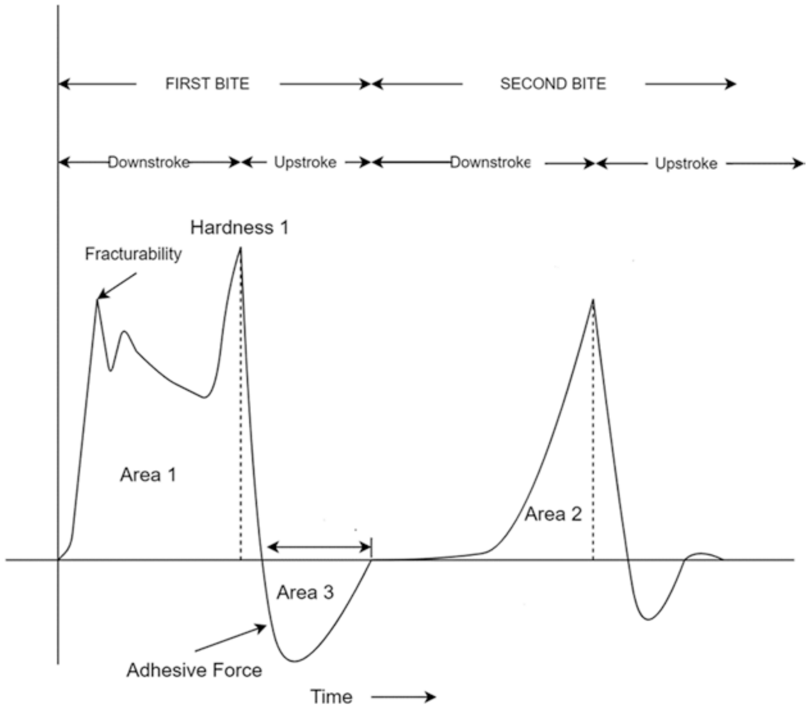

Fig. 10 A typical TPA curve obtained during a two-compression test

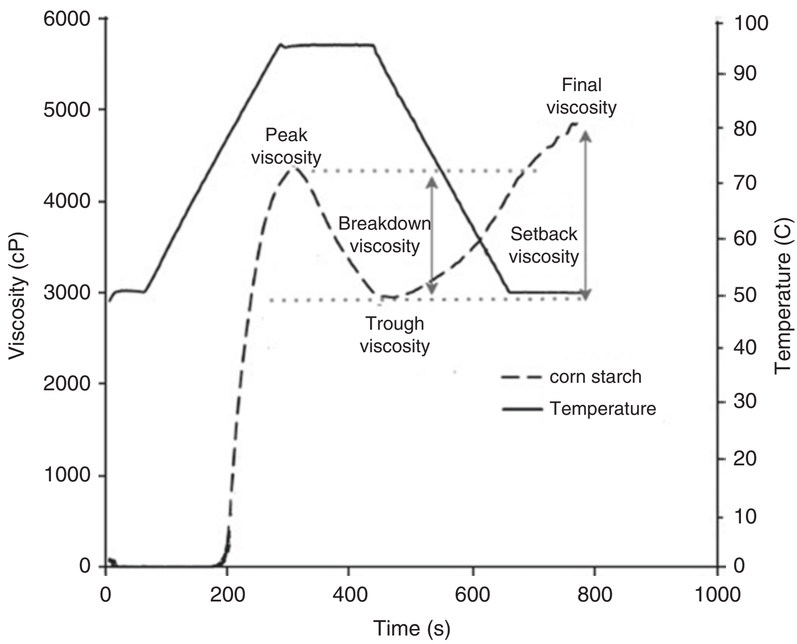

Fig. 11 An RVA graph showing the changes in viscosity of a corn starch dispersion, with respect to time and temperature on constant stirring

snacks, however, are generally extruded at moisture conditions of 12–16% wet basis, which is much below those needed for gelatinization, and hence the swelling forces are not relevant. The short residence time is inadequate to allow the heat to raise the temperature of the starch and additional heat is generated from the high shear exerted by the rotating screw(s) which additionally tear the starch granules apart and achieve rapid water mixing (Roman et al., 2018). It is the mechanical disruption of the molecular bonds by intense shear within the extruder barrel that causes loss in starch crystallinity and not swelling due to water penetration. Upon heating, at temperatures much higher than the gelatinization temperature in excess water, the remaining crystallites melt forming a viscoelastic mass. In low moisture extrusion, therefore, starch exists as a viscoelastic melt comprising the gelatinized, melted, as well as fragmented states.

As the viscoelastic melt is pushed through the barrel by the rotating screws, the pressure and temperature conditions reach a maximum at the die. Under the extreme pressure and temperature conditions, small, thermodynamically unstable gas bubbles are formed within the melt. Suspended unwetted solids act as nuclei for bubble formation and these along with compressed entrapped gas bubbles also act as nuclei (Horvat et al., 2014). Nucleating agents such as calcium carbonate may also be added to promote bubble formation in products when a porous structure is desired. As superheating increases, the radius of the nuclei decrease in size, reaching molecular dimensions at high degrees of superheat. As the hot melt exits the extruder die, it experiences a sudden decrease in pressure. This leads to rapid vaporization of moisture and generation of superheated steam at the nuclei. The pressure of the superheated steam exceeds the mechanical resistance of the viscoelastic melt leading to expansion of the air bubbles and puffing of the product. As the product cools down, the viscoelastic melt reaches the glassy state after crossing the rubbery region and the porous matrix hardens, inhibiting further expansion (Beck et al., 2018). The porosity of an extruded product is directly related to its crispness and inversely to its textural hardness.

11.2 Parameters Affecting the Textural Properties of the Starch-Based Extrudates

The final texture of the extruded product is affected by several material parameters such as moisture content, composition, and molecular structure of the feed and interactions between the components, processing parameters such as barrel and die temperature, screw speed and geometry, mechanical energy input, die geometry, and incorporation of air. High amylose content results in dense, hard products, whereas a high amylopectin leads to a light, elastic, and a homogeneously expanded extrudate. As the die nozzle length-to-diameter ratio increases, so too does the expansion ratio (diameter of extrudate/diameter of die) leading to higher shear rates, which lowers the shear viscosity, thereby increasing expansion (Brennan et al., 2013). Expansion also increases at high shear and temperature as the viscosity of extruded melt drops. Under low shear conditions, starch granules tend to remain intact, reducing the viscoelasticity of the melt, thus lowering the expansion.

Specific mechanical energy input is a quantitative descriptor used for comparison of different combinations of extrusion parameters such as torque, screw speed, and feed rate. Higher specific mechanical energies increase macromolecular transformations and interactions taking place, reducing melt viscosity and promoting bubble growth (Day & Swanson, 2013). A higher expansion in the extrudates reduces its bulk density creating a light crisp product which is a desired attribute for snack food. Depending on the actual starch, there is a temperature range within which higher temperatures result in greater expansion. Beyond this range, structural degradation of the melt occurs leading to softening, and the melt can no longer withstand the high vapor pressure and hence collapses. During extrusion, water acts as a plasticizer, raising the glass transition temperature, facilitating deformation of the matrix and its expansion. An increase in water content reduces the specific mechanical energy, apparent viscosity, and expansion ratio of the extrudates (Saeleaw et al., 2012).

12 Application of Extrusion for Production of Modified Starch

Conventionally, starch modification involves mixing suspensions of intact granules with high levels of water and chemicals/enzymes at temperatures typically below 60 °C in stirred tank reactors. The addition of salts (e.g., sodium chloride or sodium sulfate) allows higher temperatures for processing by inhibiting gelatinization, but adds extra processing cost through the removal of salts at the end of the process. High levels of water lead to a poor reaction selectivity and increase in reactor residence times (Moad, 2011).

Using an extruder as a bioreactor for starch modification eliminates some of these drawbacks of wet starch modification such as waste water generation. Developed in the 1980s, reactive extrusion (REX) refers to the concurrent reaction in extrusion processing of starch and is applied in various areas such as cross-linking, grafting, and polymerization, among others. An extruder enables handling and mixing of high viscosity polymers (gelatinized starch, for example) in a continuous process. It also offers significant operational flexibility due to the broad range of processing temperature (70–500 °C) and pressure (0–500 bar) conditions, ability to control extent of mixing, residence time, and possibility of multiple injection. REX is a two-stage process in which starch is first gelatinized by shear in low moisture conditions and then allowed to interact with the modifier, plasticizer, or reactant. Adding the reactant immediately after gelatinization of starch in the extruder drastically reduces the reaction time by eliminating the barrier in mass transport caused due to the highly organized crystalline structures in intact native starch granules (Wang et al., 2012). REX can be employed to modify starch physically, chemically, or by dextrinization.

12.1 Physical Modification

Improved extrusion cooking technology (IECT) was developed by Liu et al. (2011) as high-pressure, low-temperature starch gelatinization system to produce texturized rice product using broken rice and bran. Ye et al. (2016)) used IECT to improve the freeze-thaw stability of rice starch. The starch gel structure was compact before freezing, but after the first freeze-thaw cycle, the honeycomb structure became larger. Zhang et al. (2014) reported similar findings while Liu et al. (2017a, b) prepared pregelatinized rice starch with higher water solubility and absorption indexes, lower gelation viscosity, and improved gel stability and retrogradation properties.

12.2 Chemical Modification

Huo et al. (2017) used a twin-screw extruder to modify pea starch by phosphorylation without disrupting its crystalline structure and reported that the process slightly improved the slowly digestible starch content. Hasjim and Jane (2009) also reported an increase in slowly digestible starch due to increased retrogradation in hydrochloric acid–modified maize starch using an extruder. de Graaf et al. (1995) reported that acetylation of potato starch by extrusion had a 15-fold enhanced rate of acetylation than batch process. RE is also reportedly better for the production of thermoplastic starch as it enables greater diffusion of the plasticizer during mixing (Montilla-Buitrago et al., 2021).

12.3 Dextrinization

The high shear, pressure, and heat during extrusion lead to the cleavage of glycosidic bonds that hold the polymeric structure together resulting in dextrinization. The extrusion parameters can be controlled to achieve the desired extent of cleavage. Kowalski et al. (2018) noted that specific mechanical energy has a large impact on the degradation of starch in waxy wheat flour, causing breakdown of amylopectin and heavy destruction of gliadin protein. Vasanthan et al. (2001) probed the dextrinization of starch in barley flour in the presence of α-amylase during extrusion. They reported that the degree of hydrolysis increased with increase in the concentration of the enzyme and the feed moisture content. This result was contrasted by that of Van den Einde et al. (2005) who report an increase in dextrinization at low moisture content. Sarifudin and Assiry (2014) document that increasing the screw speed and temperature increases dextrinization and water solubility index of maize starch while reducing its water absorption index.

13 Summary

Starch has evolved from its traditional use as a food source for energy to a more sophisticated food ingredient/additive, and its importance is on the upward trend because of its versatility, abundance, and low cost. The amylose, amylopectin, proteins, lipids, and phosphorus content present in the granules have significant impacts on physicochemical and functional properties of starch. The inherent structural, textural, pasting, and thermal properties of starch have limited its application in the food industry. These can, however, be altered via a number of modification techniques involving physical, chemical, enzymatic, or genetic manipulation. Its ease of modifying and customization, which allows altering the native properties of starch into more desirable characteristics for specific applications, is the main reason for its catapulted relevance in the modern technological applications. Starch from different botanical sources and of varying degree of modification can exhibit a range of different textural properties such as springiness, brittleness, chewiness, creaminess, among others, and can be used to obtain a plethora of textures from creamy velvety textures in puddings, "pulpy" textures in sauces, chewiness in noodles, crispness in fried products, etc.

Chemical modification is the earliest and the most popular method of starch modification, due to its ease and precision and has more advanced capabilities. However, owing to the increasing push for chemical-free clean labeling and environmentally friendly processing, chemical modification is facing extreme scrutiny, and physical, enzymatic, and genetic modification techniques are gaining popularity. Modified starches have found widespread applications in a number of food industries, including but not limited to dairy, bakery, canned food, baby food, frozen food, and beverage industry as a thickener, gelling agent, stabilizer, emulsifier, fat replacer, etc. Dual modification is introduced to overcome any drawbacks of singly modified starches. In line with consumer demands for healthier foods, more innovative food ingredients (e.g., dietary soluble and insoluble fibers) and products are being developed from starch.

In this aspect, extrusion cooking of starch is becoming increasingly popular due to its ease of operation and short processing times paired with the ability to produce a broad range of products and modified starches. With accelerated advancement in analytical and processing technology, the new insights into molecular structure and architecture of starch components and ability to manipulate them are expected to provide continued opportunities for the application of starch in the food industry.

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Hydrocolloids as Texture Modifiers

Vassilis Kontogiorgos

1 Introduction

Hydrocolloids are frequently used as ingredients to create and modify the texture of many processed foods and rarely constitute a finished product. Hydrocolloids used in foods are primarily polysaccharides (e.g. starch and non-starch polysaccharides) and proteins (e.g. gelatin). The functionality of hydrocolloids in food is distinguished into two main classes: structure formation and structure stabilisation. Structure formation usually refers to gelation and emulsification properties, whereas stabilisation is mostly linked with viscosity enhancement. Frequently, the same polysaccharide may have more than one function depending on the formulation, e.g. form gels or simply enhance viscosity. For example, pectin can be used as a gelling agent in confectionery or improve viscosity in a fruit beverage. Consequently, their multifaceted functionality makes polysaccharides irreplaceable in food formulation and texture design (Funami, 2011; Yang et al., 2020).

