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Compositional, structural design and nutritional aspects of texture-modified foods for the elderly

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Abstract

Background

Texture-modified foods (TMF) are commonly used as a therapeutic strategy for people with chewing or swallowing difficulties such as the elderly, which is the fastest growing segment of the global population. These foods need to be soft, safe and easily swallowed as well as have nutritive properties and attractive sensory attributes in order to help overcome physiological dysfunctions and cover specific nutritional requirements.

Scope and Approach

This review provides an overview about common and novel ingredients and techniques used to obtain TMF with desired textural characteristics as well as methods or processes aimed to improve nutritional and sensory characteristics. Digestibility aspects of TMF are also presented, specially the influence of food matrix structure and material properties on digestion and bioaccessibility of nutrients.

Key Findings and Conclusions

The design of products with textural, nutritional and sensory characteristics suitable for the elderly should consider not only compositional and structural aspects during formulation but also the modification of food structure during oral processing and gastrointestinal digestion. Increasing the knowledge in these issues will assist the development of products with enhanced functionalities in order to meet the needs of specific populations such as the elderly.

Keywords: texture modification, food structure, digestibility, bioaccessibility, elderly population

1. Introduction

The increasing life expectancy of world population and decreased mortality have led to a growing rate of an ageing society in which elderly people represent an important segment of the global population. In 2020, the percentage of people over 65 years of age was 9.3 %, and projections estimate to reach approximately 16 % in 2050, which correspond to 1.5 billion older people or over the world. Asia, Europe and Northern America are the regions expecting major increases in the number of older people in the next 30 years (United Nations, 2020). In addition, the number of people older than 80 years is growing even faster and it is projected to nearly triple by 2050, reaching around 426 million people worldwide (United Nations, 2019).

Elderly people can experience difficulties associated with safety and efficiency in feeding, chewing or swallowing due to anatomical and physiological alterations developed during ageing. Among these dysfunctions, dysmasesis refers to the difficulty in mastication caused by the loss of teeth whereas dysphagia can be described as the difficulty in swallowing safely oral contents to the stomach. Moreover, a progressive loss is sensory perception and appetite, limited salivation (xerostomia), as well as a decline in skeletal muscle mass (sarcopenia), loss of bone mass and strength (osteoporosis), and gastrointestinal alterations are commonly suffered by older people. The consequences of these disorders can include reduced oral intake, malnutrition, anorexia, dehydration, aspiration, asphyxiation, as well as a negative impact on health and quality of life, dietary habits, and social participation (Cichero, 2015; Aguilera & Park, 2016; Lutz, Petzold, & Albala, 2019).

Considering these factors, food ideally suited for elderly people with chewing or swallowing difficulties needs to have soft and moist textures that are reduced with minimal chewing effort and easy to swallow. On the other hand, foods that tend to be dry, hard, fibrous, sticky and adhesive should be avoided due to difficulties with safe particle size reduction, bolus formation for swallowing, and risk for choking and residue (Cichero, 2016). Texture-modified foods (TMF) are used as a therapeutic strategy to attempt to achieve a safe and efficient food intake in older people; however, the importance of food oral processing does not only comprise a safe and efficient intake. TMF should also suit nutritional requirements in terms of digestion and