Sensory food attributes are usually determined by taste, smell, colour and texture. While molecules responsible for the taste, smell and colour are of low molecular weight (e.g. ketones, aldehydes or carotenoids), the texture is generally associated with the high molecular weight biopolymers (i.e. proteins and polysaccharides) or the crystallisation behaviour of lipids. In addition, taste and smell are chemosensory food attributes, i.e. they are responsive to chemical stimuli interacting with taste buds or olfactory receptors, whereas texture is perceived through the trigeminal nerve that is responsive to pressure during mastication. The rheological properties of food soft matter, i.e. the way it responds to forces during mastication and swallowing, generally define its textural characteristics (Pascua et al., 2013). Much literature focuses on small deformation rheological testing that may yield molecular information about foods' properties in conjunction with other techniques. However, the large deformation and fracture properties of gels are primarily responsible for their eating characteristics, and recent research efforts focus on understanding and quantifying their changes during oral processing with *in vivo* measurements (Funami, 2017). While texture formation and modification of aqueous systems using hydrocolloids is a well-established technology, attention gradually shifts to the structuring of the edible oils (Bascuas et al., 2021; Davidovich-Pinhas et al., 2016; Davidovich-Pinhas, 2019). At present, the technology is nascent, but there is evidence that hydrophobically modified hydrocolloids may provide solutions for texture modification of fat-reduced foods (Patel et al., 2013; Tanti et al., 2016; Oh & Lee, 2018).

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From the three classes of compounds responsible for texture creation in food (i.e. polysaccharides, proteins and lipids), this chapter focuses on polysaccharides and gelatin. It introduces the basic mechanisms of structure formation and texture modulation using hydrocolloids and discusses the structure and functionality of the most commonly used in the food industry.

1.1 Mechanisms of Texture Formation

1.1.1 Gelation

Structure formation through gelation is a primary functional property of food hydrocolloids in texture creation. Polysaccharide gels are three-dimensional networks with the chains being connected with the aid of functional or associative groups (Cao & Mezzenga, 2020). A functional group is, for instance, a carboxyl group forming calcium bridges, as in alginate gels. Associative groups interact reversibly through weak physical interactions, most frequently hydrogen bonding (e.g. β-glucan) and hydrophobic interactions (e.g. methylcellulose). The points of interaction are called cross-links or junction zones. The difference is that cross-links are localised, whereas junction zones extend to multiple contiguous sites on the hydrocolloid chain (Tanaka, 2011). Even though gels mostly consist of water, they exhibit a solid-like behaviour due to junction zone formation. It is precisely the strength of these interactions that control the texture of the resulting gel. When a technologist needs to modify the texture of the product, they should aim to modify the intensity with which hydrocolloid chains interact at the molecular level. This can be achieved in multiple ways and depends on the specific food. It may include changes in the pH, NaCl, sucrose or temperature, just to name a few, and a selection of a hydrocolloid with suitable molecular characteristics such as molecular weight or specific functional groups.

Gels are classified into chemical or physical depending on the persistence time (lifetime) of their interaction points. Chemical gels form covalent bonds between the chains so that the connection of the constituent molecules cannot be broken by thermal motion (Djabourov et al., 2013). Chemical gels of polysaccharides formed with covalent cross-linking rarely play a determinant role in food texture modification. For example, covalently cross-linked diferulic acids in wheat arabinoxylans (Carvajal-Millan et al., 2005) may influence bread structure and, consequently, sensory characteristics (Courtin et al., 2001). However, physical gels formed and stabilised mainly through conformational changes or hydrophobic interactions represent the majority of food gels.

Following aqueous dispersion that frequently, but not always, involves heating (e.g. gelatin or carrageenan), hydrocolloid chains are in a random coil conformation (Fig. 1a). When heating is used, certain hydrocolloids on cooling undergo conformational changes known as coil-to-helix transitions. Depending on the hydrocolloid, double (Fig. 1b) (e.g. carrageenan (Campo et al., 2009)) or triple helices (Fig. 1c) (e.g. gelatin (Dille et al., 2021)) are formed which aggregate, leading to three-dimensional rigid structures as the macromolecules form elastically active domains. Frequently, the inclusion of cations assists aggregation accompanied by further changes in the mechanical properties and textural characteristics of the gels (Fig. 1b). These structures are mostly stabilised through hydrogen bonding, which is the most important type of interaction in physical gels due to the presence of multiple hydroxyl groups. Hydrogen bonds link hydrocolloid chains by forming transient zipper-like junction zones. 'Transient' means that they break and reform with a characteristic timescale since the interaction energy of hydrogen bonds is of the order of the thermal energy. This signifies that gels are never at equilibrium but are subject to structural changes over time. For instance, reorganisation of the network during food storage results in syneresis, which is the expulsion of water from the structure, accompanied by changes in the stiffness of the network that directly influences texture (Renard et al., 2006). Ionic interactions are involved in the association of various anionic polysaccharides. Interaction of carboxyl groups with cations, most commonly

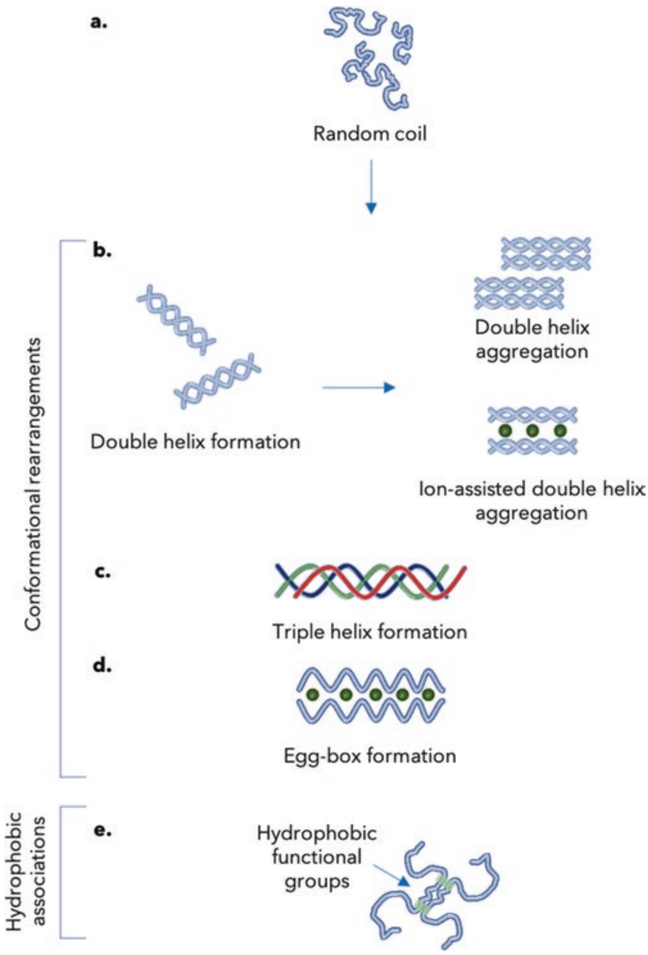


Fig. 1 Conformational rearrangements that promote the formation of organised domains (e.g. through helices or egg-box formations) and interactions through hydrophobic associations are the two major classes of mechanisms in hydrocolloid gel formation. (**a**) Most hydrocolloid chains are in a random-coiled state in solution before gelation, (**b**) double helix formation occurs in many polysaccharides including carrageenan, agar or gellan, (**c**) triple helix formation mainly occurs in gelatin and some polysaccharides such as curdlan, (**d**) egg-box formation mainly occurs in alginates and LM- and amidated pectins and (**e**) hydrophobic associations occur in cellulose derivatives and, under certain conditions, in HM-pectin

calcium (e.g. alginates, low methoxylated pectin), sodium (e.g. gellan) or potassium (e.g. helix aggregation of carrageenan), results in the formation of egg-box structures (Fig. 1d). In most cases, the carboxyl group is usually found in the form of a uronic acid on the polysaccharide backbone. Hydrophobic associations are mostly observed in cellulose derivatives, with hydrophobic functional groups interacting and forming a continuous network (e.g. methylcellulose) (Fig. 1e). Association by hydrophobic interactions ensues from temperature increase and is reversible. The thermoreversible nature of these gels is routinely exploited in fabricating coatings (e.g. for chicken fingers), where gelation with temperature increase during deep-frying and 'melting' on cooling define the textural profile of the product during mastication.

1.1.2 Viscosity

Another main functional property of polysaccharides is the increase of viscosity. The extent to which hydrocolloids can influence viscosity depends on the molecular characteristics of the chains (e.g. molecular weight, functionalisation or branching) and the environmental conditions (e.g. concentration, pH or salt). The shape of the polysaccharide is of particular importance. All other parameters being equal, compact macromolecules have a lower capacity than linear to influence viscosity. Examples that illustrate this are gum Arabic and xanthan. With its compact conformation, gum Arabic has a limited capacity to increase viscosity and can be dispersed at concentrations of >20% w/v (Williams & Phillips, 2021). In contrast, xanthan has an exceptionally stiff structure and forms highly viscous solutions at concentrations as low as 0.05 % w/v (Yaseen et al., 2005). The shape can be controlled by adjusting the interactions between the chains and between the buffer and the chains. Because the solvent in foods is usually an aqueous system, the interactions are controlled mainly by pH, salts (e.g. NaCl or $CaCl_2$) or other compounds (e.g. sugars) depending on the formulation. The former two factors play a crucial role when the polysaccharides carry charged groups (e.g. $–COO^-$, $–SO_3^-$) as the main effect will be on modulating the electrostatic interactions. The repulsion or attraction between the chains will result in an extended or compact conformation with an associated effect on viscosity. These two parameters do not strongly influence neutral polysaccharides (e.g. guar gum).

Concentration is another parameter influencing the viscosity of hydrocolloid solutions, and a specific concentration value termed critical concentration (c^*) plays a special role in the flow behaviour of the solutions (Alba & Kontogiorgos, 2021). It is important to understand that texture modification by viscosity adjustments requires knowledge of the c^* as its imprecise control may lead to textural losses. Specifically, at concentrations below c^*, the flow of polysaccharide solutions is Newtonian. Additionally, below c^*, viscosity has a weak dependency on concentration, and adding polysaccharide does not correspond to large increments in viscosity. In contrast, at concentrations above c^*, small increments in polysaccharide concentration result in significant changes in viscosity, and textural properties may change dramatically even by slight concentration changes. When concentration increases above c^*, the viscosity curve exhibits three different regions (Fig. 2a). The zero-shear region represents the product's viscosity on the shelf, and the flow is Newtonian. Knowledge of the zero-shear viscosity is important as higher values usually correspond to greater stability. Within this region, polysaccharide chains are entangled and interact strongly. The imposed stress generated at such low shear rates, i.e. gravity when the item is on the shelf, breaks up some of the entanglements, but most disentangled chains recoil, and as a result, there are no changes in the overall flow resistance, and the liquid appears to have a constant viscosity (Mezger, 2011). This region is usually observed at shear rates < ~1 s^{-1}. In the power-law region, viscosity depends on the shear rate and is of great technological significance in texture design. Shear rates between 1 and 100 s^{-1} are associated with flow behaviour during swallowing, pouring from a bottle or mixing, and the viscosity in this region needs to be carefully controlled. In this region, polysaccharide chains disentangle and align with the flow field faster than they recoil, and viscosity appears to decrease. Polysaccharides can be successfully used in food formulations to match the viscosity of food dispersions with low-calorie content and prevent textural losses. For instance, in Fig. 2b, the desired viscosity of a salad dressing with an oil volume fraction (φ) of 0.7 is shown with the dotted blue line. Removing oil from the formulation to bring it down to φ = 0.1, as in the case of "light" products, is associated with dramatic changes of viscosity (red line) that, apart from a noticeable influence on texture, will also affect shelf life due to phase separation. Introduction to the salad dressing with φ = 0.1 of 0.85% w/v guar gum (green line) results in identical flows with the original product.

It should be emphasised that even though it is possible to match the bulk rheology with smart product reformulation, the textural characteristics of the food are not easy to replicate (Stokes et al., 2013). In the infinite shear region, flow behaviour becomes once again Newtonian as all polysaccharide chains are now disentangled and aligned with the flow field. The last region is important in texture perception as it defines the lubrication properties of foods, especially of

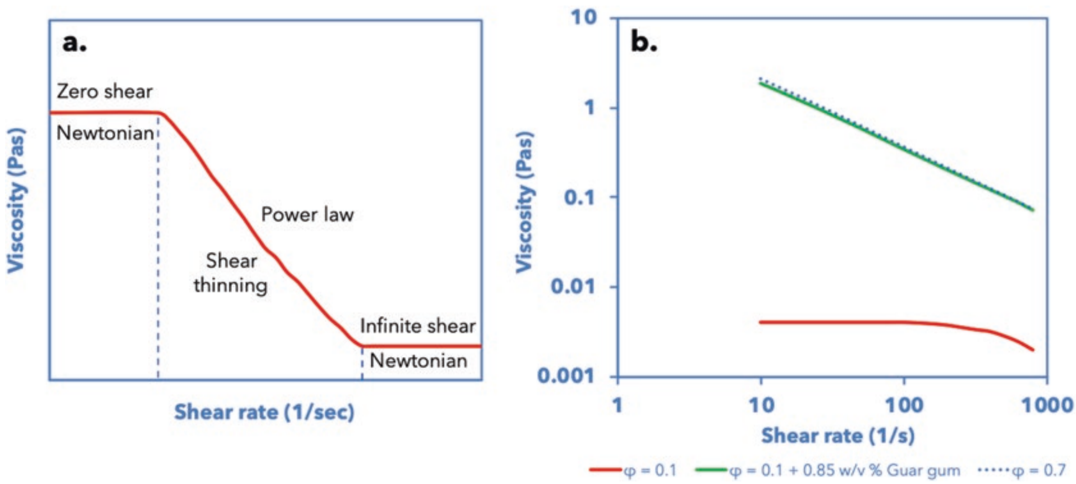


Fig. 2 (**a**) Typical rheological behaviour of hydrocolloid solutions. The viscosity curve is divided into the zero-shear, power-law and infinite shear regions (see text for description). (**b**) Use of guar gum for texture modification of a salad dressing. The addition of 0.85 % w/v to an emulsion with a volume fraction of 0.1 (green line) gives identical rheological behaviour as the emulsion with a volume fraction of 0.7 (dotted blue line)

homogeneous liquids (Pradal & Stokes, 2016; Sarkar et al., 2019). It should be noted that solution rheology and tribology will be influenced by other macromolecules in the formulation, particularly proteins. The interplay of interactions is complex and specific to the product under consideration, and it is difficult to generalise, but phase separations into polysaccharide-enriched and protein-enriched phases or complexation between the protein and polysaccharide are two typical outcomes (van de Velde et al., 2015).

1.1.3 Emulsification

The technological performance of hydrocolloids as emulsifiers is controlled by the same factors mentioned previously (i.e. conformation, molecular weight, etc.). The interplay between these parameters determines the adsorption strength at the oil-water (emulsions) or air-water (foams) interfaces. Rigorously controlled macromolecular structures cannot be used in food formulations, as with synthetic materials, posing challenges to the functionality of natural polymeric surfactants. However, polysaccharides and gelatin may be modified with chemical or physical methods to improve their emulsification properties (Tang & Huang, 2022). Depending on the structure, hydrocolloids can adsorb at the interface, reduce interfacial tension to facilitate droplet disruption and impede droplet aggregation (Murray et al., 2021). This is typically attributed to hydrophobic elements in the structure such as proteins, ferulic acids, methyl groups, etc. It should be noted that adsorption is sensitive to the type of surface (i.e. solid, liquid or gaseous) and its structure (e.g. curved or flat) (Fleer et al., 1998), with the most realistic scenarios for food systems being 'soft' interfaces (i.e. a droplet in emulsions or a bubble in foams) rather than solid, impenetrable surfaces. Once at the interface, polysaccharides may form trains, loops or tails and the specific adsorption mode depends on the chain architecture. For instance, polysaccharides may be described as random copolymers with randomly distributed functionalised sugar residues (e.g. modified celluloses or modified starches), di-block copolymers consisting of sugar monomers with a distinct substitution pattern (e.g. pectin) or graft copolymers containing moieties that protrude laterally from the main chain (e.g. gum Arabic, or sugar beet pectin) (Kontogiorgos, 2019b). In each of these main structures, the proportion of trains, loops or tails at the interface and the adsorption strength dictate the dispersion's stability. It should be noted that the interactions between the chains at the interface can be controlled by the same factors described previously (e.g. pH and ionic strength) and also by the chemical nature of the dispersed phase (e.g. triglyceride or terpene). For instance, the aqueous solubility of the dispersed phase, even when it is infinitesimal, may influence the overall stability of the dispersion (Ürüncüoğlu et al., 2021; Wooster et al., 2008). The pseudo-equilibrium that has been established on storage will be lost during consumption, as it is exposed to drastic changes in temperature, pH, or ionic strength, it is diluted by the saliva and is subject to high shear forces resulting in changes in the sensory perception (Sarkar et al., 2017; Chen, 2015). Hydrocolloids play a critical role in the sensory perception of such systems when they are added either as emulsifiers or as thickening agents (Riquelme et al., 2021; Dickinson, 2018).

2 Hydrocolloid Structure and Functionality

Regarding production volume, the main hydrocolloids used in the food industry are starches and gelatin, which account for about 80% of all hydrocolloids used. Specifically, the hydrocolloids used in order of production volume in 2020 was starch > gelatin > xanthan > cellulose derivatives > galactomannans > pectin > carrageenan > gum Arabic > alginates > agar > gellan (Seisun & Zalesny, 2021). This section aims to discuss the structure of the hydrocolloids with industrial significance and how they are employed in the texture modification of foods.

3 Starch

Starch is the carbohydrate source of plants found in tubers, fruits, and seeds. Naturally found starch that has not been further processed is termed native. However, native starches should be physically, chemically or enzymatically changed to obtain technological consistency and are called modified starches. Starch and its modified derivatives are the most widely used hydrocolloids with broad functionality and may influence all aspects of a food's texture profile. Starch is an α-D-glucose homopolysaccharide consisting of amylose and amylopectin with glucose units connected via α-(1,4) and α-(1,6) linkages. Amylose is a linear polysaccharide, whereas amylopectin has most of the α-(1,6) branching points (BeMiller & Whistler, 2009). Starches have different amounts of amylose and amylopectin depending on the source, and the ratio of these two biopolymers plays a critical role in texture modification. In addition, granule size and its size distribution, the molecular arrangement of amylose and amylopectin within granules, and many agronomical considerations (e.g. plant genetics, soil quality and weather patterns) also play a role in starch properties.

The two main physicochemical changes that starch undergoes during processing are gelatinisation and retrogradation, which determine the texture of starch-containing foods (Ai & Jane, 2015). Gelatinisation refers to the disruption of the molecular order within the granules resulting in loss of crystallinity and amylose leaching. This process is highly variable and depends not only on starch type but also on starch-to-water ratio, pH or other compounds found in the formulation (e.g. lipids). Following cooling, retrogradation has a remarkable influence on food texture. Retrogradation refers to the aggregation of amylose and amylopectin to partially ordered structures. Retrogradation is associated with physical changes that may be undesirable (e.g. staling of bread) or desirable (e.g. crispiness of breakfast cereals) (Wang et al., 2015). Very frequently, minor differences in the fine structure of starch may influence its functional properties (Yu et al., 2019; Bertoft et al., 2016; Roman et al., 2020), and as a result, they frequently exhibit unpredictable behaviour (Hamaker, 2021), highlighting that the structure-function relationships in starches have not yet been fully understood. Modified starches (Ashogbon & Akintayo, 2014) or starch blends (Waterschoot et al., 2015) offer a wide gamut of hydrocolloids that may tackle gelatinisation and retrogradation in different ways suitable for a broad range of foods. Since starch is particularly hydrophilic, it needs hydrophobic modification to act as an emulsifier. It can be modified with esterification using various hydrophobic groups, for example, dodecenyl succinic anhydride or propionate, and most commonly with octenyl succinic anhydride (OSA).

The surface activity of OSA-starches is comparable to that of whey proteins and is approved for food uses (Tesch et al., 2002; Agama-Acevedo & Bello-Perez, 2017).

4 Gelatin

Gelatin is a protein obtained by partial hydrolysis of collagen. The most abundant sources for gelatin extraction are pig skin, bovine hide, and pig and cattle bones, with gelatin obtained from fish having only a minor contribution. Collagen consists of three protein chains forming a triplehelix consisting primarily of glycine, alanine, proline and hydroxyproline. Depending on collagen treatment, two types of gelatin can be obtained. Type A gelatin (pI ~8–9) is obtained by acidic treatment and type B (pI ~4–5) by alkaline treatment of collagen (Liu et al., 2015). Depending on the extraction conditions and raw material, the final gelatin mainly consists of three protein fragments: α-chains; β-chains consisting of two α-chains covalently linked; and γ-chains consisting of three α-chains covalently linked with other fragments of lower molecular weight (Fig. 3a). As a result, gelatin is not a monodisperse protein but a polydisperse biopolymer, and it is treated as a 'hydrocolloid', which means that concepts from synthetic polymer science are suitable to describe its behaviour and properties, similar to polysaccharides.

The main quality characteristics of gelatin that influence food texture are its gel strength and melting characteristics. These two characteristics are linked to the amino acid composition, which depends on the extraction source and conditions. A quantitative parameter that can be used to measure gelatin gel strength is the bloom strength. The bloom strength is the force in grams required to depress a surface of a gelatin sample with specific geometrical characteristics, and it is determined using a uniaxial compression method (e.g. with a texture analyser). The bloom strength determination is now a standardised AOAC method and the gelatin manufacturers of Europe and America use it to classify gelatin into high-bloom (200–300 g), intermediate-bloom (100–200 g) and low-bloom gelatin (50–100 g). A higher bloom corresponds to gelatins with a stronger gel network and a higher melting temperature. The second characteristic that makes gelatin an invaluable hydrocolloid is the thermoreversibility of the gels near-body temperatures. On cooling hot gelatin solutions, the α-chains form triple helices creating a gel network (Fig. 3b) (Djabourov et al., 1988). During consumption, heating the gel (i.e. during chewing) results in sharp melting, occurring in a narrow temperature range of around 35 °C. This gives mouth-melting characteristics to the gels important in texture design, especially in desserts and confectionery products (Dille et al., 2021). Gelatin can be used in many foods as it has a broad range of functional properties (Baziwane & He, 2003; Schrieber & Gareis, 2007), and new sources are continuously explored (Gómez-Guillén et al., 2011).

5 Microbial Polysaccharides (Xanthan, Gellan)

Xanthan gum is an extracellular polysaccharide secreted by the microorganism *Xanthomonas campestris* (Habibi & Khosravi-Darani, 2017). Xanthan has a cellulose backbone with a trisaccharide side chain on every other glucose. The side chain consists of glucuronic acid and two mannose residues that may carry acetyl and pyruvate groups, making xanthan anionic. Xanthan at the operating temperatures in most food formulations attains a very rigid conformation, whereas at higher temperatures, it has a flexible conformation. The temperature at which this transition occurs depends on the ionic strength and the pyruvic acid and acetyl contents of the molecule. Xanthan exhibits high viscosity even at very low concentrations (~0.1%), making it an ideal dispersion stabiliser. Additionally, its steep shear thinning profile makes xanthan suitable to impart good textural characteristics to the food during oral processing and swallowing. Xanthan does not gel by itself and is not a gelling agent. However, it may interact with galactomannans resulting in enhanced viscosity or even gelation under certain conditions (Rinaudo & Moroni, 2009). Xanthan is a diverse ingredient in texture modification and can be used in bakery and dairy products, salad dressings or confectionery products.

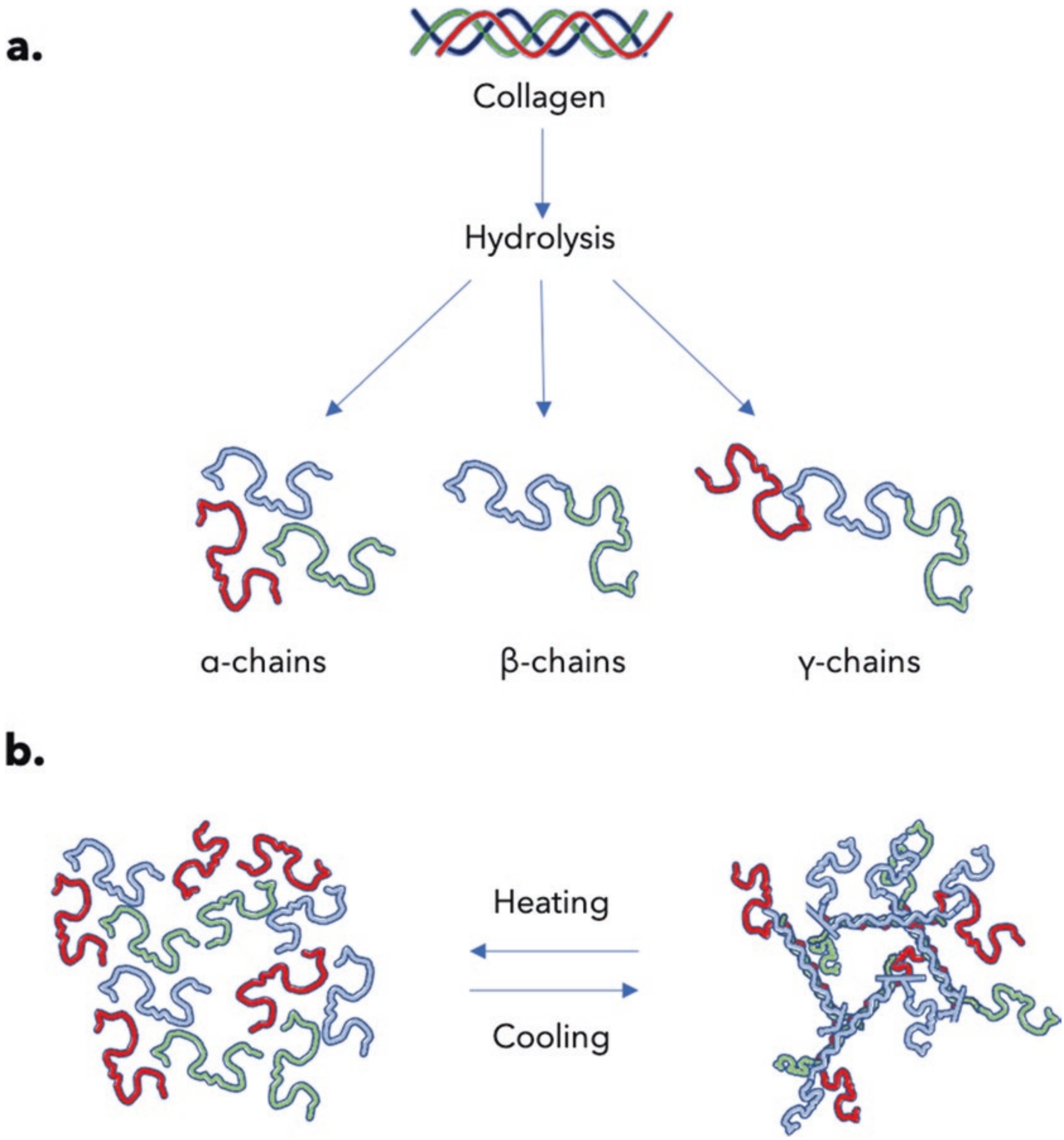


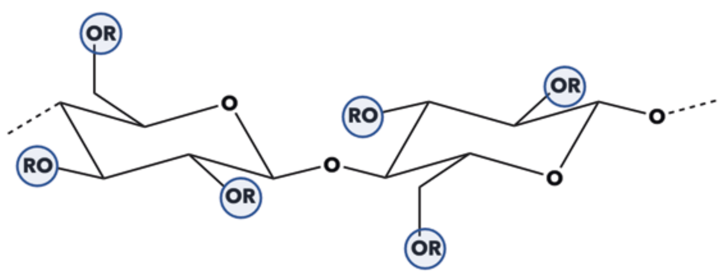
Fig. 3 (**a**) Partial hydrolysis of collagen yields gelatin. Gelatin consists of three protein fragments: α-chains; β-chains consisting of two α-chains covalently linked; and γ-chains consisting of three α-chains covalently linked. (**b**) Gelation mechanism of gelatin. A coil-triple helix transition occurs on cooling leading to gel formation. Heating the gel results in a sharp melting, occurring in a narrow temperature range around 35 °C

Gellan is an extracellular polysaccharide secreted by the microorganism *Sphingomonas elodea*. Gellan is composed of a tetrasaccharide repeat unit with two residues of D-glucose, L-rhamnose and D-glucuronic acid. Gellan is divided into low acyl- (LA-gellan) and high acyl- (HA-gellan), depending on the degree of acetylation. After fermentation, the product is naturally found in its HA form, but it can be easily deacetylated under alkaline conditions. Both HA- and LA-gellan form gels even at low concentrations on cooling, and LA-gellan requires the presence of cations (Morris et al., 2012; Zia et al., 2018). The difference in texture characteristics of these two types of gellan is remarkable as HA-gellan produces soft and elastic gels, whereas LA-gellan produces hard and brittle gels. Blending HA- and LA- gellan to the appropriate proportions can give gels with characteristics that cover the entire spectrum of desirable textures (from hard to soft). Gellan is mostly used in confectionery, beverages and some dairy products.

6 Cellulose Derivatives

Cellulose derivatives are chemically modified celluloses approved for food use. Modification proceeds through an etherification reaction of the free -OH groups on positions C-2, C3 and C-6. Depending on the substituent group that is used, five main cellulose derivatives can be distinguished, i.e. methylcellulose (MC), hydroxypropyl cellulose (HPC), hydroxypropyl methylcellulose (HPMC), carboxymethylcellulose (CMC) and ethyl cellulose (EC) (Fig. 4) (Heinze et al., 2018). The functionality of cellulose derivatives is controlled by the substituent type, their distribution along the chain and the degree of substitution (DS), and as a result, hydrocolloids with a broad range of functionality may be obtained. When the average DS = 0, it is pure cellulose, whereas when DS = 3, all three hydroxyl groups have been substituted. Depending on the reaction and the specific group, DS usually ranges between 0.2 and 2.8 with associated changes in functionality.

Methylated celluloses (MC, HPMC) form thermoreversible gels on heating through hydrophobic interactions (Fig. 1e) (Nasatto et al., 2015; Jain et al., 2013). This characteristic makes them irreplaceable in the texture modification of deep-fried and meat-alternative foods (e.g. plant-protein burgers). The batter that usually covers such products (e.g. chicken nuggets and fish fingers) may disintegrate upon high-temperature deep frying. Methylated cellulose derivatives form a gel and keep the parts of the batter intact. Additionally, the gel forms a barrier to oil and moisture migration, and the product has desirable sensory characteristics. For instance, the product does not have an oily texture, and as moisture losses are reduced, it maintains its succulent characteristics. In products made with plant proteins (e.g. plant protein burger or sausage), cellulose derivatives bind the components together, enabling a uniform grilling. As hydrophobic interactions weaken on cooling, the gel reverts to the liquid state and methylated celluloses now perform as viscosity enhancers providing desirable swallowing characteristics to the product. Gluten-free aerated products (bread, sponge cakes, etc.) are another class of foods that are challenging to fabricate without gluten. In these products, methylated celluloses are the essential ingredient responsible for structure formation (Salehi, 2019). In the absence of gluten, the structure produced by CO_2 bubbles either by fermentation (i.e. bread) or chemicals (i.e. leavening agents) collapses. However, methylated celluloses stabilise the structure during baking with the same gelation mechanism described above. After baking, the entire structure is arrested in a glassy state, resulting in a product with volume, crumb softness and elasticity similar those made with wheat flour. CMC also finds a broad range of applications in texture modification, including moisture retention, mouthfeel improvement and structure collapse prevention.



R = H, cellulose
R = CH_3 or H, methyl cellulose (MC)
R = $CH_2CH(OH)CH_3$ or H, hydroxypropyl cellulose (HPC)
R = CH_3, or $CH_2CH(OH)CH_3$, or H, hydroxypropyl methyl cellulose (HPMC)
R = CH_2COOH or H, carboxy methyl cellulose (CMC)
R = CH_2CH_3 or H, ethyl cellulose (EC)

Fig. 4 Cellulose derivatives are chemically modified celluloses suitable for food use. Depending on the R group used, five main cellulose derivatives can be distinguished

7 Galactomannans

Galactomannans consist of D-mannose, making up the backbone of the chain, with D-galactose forming single branches along the mannan chain. Galactomannans are neutral polysaccharides and are differentiated from each other based on the mannose-to-galactose ratio (M:G). For instance, an M:G ratio of 4:1 indicates that a galactose residue is found in every four mannose units. Four galactomannans are distinguished obtained from fenugreek (1:1), guar (2:1), tara (3:1) or locust bean (4:1). Guar and locust bean gums are the most widely used galactomannans in the food industry (Kontogiorgos, 2019a). The main reason for introducing galactomannans in a food formulation is to modulate viscosity with its concomitant effects on texture. For instance, when increased viscosity is needed to avoid phase separation, the introduction of guar gum will also have textural implications (e.g. increasing thickness perception). Although not gelling agents, galactomannans may form gels through synergistic intermolecular chain associations with xanthan or other helix-forming polysaccharides (Prajapati et al., 2013). The mechanical (i.e. texture) and thermal characteristics (i.e. mouth-melting) of these gels resemble the properties of gelatin, making it possible to replace them in certain applications, e.g. in products for religious or vegetarian diets. They also allow texture modification in a range of products (e.g. bakery formulations, fruit-based desserts, gluten-free formulations), where gelation using a single polysaccharide may not provide the optimum textural characteristics (Gidley & Grant Reid, 2006).

8 Seaweed Polysaccharides (Carrageenan, Alginates, Agar)

Seaweed polysaccharides include sulfated galactans (carrageenan, agar) and derivatives of alginic acid (alginates). The compositional differences between these polysaccharides give a set of materials with a broad spectrum of physicochemical properties that may be exploited in the texture modification of many foods (Alba & Kontogiorgos, 2019).

The disaccharide repeating unit of carrageenan is an alternating β-D-galactose and α-D-galactose or 3,6-anhydro-α-D-galactose. The most industrially relevant types of carrageenan are kappa (κ-), lambda (λ-) and iota (ι-), with the major difference being their sulfate ester content. This difference controls its water solubility that follows the order: (most soluble) λ- (~ 35% ester sulfate) > ι- (~ 30% ester sulfate) > κ- (~ 25% ester sulfate) (least soluble) (Li et al., 2022). Agar is also a linear galactan with a backbone composed of β-D-galactose and 3,6-anhydro-α-L-galactose. Agar consists of two major polysaccharide fractions: agarose and agaropectin. Agarose is a neutral fraction with a low sulphate and methoxyl content that exhibits a high gelling capacity. Agaropectin is charged, heterogeneous, highly substituted with low gelling capacity. The ratio of agarose to agaropectin controls its gelling characteristics and varies depending on the seaweed species and isolation conditions. In contrast to carrageenan, agar is only lightly sulphated (<0.15%). Alginates are linear polysaccharides composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) residues. The alginate backbone consists of sequences of blocks of mannuronic acid (M-blocks) or guluronic acid (G-blocks) and regions of alternating sequences (e.g. MG, MMG, GGM). The M:G ratio of alginates determines their functionality (Rhein-Knudsen & Meyer, 2021).

All three seaweed polysaccharides may gel under appropriate conditions. Carrageenans and agar follow the double helix or the ion-assisted double helix aggregation mechanisms, whereas alginates the egg-box mechanism (Fig. 1). The difference between the gels is their elasticity which directly influences the textural profile of food. For example, the succulent texture of agar gels is caused by rapid syneresis during oral processing (Nussinovitch & Hirashima, 2014). They are also frequently used as thickeners or structure-forming agents in dairy products (Rioux et al., 2017). In addition, depending on food composition or the steps followed during processing, some of them may not be suitable. For instance, agar may be used in the baking industry due to its ability to withstand high temperatures compared to carrageenan. In another example, the gelation of alginates is independent of temperature and can be used to restructure foods that may become damaged or oxidised at high temperatures (e.g. meat products, fruits and vegetables).

9 Pectin

Pectin is a galacturonic acid-rich polysaccharide commercially obtained from citrus fruits (e.g. oranges or lemons) and apples. Pectin primarily consists of homogalacturonan (HG) and rhamnogalacturonan-I (RG-I) segments. HG is the most abundant, with some of the carboxyl groups of the galacturonic acid being methyl-esterified. RG-I is composed of the repeating disaccharide galacturonic acid-rhamnose. RG-I segments usually have branches of galactose or arabinose that may also carry a significant amount of protein attached (Kontogiorgos, 2020).

Pectins are divided into high-methoxy pectin (HM pectin) with a degree of esterification (DE) > 50% and low-methoxy pectin (LM pectin) with DE < 50%. The gel formation mechanism is the most important distinguishing characteristic between HM and LM pectins. HM pectin forms gels at pH < 3.5 at high sucrose concentrations, and the gel is stabilised through hydrophobic interactions due to sucrose-induced dehydration of pectin chains. In contrast, LM pectin forms gels that do not require sucrose but Ca^{2+}, following a mechanism similar to alginates (egg box) (Fig. 1d). Pectin is a significant contributor to the texture of fresh fruits and vegetables, and its degradation during ripening is responsible for tissue softening (Prasanna et al., 2007). Apart from fruit formulations, pectin is also used in dairy products, where interactions between pectin and proteins may modify the texture of dairy formulations drastically (Harris & Smith, 2006).

10 Gum Arabic

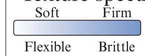
Gum Arabic is a highly branched polysaccharide with galactose forming the backbone and branches consisting of galactose, arabinose, rhamnose and glucuronic acid. This structure is attached to a protein component that plays a key role in its functionality. Gum Arabic consists of three fractions, the arabinogalactan-peptide (AGp) fraction, which is its major fraction, the arabinogalactan-protein complex (AGP), and a minor fraction referred to as glycoproteins (GP) (Sanchez et al., 2018). Because of its compact molecular architecture, gum Arabic can be dispersed at concentrations > ~30% forming low-viscosity solutions. The main functional property of gum Arabic is its emulsification capacity for essential oils and flavours. The AGP component of the structure is the fraction primarily responsible for its interfacial properties. It is used in beverages and confectionery industries to stabilise flavour oils, but it cannot form gels.

11 Concluding Remarks

From the description of the structure and functional properties of hydrocolloid, it becomes evident that texture modification relies heavily on the correct selection of hydrocolloid. Its intrinsic characteristics (i.e. structure) and environmental conditions (e.g. pH or temperature) related to specific formulation lead to forming a broad range of textures, sometimes even when the same hydrocolloid is used. Additional considerations, such as lubrication, interactions with saliva during oral processing or gastrointestinal interactions, frequently come into play, creating further challenges in selecting a suitable hydrocolloid. It should be emphasised that although it is impossible to obtain all textures using one hydrocolloid, we can generate a "texture spectrum" ranging from very soft and flexible to firm and brittle (Table 1).

Table 1 is not exhaustive, but it captures the diversity of the hydrocolloids used in the food industry and highlights the need for careful selection depending on the application and the

Table 1 Functionality of hydrocolloids in texture formation in food with their gelation conditions

Hydrocolloid	Gelling	Thickener	Emulsifier	Gelation conditions – Notes	Main applications	'Texture spectrum' 
Starch/modified starch	✓	✓	✓	Cooling – very broad functionality	Nearly all foods	
Gelatin	✓	✗	✗	Cooling – sharp melting near body temperature	Confectionery	
Xanthan	✗	✓	✗	Gels with galactomannans – high viscosity at low concentrations, highly shear thinning	Salad dressings, bakery, dairy	 (with galactomannans)
HA/LA gellan	✓	✗	✗	Cooling and ions – a broad range of elasticities from very soft to very brittle	Confectionery, beverages	
MC/HPMC	✓	✓	✓	Heating – thermoreversible gels	Deep-fried food, meat analogues	
Galactomannans	✗	✓	✗	Gels with xanthan – high viscosity and highly shear thinning	Salad dressings, dairy	 (with xanthan)
κ-Carrageenan	✓	✗	✗	Cooling and salt – thermoreversible gels	Dairy	
Agar	✓	✗	✗	Cooling – very low gelation concentration	Limited use in dairy and confectionery	
Alginates	✓	✗	✗	Ions	Restructured foods	
HM/LM Pectin	✓	✗	✗	Sugar or ions	Confectionery	
Gum Arabic	✗	✗	✓	Does not gel – low viscosity at very high concentrations	Beverages	N/A

The table is not exhaustive, but it captures the main functional characteristics of each hydrocolloid. The red arrows in the last column indicate the texture of the gel within the "texture spectrum" (from soft to firm). Two red arrows indicate that the hydrocolloid forms gels with an extensive range of textures necessity of having a broad spectrum of hydrocolloids in food formulation. Further understanding and quantification of the structural changes of food during oral processing, e.g. *in vivo* mechanical measurements, bolus rheological and tribological properties and interactions with gastrointestinal fluids, are essential for the selection of hydrocolloids with correct functionality to rationally design food texture.

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Textural Aspects of Special Food for Dysphagia Patients

Enrico Hadde and Jianshe Chen

1 Introduction

Dysphagia, a swallowing disorder, is a life-threatening condition that affects the safety, efficiency, and quality of life. There are many ways to manage dysphagia, including feeding tubes, swallowing therapy, and texture modification of foods. Although feeding tubes can be used to provide nutrition while recovering the ability to swallow, they are not recommended for long-term use because they carry a great risk of complications, such as infection and/or internal bleeding.

Long-term treatment of dysphagia can be achieved by either rehabilitation or compensation. The goal of rehabilitation is a resumption of swallowing functions as near as possible to the healthy situation. This can be achieved with swallowing therapy that can improve the swallowing capability of dysphagia patients. The therapy involves postural techniques and swallowing maneuvers. However, just like any kind of rehabilitation, this process takes time, ranging from months to years. Compensation includes swallowing, posture training, as well as changes in diets to texture-modified foods and thickened fluids. Individuals who undertake rehabilitation often begin with a period of compensation. Gradually, the compensatory mechanisms become less crucial and can eventually be dispensed with as the swallowing function is restored.

This chapter will examine compensation in the improvement of swallowing, by changing the diet to texture modified foods and thickened fluids, as part of dysphagia management. Texture modification of foods and drinks plays a major role in the clinician's toolbox.

2 Dysphagia

Dysphagia is defined as a mechanical disorder that affects safety, efficiency, and/or quality of eating and drinking (Whelan, 2001; Logemann, 1998). It is a serious disorder as it contributes to reduced dietary intake, and thus potentially malnutrition, aspiration, and asphyxiation (Logemann, 1998; Atherton et al., 2007; Vivanti et al., 2009). There are two types of dysphagia: esophageal dysphagia and oropharyngeal dysphagia. Esophageal dysphagia occurs when food or drink stops in the esophagus, whereas oropharyngeal dysphagia occurs when a person has difficulty moving food to the back of the mouth to be swallowed and/or through the pharynx and safely past the airway (Althaus, 2002). Both types of dysphagia are serious conditions.

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Dysphagia is a symptom of many conditions, such as premature birth, cerebral palsy, Alzheimer's disease, or stroke (Althaus, 2002). Dysphagia affects individuals of all ages from infants to the elderly. The majority of patients are elderly and face swallowing difficulties due to illness, polypharmacy, or weakened capability reserves of eating and swallowing (Barczi et al., 2000; Cabre et al., 2010). It is estimated that 8% of the global elderly population is affected by dysphagia (Cichero et al., 2013). Oropharyngeal dysphagia occurs when a person has difficulty in moving food or drink to the back of the mouth, or through the pharynx and safely past the airway. Normally when the bolus is swallowed and enters the pharyngeal area, the epiglottis (a valve that separates the pharynx from the larynx) is closed to ensure that the bolus enters esophagus but not the trachea. However, for individuals with dysphagia, this valve often operates at a slower pace, resulting in the bolus entering the airpipe, causing aspiration (Hadde & Chen, 2021; Logemann, 2007).

Patients are assessed for oropharyngeal dysphagia by speech pathologist using a clinical examination. Following the clinical examination, some patients are referred for a videofluoroscopic swallow study (VFSS) to determine the nature and extent of oropharyngeal dysphagia (Hind et al., 2012; Cichero et al., 2000). The VFSS is not only used to diagnose dysphagia, but also to verify the immediate treatment when recommending a diet. Texture-modified foods and thickened fluids play a major role in clinicians' treatment (Leonard & Kendall, 2013; Steele et al., 2015). Texture-modified foods refer to solid food products or soft-solid foods which require a degree of mastication during eating (e.g., puree). In contrast, thickened fluids/liquids refer to drink products or beverages (e.g., water, milk, alcohol). The modification of food texture compensates for chewing difficulties or fatigue, thus improving swallowing safety and avoiding asphyxiation. Thickened liquids flow more slowly, and thus increase the duration of swallowing and pharyngeal transit time, allowing an adapted reflex response time while swallowing (Chen, 2009; Goldfield et al., 2013).

3 Diet

Diet recommendations for dysphagic patients are specific to the signs and symptoms of the disorder. To compensate for impairments and deficiencies in swallowing, adjustments need to be made, for example, serving temperature, viscosity, food texture, and tastes. Additionally, recommendations may be made to increase the energy density in foods and drinks. For long-term treatment of dysphagic patients, changing the type or texture of food and/or fluid play a major role in clinicians' treatment (Leonard & Kendall, 2013; Cichero et al., 2013). The use of texture modification of foods and thickened liquids is the commonest way to treat dysphagia as they are effective and easy to implement.

Thickened liquid is more cohesive than a thin liquid boli, thus slowing the swallowing process and increasing the pharyngeal transit time, allowing an adapted reflex swallowing response (Reimers-Neils et al., 1994). During human development, the transition of feeding begins with the child by taking smooth, lump-free pureed foods; they then progress to minced and soft foods, while eventually reaching solid foods as healthy adults. The recommended diet for individuals with dysphagia is reverted to the safe pureed foods and progresses through the continuum back up to regular solid foods. The modification of food texture compensates for chewing difficulties or fatigue, thus improving swallowing safety and avoiding asphyxiation. The following section will describe the types of foods and drinks that are recommended by clinicians for individuals with dysphagia.

3.1 Foods and Drinks Classification Used in Dysphagia Management

Classification of the texture-modified foods and thickened fluids has recently been standardized by the International Dysphagia Diet Standardisation Initiative (IDDSI). Many countries have now adapted these standards as part of dysphagia management. Prior to IDDSI, there were differences in terminology and classification, for example, since 2007, texture-modified foods in Australia has been classified as texture A – soft, texture B – minced and moist, and texture C – smooth pureed, while thickened fluids have been classified as level 150 – mildly thick, level 400 – moderately thick, and level 900 – extremely thick (Atherton et al., 2007). Similarly, thickened fluids used in dysphagia management in North America have been known as thin (0–50 mPa.s), nectar-like fluids (51–350 mPa.s), honey-like fluids (351–1750 mPa.s), and spoon-thick fluids (>1750 mPa.s) since the publication of National Dysphagia Diet (NDD) in 2002 (National Dysphagia Diet Task Force, 2002). Note that the NDD specified that the viscosity range was measured at shear rate of 50 s^{-1} as a precise measurement between thickness categories. However, implementation of NDD approach faced practical problems, such as the need for expensive machinery, like a rheometer or viscometer and skilled personnel to perform the measurements. Such equipment is rarely accessible to clinicians, carers, or patients with dysphagia. Additionally, it is known that most thickened liquids are non-Newtonian fluid, which makes the choice of shear rate at 50 s^{-1} questionable.

In 2017, IDDSI developed an international framework for classifying foods and drinks used in dysphagia management which consists of a continuum of 8 levels (0–7), where drinks are described from level 0 to level 4 and foods from level 3 to level 7 (Fig. 1) (International Dysphagia Diet Standardisation Initiative, 2019; Cichero et al., 2017). In addition to descriptive terms, the levels are also expressed with numbers and colors for easy application in clinical practice. It should be noted that level 3 and level 4 of IDDSI have two parallel terms. Liquidized and pureed refer to those developed or modified from solid food, while moderately thick and extremely thick refer to thickened fluid from a liquid.

The IDDSI systematic review suggested that liquids and food should be classified in the context of the physiological process involved in oral processing, oral transport, and flow initiation. Different devices are needed to best describe the behavior of the bolus (Steele et al., 2015). Accurate measurement of fluid flow properties is a complex task. The flow of a drink as it is consumed is influenced by many factors, including shear viscosity, extensional viscosity, density, yield stress, temperature, propulsion pressure, and fat content (Nishinari et al., 2019b; O'Leary et al., 2010; Sopade et al., 2007).

3.2 Testing Methods

Testing methods were suggested by IDDSI guidelines to identify the food and drink category. For example, the IDDSI flow test was recommended to classify drinks from level 0 to level 3. A gravity flow test using a 10 mL slip tip hypodermic syringe (ISO 7886-1) is used to perform IDDSI flow test. It should be noted that IDDSI flow test specifically uses a reference syringe with a measured length of 61.5 mm from the zero point to line 10 mL.

Prior to the test, the syringe is sealed by covering the nozzle of the syringe with the finger and the samples are filled up to 10 mL line with another syringe. The flow test starts by removing the finger from the nozzle and allowing the sample to flow out of the syringe for 10 s and measure the volume of the sample remaining in the syringe (see Fig. 2).

To identify level 3 or 4, fork drip test is recommended; this test assesses whether the food/fluid flows through the prongs of a fork, which is compared against the detailed description of each level (see Fig. 3). This test is described in existing national terminologies in Australia, Ireland, and the United Kingdom (Atherton et al., 2007; Irish Nutrition and Dietetic Institute, 2009). This test relies on qualitative observation.

Another testing method recommended by the IDDSI guideline is spoon tilt test. The spoon tilt test is used to determine the stickiness of the sample (adhesiveness) and the ability of the sample to hold together (cohesiveness). It is used predominantly for measures of samples in levels 4 and 5. The samples are placed on a spoon and tilted or turned sideways to observe the following (see Fig. 4):

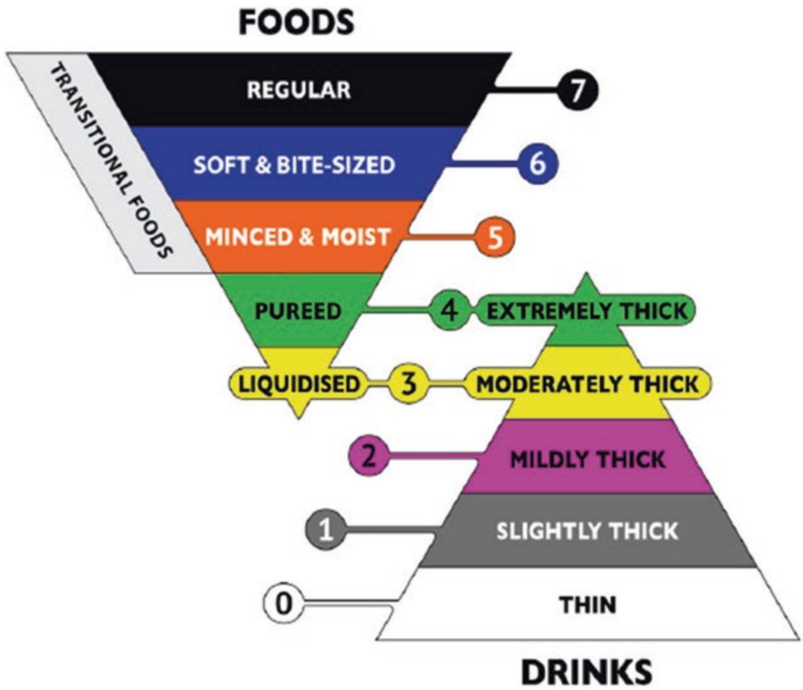

Fig. 1 The IDDSI framework and descriptors. (Adapted from International Dysphagia Diet Standardisation Initiative, 2019)

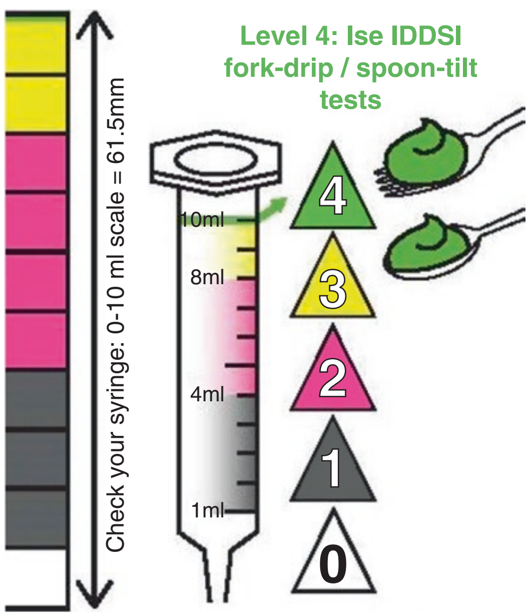

Fig. 2 IDDSI flow test level description. (International Dysphagia Diet Standardisation Initiative, 2019. ©IDDSI 2017)

- Whether the sample is cohesive enough to hold its shape of the spoon
- How easily the sample pours or slides off the spoon when the spoon is tilted or turned sideways
- How much food is left on the spoon (i.e., whether the sample is sticky or not)

IDDSI level 4 food texture describes the sample as cohesive (hold its shape of the spoon), not firm (easily slide off with only gentle flick), and not sticky (little leftover on the spoon). On the other hand, IDDSI level 5 food texture describes the sample as cohesive (hold its shape on the spoon), firm (slides off with a light shake), and not sticky (little leftover on the spoon). Similar to fork drip test, this test relies on qualitative observation.

Finally, fork pressure test or spoon pressure test is also suggested to measure the hardness/firmness of the food for level 5 to level 7. A fork is applied to the food sample to observe its behavior when pressure is applied. For assessment, the fork is to be pressed onto the food sample by placing the thumb onto the bowl of the fork (just below the prongs) until the thumb nail blanches noticeably to white (see Fig. 5). The pressure applied to make the thumb nail blanch has been measured at ~17 kPa (Cichero et al., 2017). This pressure is consistent with tongue force used during swallowing (Steele et al., 2014).

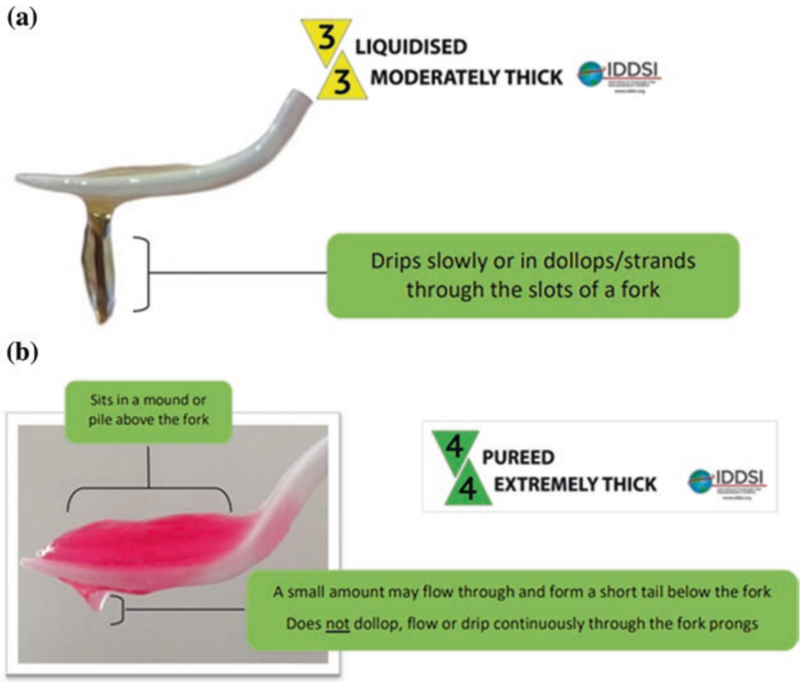

Fig. 3 (**a**) Fork drip test for IDDSI level 3, (**b**) fork drip test for IDDSI level 4. (International Dysphagia Diet Standardisation Initiative, 2019)

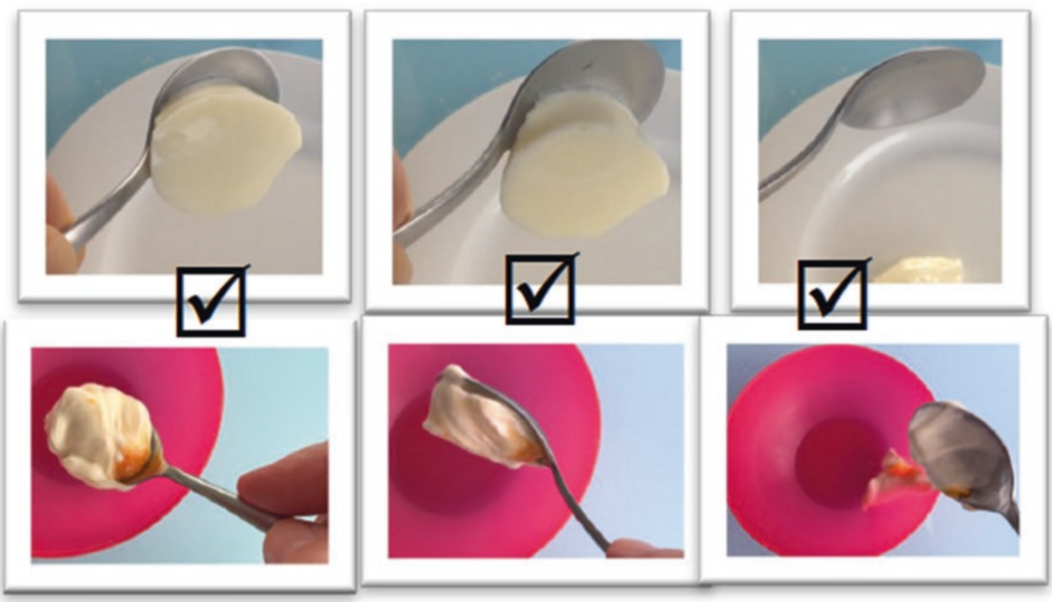

Fig. 4 Spoon tilt test measurement. (International Dysphagia Diet Standardisation Initiative, 2019)

The sample is categorized as IDDSI level 6 if the sample is squashed and does not return to its original shape when pressure is released. If the sample is easily squashed with little pressure from a fork (i.e., pressure applied does not make the thumb nail blanch to white), the sample is categorized as IDDSI level 5. On the other hand, if the sample is not squashed or returns to its original shape when pressure is released, the sample is categorized as IDDSI level 7 or regular foods.

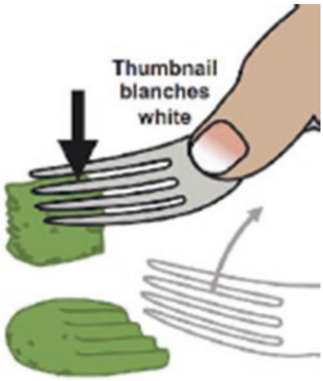

Fig. 5 Fork pressure test measurement. (International Dysphagia Diet Standardisation Initiative, 2019)

3.3 Thickened Fluids

Thickened fluids/liquids can be purchased commercially from the market as a fully prepared product. These are ready-to-drink liquid that have a long shelf life. Thickened liquids can also be made up to the desired level of thickness using commercial thickener. Depending on the thickening agent used, most varieties of drinks can be thickened, including hot and cold drinks. Carbonated beverages can be also thickened; however, it may become quite challenging with thickening powder as bubbles will be produced when the drink is stirred. The bubbles will also be thickened and become a stable froth, thus changing the experience of drinking carbonated beverages. The carbonation can be let out first before adding the powder thickener to reduce the number of bubbles produced when stirring the drink. However, the beverages will lose their fizziness and thus reduce the tingling sensation and can taste quite syrupy. Alternatively, thickening agent can be purchased commercially in the form of a liquid (sometimes referred to as gels). Thickening carbonated drinks or beer with liquid thickener is found to be easier in practice as less bubbles or froth are produced. Both forms (powder or gels) of thickener are clinically safe and effective in improving the swallow safety of individuals with dysphagia (Hadde et al., 2021). Depending on the type of thickeners used, thickened drinks may acquire the taste of thickener (mildly). Due to this, a weak flavoring beverage (e.g., cordial, juices) is preferred to thickened water as it can masks the mild flavor of the thickener.

Underlying liquid thickening for dysphagia management had been focused on the principles of flowability or shear rheology. However, it has become clear that cohesiveness is a very important factor which critically influence bolus flow during swallowing. Therefore, xanthan gum–based thickeners have increasingly become the thickener of choice, displacing starch-based thickeners (e.g., modified maize starch and potato) in commercial thickening products for the clinical management of dysphagia. The advantages of xanthan gum are better oral texture, greater degree of cohesiveness, less taste, and better stability. The more cohesive the bolus, the lower the risk to break up into multiple droplets, thereby allowing the liquid to flow safely into the esophagus. Figure 6 shows a fluid of appropriate cohesiveness flowing as a single body with no splashing/fracturing and therefore without any residue left behind (Fig. 6a). However, a low cohesive liquid splashes during swallowing, giving a much higher risk of coughing once residual droplets enter the air pipe (Fig. 6b).

Despite the fact that cohesiveness as a material property is widely accepted in the literature and daily life, precise definition and objective measurement of cohesiveness are still not available (Rosenthal & Thompson, 2021). However, it is generally believed that cohesiveness is closely related to the flow and deformation properties of a fluid. Rheological measurement may give a useful indication of how cohesive a fluid is (Cichero et al., 2000; Hadde & Chen, 2019). Rheological behavior of thickened liquids can be classified in terms of two types of deformation, shear and extensional. Shear deformation is often measured in terms of shear viscosity, which describes the fluid's thickness and more specifically its resistance to shear flow. On the other hand, extensional deformation is measured in extensional viscosity, which describes the fluid's resistance to stretching or elongation.

Shear viscosity has been an established way of reporting flow properties of thickened liquids in the field of dysphagia. Thickened liquids are gen-

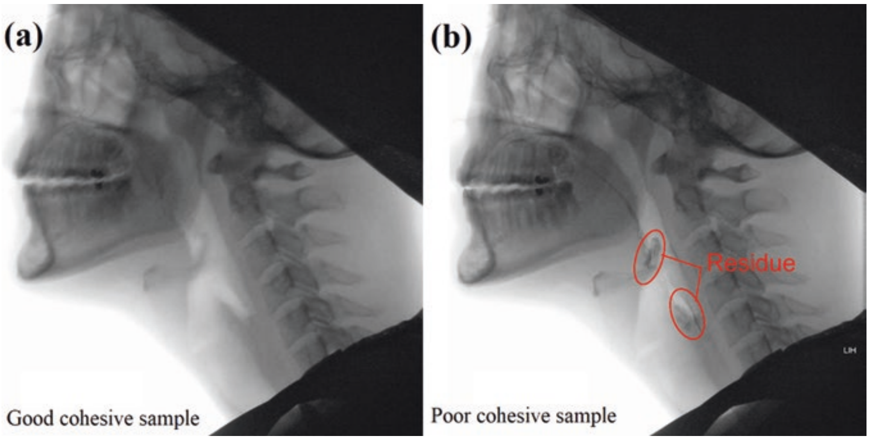

Fig. 6 Photograph of residual coating left in the pharyngeal area after (**a**) swallowing of a fluid sample with a good cohesive (RTC 6.50%, no residue) and (**b**) a fluid sample of poor cohesiveness (ThickenUp 5.34%, some residual coating). Both samples have equal apparent viscosity at 50 s^{-1}. (From Hadde et al., 2019)

erally shear-thinning fluid with existence of an apparent yield stress for some of them. The degree of shear-thinning is dependent on the types of thickener. For example, xanthan gum–based thickeners are more shear-thinning than starch-based thickeners (Hadde et al., 2021). It is believed that a higher shear viscosity slows down the flow of the bolus in the pharynx, thus leading to longer transit time in the pharyngeal phase of swallowing, allowing better oral and pharyngeal coordination and enhancement of safe swallowing (Dantas et al., 1990; Barbon & Steele, 2018; Robbins et al., 1992). On related note, the rheological properties in extensional deformation of thickened liquids have recently been focused on the importance of extensional deformation to bolus flow. It was reported that a higher extensional viscosity of liquid reduces the elongation of the bolus in the pharyngeal phase during swallowing, thus potentially reducing the risk of post-swallow residue due to bolus breakage (Hadde et al., 2019).

The IDDSI syringe flow test relies heavily on the shear viscosity of the liquid. The higher the shear viscosity of a liquid, the slower that liquid flows out of a syringe, thus a greater volume remains in the syringe after 10 s. However, the extensional viscosity of the liquid also affects the IDDSI flow test. The fluid's behavior coming out of nozzle depends heavily on the extensional viscosity of the liquid. When IDDSI flow test is performed, a column of material is formed by extrusion through the tip of the syringe. Once the weight of the extruded column exceeds the force of cohesion, the column will break into one or more droplets. Therefore, a liquid with a high extensional viscosity (high cohesive) will stretch further before it breaks into droplets than that of low extensional viscosity liquid (see Fig. 7). This phenomenon was the base principle of the cohesiveness measuring technique developed by Hadde et al. (2020) to measure the cohesiveness of a thickened liquid. The technique uses a Texture Analyzer to drive syringe, and the droplet aspect ratio (i.e., length/width) is measured at the point where the liquid breaks into droplets. As can be seen from Fig. 7, the highly cohesive sample will elongate further before it snaps into droplets, thus increasing the droplet aspect ratio. It was shown that the cohesiveness of the liquid is highly correlated with its extensional viscosity (Hadde et al., 2020). Despite sufficient evidence now available demonstrating the critical importance of cohesiveness in safe swallowing, consensus has yet to be reached.

Most regions in the world (e.g., Australia, North America, Europe, and China) have followed the food and drink classification introduced by IDDSI. For drinks, the liquids are categorized by their "thickness" and their ability in a gravity flow testing method using a syringe.

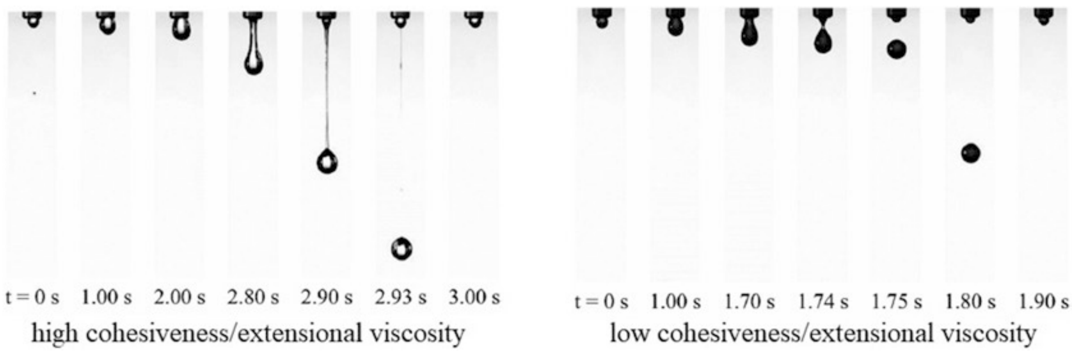

Fig. 7 Flow behavior of fluids with similar shear viscosity, but different extensional viscosity when extruded from the syringe

3.3.1 Level 0 – Thin

These are liquids healthy individuals ingest on a daily basis. They flow like water and fall rapidly when poured. They can be drunk easily through cup or straw. When measured with IDDSI flow test, less than 1 mL of liquid remain in the 10 mL slip tip syringe after 10 s of flow.

3.3.2 Level 1 – Slightly Thick

These liquids are thicker than water and requires a little more effort to drink than thin liquids. Drinks in this category can still easily flow through a straw, syringe, or teat/nipple. These liquids are often used in the pediatric population as a thickened drink that slows down the flow, yet still able to flow through an infant teat/nipple. Sometimes, these liquids are also used in adult populations where thin drinks flow too fast to be controlled safely, since these liquids will flow at a slower rate. When measured with IDDSI flow test, 1–4 mL of liquid remain in the 10 mL slip tip syringe after 10 s of flow.

3.3.3 Level 2 – Mildly Thick

Drinks in this category pour reasonably rapidly from a cup. They generally leave a residue in the cup after pouring out and may leave a coating in the mouth. These liquids are generally sippable and pour quickly from a spoon, but slower than thin drinks. It is still possible to drink this level of liquid thickness from a cup or using a straw. However, mild effort may be required to drink through a standard bore straw (i.e., 5.3 mm diameter). This level of liquids is suitable if tongue control is slightly weakened. When measured with IDDSI flow test, 4–8 mL of liquid remain in the 10 mL slip tip syringe after 10 s of flow.

3.3.4 Level 3 – Moderately Thick

Drinks in this category are cohesive and pour slowly from a cup. These liquids would pour in a slow, steady stream from a spoon. The best way to drink these liquids is directly from the cup or with a spoon. It would be very difficult to drink this thickness of liquid using a straw, although moderate effort may be required to suck through a wide bore straw (i.e., 6.9 mm diameter). If tongue control is insufficient to manage level 2 drinks (Mildly Thick), this level may be suitable. This level of liquids allows more time for oral control and may need some tongue propulsion effort to swallow liquids in this category.

IDDSI recommended to use both IDDSI flow test and fork drip test to measure the thickness consistency of the liquids in this category. When measured with IDDSI flow test, more than 8 mL of liquid remains in the 10 mL slip tip syringe after 10 s of flow. Using a fork, liquid in this category drips slowly in dollops/strands through the prongs of a fork (see Fig. 3a).

3.3.5 Level 4 – Extremely Thick

Drinks in this category are cohesive and hold a shape on a spoon. It is unlikely to be able to drink this liquid directly from the cup as they do not flow easily. These liquids may show some very slow movement under gravity, but they cannot be poured from a cup. Similarly, it is not possible to drink this thickness of liquid using a straw, and using a spoon is the optimal way to "drink/eat" this type of thickened liquid. When spoon is not accessible, a fork can be used instead. If tongue control is significantly weakened, this category may be the best choice. However, this liquid requires more tongue propulsion effort to swallow than level 3 thickened fluids. These liquids may also increase the risk of oral and/or pharyngeal residue if too sticky.

IDDSI flow test is not applicable to measure the thickness consistency for liquids in this category. IDDSI recommended to use fork drip test to measure the thickness consistency. When fork drip test is performed for this thickness level, the fluid sits in a mound/pile above the fork. A small amount of liquid may flow through and form a short tail below the fork prongs, but it does not flow or drip continuously through the prongs of a fork (see Fig. 3b).

3.4 Texture Modified Foods

Soft solid foods require oral effort to break down the structure and to form a swallowable bolus. Dysphagia patients are likely to have trouble in forming a proper bolus. Therefore, most of the food for dysphagia patients should be smooth and lump free, which does not require chewing.

For firm solid foods, oral processing and swallowing could be more complicated than that for drink or soft solid food. Oral destruction and manipulation of a solid food could be a challenging task for dysphagia patients. Hutchings and Lillford (1988) stated that a certain "degree of structure" and "degree of lubrication" of the bolus is required before swallowing can be taken place. The food structure must be broken down sufficiently to reduce the risk associated with choking and asphyxiation. Additionally, the food must be lubricated sufficiently to improve the ease of swallowing. The oral processing that is required to meet the swallowing thresholds of both of these factors is referred as the oral trajectory (Nishinari et al., 2019a; Hawthornthwaite et al., 2015) (Fig. 8).

The degree of structure defines the physical properties of the food during breakdown, such as hardness, firmness, particle size, and many more. Degree of structure decreases over time during mastication and needs to be reduced to a threshold where the food can be swallowed. On the other hand, degree of lubrication is a combination of moisture initially present in the mouth, food's moisture content, salivary flow rate, and other factors such as presence of oil or fat. Degree of lubrication generally increases over time during mastication due to salivation. It must reach to a threshold where the food is slippery enough to be swallowed. Without a doubt, saliva is the most essential ingredient for lubrication. It moistens the food bolus and assists food softening, structure breakdown, and dilution (Assad-Bustillos et al., 2019). However, individuals with dysphagia are typically dehydrated and present with dry mouth or xerostomia (Stokes et al., 2013), which means they do not produce saliva as much as healthy individuals and thus moistening the food may be challenging for them.

Texture-modified foods are designed with a low degree of structure and elevated degree of lubrication to assist the oral effort of mastication. Individuals with dysphagia often have lower biting force and tongue pressure and present with a dry mouth; therefore, they are recommended to consume soft solid food which contains a high initial moisture content. Texture-modified foods are categorized by their texture properties and sizes.

3.4.1 Level 7 – Regular and Easy to Chew

Level 7 is divided into two subcategories: level 7 (regular) and level 7 (easy to chew). Level 7 (regular) refers to food that healthy individuals consume daily. There are no limitations to texture or types of food in this category. The food can be hard, crunchy, naturally soft, tough, chewy, contain seeds, stringy, fibrous, or crispy. Sample size is not restricted at this level. Any method may be used to eat these foods. Individuals who consume foods in this category may need a fully functioning dentition (i.e., own teeth or well-fitting dentures) and have no weakness for oral

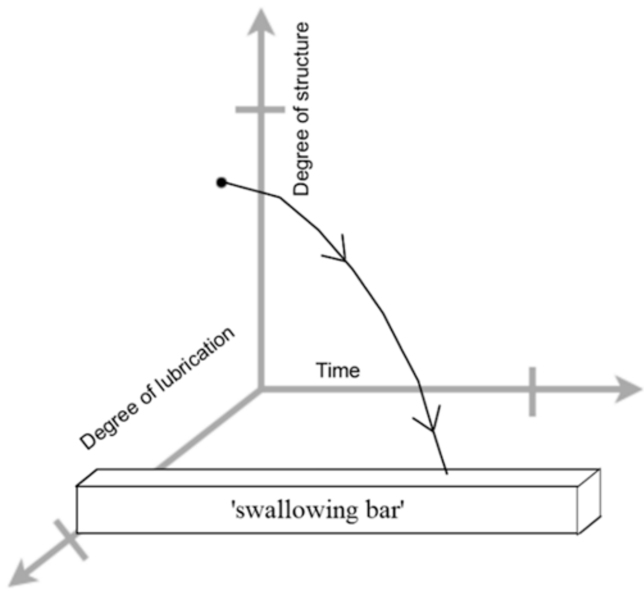

Fig. 8 Food is swallowed after reaching the "swallowing bar," where two thresholds of "degree of structure" and "degree of lubrication" have been reached

mastication. Additionally, individuals need to have the ability to bite hard foods and chew them for long enough to form a soft cohesive bolus that is safe to swallow. Testing methods are not required to measure the texture consistency of the foods in this category.

Level 7 (easy to chew) is similar to level 7 (regular), except that the foods in this category are modified to exclude food that are particularly hard, tough, chewy, fibrous, stringy, sticky, crunchy, or excessively seeded. The sample size is also not restricted in this category and any methods may be used to eat these foods. However, individuals who consume foods in this category still require the ability to bite soft foods and orally process the food to form a soft cohesive bolus that is safe to swallow. This level may be suitable for people who find hard and chewy foods difficult or painful to chew or swallow. This category is often used by clinicians for developmental teaching, or progression to foods that need more advanced chewing skills than level 6.

Unlike level 7 (regular), level 7 (easy to chew) is recommended to be measured with fork pressure test for its texture consistency. The food is considered "soft" enough and can be categorized as level 7 – easy to chew if the sample squashes, breaks apart, changes shape, and does not return to its original shape when fork pressure test is performed (thumb nail blanches to white, see Fig. 5). Additionally, the pressure from a fork held on its side should be able to cut or break apart or flake the food into smaller pieces (see Fig. 9).

3.4.2 Level 6 – Soft and Bite-Sized

Foods in this category have similar texture with level 7 (easy to chew). However, the foods are soft, tender, and moist throughout with no visible separate thin liquid and can be mashed or broken down with pressure from fork, spoon, or chopsticks. However, the sample size in this category has to be "bite-sized" pieces as appropriate for size and oral processing skills. This is typically no larger than **8 mm pieces for pediatric or 15 mm pieces for adults**. These food piece sizes were designed to minimize choking risk. Generally, the food in this category can be eaten with a fork, spoon, or chopsticks. Individuals who consume food in this category do not require to bite the food, but appropriate chewing capability is still required to orally process the food to form a soft cohesive bolus that is safe to swallow. Additionally, tongue manipulation is required to move the food and keep it within the mouth for chewing and oral processing and to move the bolus for swallowing.

Fig. 9 Samples of food were cut into smaller pieces using the side of a fork. (International Dysphagia Diet Standardisation Initiative, 2019)

IDDSI recommended to perform fork pressure test to measure the hardness of the food. When the food sample is pressed with the tines of a fork to a pressure where the thumb nail blanches to white, the food sample squashes, breaks apart, changes shape, and does not return to its original shape when the fork is removed. Examples of food in this category include cooked meat, cooked fish (no bones or tough skins), canned or soft fruits (fibrous part of fruit is not suitable), steamed or boiled vegetables, rice.

3.4.3 Level 5 – Minced and Moist

Foods in this category are soft and require minimal chewing effort. The food should be moist with no visible separate layer of liquid and should be easy to be converted into a bolus. Small lumps may be visible within the food, but the lumps should be easily deformed using the tongue to squeeze the bolus against the palate. The lumps should be **equal or less than 2 mm width and no longer than 8 mm in length for pediatrics**, and **equal or less than 4 mm width and no longer than 15 mm in length for adults**. The food in this category should be cohesive enough, to be scooped and shaped (e.g., into a ball shape) on a plate. The food can be eaten with a fork or spoon. Eating this food with chopsticks may be difficult. Individuals who consume food in this category do not require to bite the food and only minimal chewing is needed. However, tongue strength is still required to move the bolus and can also be used to separate the soft small particles in this texture.

For the food to be categorized as level 5 (minced and moist), the food samples need to be soft, cohesive, not firm, not sticky, and have the right lump size by passing the fork pressure test, spoon tilt test, and lump size requirements. When fork pressure test is performed, the food samples can be easily mashed with little pressure (pressure should not make the thumb nail blanch to white), which means that the food should be soft enough to squash easily with a fork. In addition to softness, the lump size of the food sample should be equal to or less than 2 mm width and no longer than 8 mm in length for pediatric, and equal to or less than 4 mm width and no longer than 15 mm in length for adult. The slot between fork prongs can be used to determine whether the minced pieces are of the correct size or not (see Fig. 10). The slot between prongs of a standard dinner fork is approximately 4 mm. Moreover, when spoon tilt test is performed, the sample is cohesive enough to hold its shape on the spoon and slides off easily if the spoon is tilted or turned sideways or shaken lightly with very little food left on the spoon. This shows that the sample is not sticky. If needed, fork drip test can also be performed. When a sample is scooped with a fork, it sits in a pile or can mound on the fork and does not flow through the tines/prongs of a fork. Examples of food in this category include minced or finely chopped meats and vegetables, finely mashed fish, finely minced or chopped soft fruits, puddings and custards, and scrambled eggs.

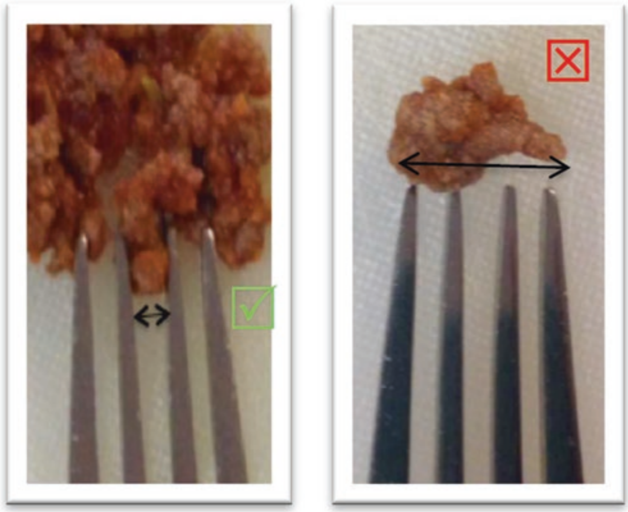

Fig. 10 The slot between fork prongs (approximately 4 mm) can be used to determine whether the minced pieces are of the correct size or not for adult. (International Dysphagia Diet Standardisation Initiative, 2019)

3.4.4 Level 4 – Pureed

Foods in this category are smooth, not sticky and lump free. The food can be piped, layered, or molded because they retain their shape (i.e., cohesive), but should not require chewing. The food in this category is usually best eaten with a spoon, though a fork may still be possible to use. Individuals who consume food in this category do not need to bite or chew the food. If capability of tongue control is significantly weakened, food in this category may be the right choice as it requires less propulsion effort than levels 5, 6, and 7.

As discussed in Sect. 3.3.5, IDDSI level 4 (extremely thick) thickened fluid, IDDSI recommends using the fork drip test to measure the texture consistency of the food sample. When fork drip test is performed, the sample sits in a mound/pile above the fork. A small amount of sample may flow through and form a short tail below the fork tines/prongs, but it does not flow or drip continuously through the prongs of a fork. In addition, spoon tilt test is also recommended to measure the cohesiveness, firmness, and the adhesiveness (stickiness) of the food in this category.

When spoon tilt test is performed, the sample should be cohesive enough to hold its shape on the spoon. A full spoonful must plop off the spoon when the spoon is tilted or turned sideways; a very gentle flick (using only fingers or wrist) may be used to dislodge the sample from the spoon, but the sample should slide off easily with very little food left on the spoon. A thin film remaining on the spoon after the Spoon Tilt Test is acceptable. This shows that the sample is not firm and not sticky. Examples of food in this category include purees suitable for infants (e.g., meat pureed, apple pureed), infant cereal, custard, and yoghurt.

3.4.5 Level 3 – Liquidized

Food in this category has smooth texture with no bits, such as lumps, fibers, bits of shell or skin, husk, particles of gristle, or bone. The food cannot be piped, layered, or molded on a plate because it will not retain its shape. Therefore, it is best eaten with a spoon. A fork may be used though it drips slowly in dollops through the prongs. No oral chewing is required to consume food of this category; thus, the food can be swallowed directly. Foods in this category require less tongue propulsion effort than those at level 4.

The texture consistency of level 3 (liquidized food) can be measured in similar ways as level 3 (moderately thick thickened fluids). IDDSI flow test can be used to measure the thickness of the sample. When measured with IDDSI flow test, more than 8 mL of the sample remains in the syringe after 10 s of flow. Fork drip test measurement should be undertaken in addition to IDDSI flow test. When fork drip test is performed, the sample in this category drips slowly in dollops/strands through the prongs of a fork. The sample should spread out if spilled onto a flat surface. When a fork is pressed on its surface, the tines/prongs of a fork do not leave a clear pattern. Examples of level 3 (liquidized food) include infant's first foods, such as runny cereal or runny pureed fruit, some sauces, and gravies.

3.5 Instrumental Assessment of IDDSI Food and Drinks Classification

The food and drink classification for dysphagia management and the practical testing methods developed by IDDSI are widely welcomed by carers and patients because of their simplicity and ease of use. However, despite being well suited to frontline application, they are less valuable for industrial purposes, where quantitative and instrumental measurements are required for quality assurance and manufacturing. The subjective nature of the IDDSI food and drink classification is the major limitation of the scheme and the one most often challenged by food industry.

In contrast to the syringe flow test, procedures like the spoon tilt of fork drip test adopted by IDDSI rely on qualitative observation to determine the food consistency level. These techniques are qualitative and subjective in nature and sometimes practitioners are inconsistent with each other. For example, it has been shown that classifying thickened liquids with fork drip test is quite difficult by laypersons (Hadde et al., 2016), especially for "mid-viscous" samples between level 2 and level 3. Another example is how vigorously the spoon is shaken in a spoon tilt test by different people. Such methods are therefore not suitable for industrial applications where quantitative, instrumental measurements are required for the purpose of quality assurance.

Hadde et al. (2022a, b) developed techniques to quantitatively categorize the IDDSI levels of texture-modified foods and thickened fluids for use as an objective framework. In Hadde et al. (2022a), the IDDSI level categories for thickened fluids (i.e., IDDSI levels 0–4) were assessed by the syringe flow test, the fork drip test, and a Ball-Back Extrusion (BBE) technique undertaken with a texture analyzer (Fig. 11). This parameter was selected because the BBE had been shown to be well correlated with a shear viscosity measured with a rheometer (Chen et al., 2021). Table 1 summarizes the recommended guidelines for IDDSI level 0–level 4 as described by Hadde et al. (2022a). It is believed that these instrumental ranges have significant therapeutic and manufacturing advantages over the qualitative description described in the IDDSI Framework.

Hadde et al. (2022b) considered the IDDSI level categories for texture-modified foods assessed by spoon tilt test and fork pressure test (i.e., IDDSI level 4–level 7) to an instrumental assessment measured with a Texture Analyzer. A small compression puncture test was performed to measure the firmness, compressive modulus, and adhesiveness of the sample. The firmness of the sample can be quantified by measuring the positive peak stress of the sample when compressed by the probe at a fixed distance of 3 mm. This firmness affects how easily the samples slides off when the spoon is turned sideways or tilted in spoon tilt test. The compressive modulus is calculated based on the slope of the stress-strain curve during the compression. The adhesiveness of the sample, which determines how much samples are left on the spoon, is measured by calculating the ratio of negative peak stress and positive peak stress when the probe was pulled apart from the sample.

The hardness of the sample was defined as the value of the peak stress resulting from the compression of the sample at 50% strain. Table 2 summarizes the recommended guidelines for texture-modified foods for IDDSI level 4–level 7 as described by Hadde et al. (2022b). It is believed that these thresholds and ranges have significant therapeutic and manufacturing advantages over the qualitative description contained in the IDDSI framework.

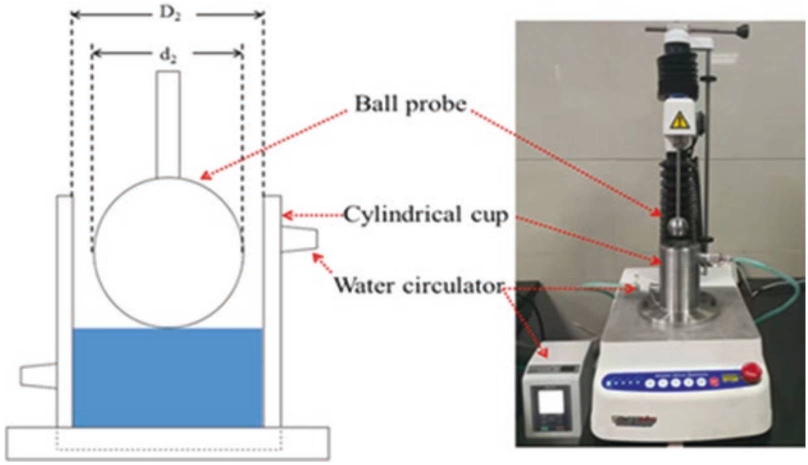

Fig. 11 A schematic illustration of the ball-back extrusion (BBE) test. Left: a ball back extrusion; right: attachment of the ball-back extrusion to a Texture Analyzer. (From Chen et al., 2021)

Table 1 Apparent stress range for the recommended guidelines for IDDSI level 0–level 4 of thickened fluids by Hadde et al. (2022a)

IDDSI level	BBE apparent stress (kPa)
Level 0	<0.059
Level 1	0.059–0.128
Level 2	0.128–0.366
Level 3	0.366–1.481
Level 4	1.481–2.126

Table 2 Cohesiveness and adhesiveness threshold, firmness, and hardness range for IDDSI framework of food texture by Hadde et al. (2022b)

IDDSI level	Cohesiveness (kPa)	Firmness (Pa)	Adhesiveness (−)	Hardness (kPa)
Level 4	>4.11	<540	<0.19	–
Level 5	>4.11	540–1700	<0.19	<12
Level 6	–	–	–	12–20
Level 7	–	–	–	>20

4 Summary

The study of food oral processing has improved our understanding of swallowing, specifically for dysphagia management. The foods and drinks classification for dysphagia management developed by International Dysphagia Diet Standardisation Initiative (IDDSI) categorizes samples by their rheological and textural parameters. For drinks, the liquids are classified by their "thickness" and their ability to flow in under the force of gravity using a syringe. This depends on the fluid's shear and extensional viscosity. In the case of solid foods, their textural properties (e.g., hardness, cohesiveness, adhesiveness) and particle sizes are important. Such properties constitute the "degree of structure" and the "degree of lubrication" of the foods to enhance safe swallowing for individuals with dysphagia.

This chapter summarizes the foods and drinks classification used in dysphagia management as developed by IDDSI. Table 3 summarizes the sample's characteristics and behavior in relation to the IDDSI categories. Each IDDSI level of thickened fluids and texture-modified foods requires testing with appropriate methods developed by IDDSI. For example, level 0 to level 2 is measured with IDDSI flow test. Level 3 drink and food is best measured with both IDDSI flow test and fork drip test. Spoon tilt test and fork pressure test can also be used to confirm level 3 food. Level 4 drink and food is best mea-

Table 3 Summary of the sample's characteristics and their behavior in IDDSI testing methods for each of the level

Level	Description/ characteristics	IDDSI flow test	Fork drip test	Spoon tilt test	Fork pressure test
Level 0	Flows like water Fast flow Can drink through cup or straw	<1 mL remaining after 10 s	–	–	–
Level 1	Thicker than water Requires more effort to drink than thin liquids Flows through a straw	1–4 mL remaining after 10 s	–	–	–
Level 2	Flows off a spoon Pours quickly from a spoon, but slower than thin drinks Mild effort required to drink through a standard bore straw	4–8 mL remaining after 10 s	–	–	–
Level 3	Can be drunk from a cup Moderate effort required to drink through a wide bore straw Drips slowly in dollops through the prongs of a fork, thus cannot be eaten with a fork Can be eaten/ drunk with a spoon No oral processing or chewing required Smooth texture with no "bits" or lumps	>8 mL remaining after 10 s	Drips slowly in dollops through the prongs of a fork	Easily pours from spoon when tilted; does not stick to spoon	The prongs of a fork do not leave a clear pattern on the surface of the sample

(continued)

Table 3 (continued)

Level	Description/ characteristics	IDDSI flow test	Fork drip test	Spoon tilt test	Fork pressure test
Level 4	Cannot be drunk from a cup because it does not flow easily Cannot be sucked through a straw Usually eaten with a spoon or fork Does not require chewing No lumps and not sticky	–	Sample sits in a mound above the fork; a small amount may flow through and form a short tail below the fork prongs, but does not flow or drip	Cohesive enough to hold its shape on the spoon. Plops off if the spoon is turned sideways; gentle flick may be necessary to dislodge the sample, but the sample should slide off easily with very little food left on the spoon	The prongs of a fork can make a clear pattern on the surface of the sample and the food retains the indentation from the fork
Level 5	Can be eaten with a fork or spoon Can be scooped and shaped on a plate Soft and moist with no separate thin liquid Small lumps visible within food: Pediatric: equal to or less than 2 mm width and no longer than 8 mm in length Adult: equal to or less than 4 mm width and no longer than 15 mm in length Biting is not required, but minimal chewing is still required	–	Sample sits in a pile or can mound on the fork and does not easily flow or fall through the prongs of a fork	Cohesive enough to hold its shape on the spoon. A full spoonful slides off if the spoon is turned sideways or shaken lightly; the sample should slide off easily with very little food left on the spoon	Can be easily mashed with little pressure from a fork without the need for the thumb nail blanch to white

(continued)

Table 3 (continued)

Level	Description/ characteristics	IDDSI flow test	Fork drip test	Spoon tilt test	Fork pressure test
Level 6	Can be eaten with a fork, spoon, or chopsticks Can be mashed or broken down with pressure from fork, spoon, or chopsticks Soft and moist throughout without separate thin liquid Biting is not required, but chewing is required Bite-sized pieces: Pediatric: no larger than 8 mm cube Adult: no larger than 15 mm cube	–	–	–	When a sample is pressed with the tines of a fork to a pressure where the thumb nail blanches to white, the sample squashes, breaks apart, changes shape, and does not return to its original shape
Level 7	Normal, everyday foods Any method may be used to these foods	–	–	–	For easy to chew – same description as level 6

sured with both fork drip test and spoon tilt test. Level 5 food is measured with spoon tilt test and fork pressure test to measure the particle size, cohesiveness, firmness, adhesiveness, and food hardness. Finally, level 6 and level 7 (easy to chew) are measured with fork pressure test.

Oral processing research continues to develop further testing methods which compliment and improve on the IDDSI testing methods. A Ball-Back Extrusion (BBE) technique is found to be feasible for quantitative assessment of dysphagia fluids. A proposed guideline is presented to enhance thickness consistency for the safety of individuals of dysphagia. The BBE technique provides unique advantages for thickener manufacturers due to its easiness of operation and lower instrumental costs than a rheometer. On the other hand, proposed guidelines for texture-modified foods are also presented to enhance texture consistency. The guidelines show thresholds of cohesiveness and adhesiveness, as well as bands of acceptable firmness and hardness for each of the levels based on IDDSI Framework.

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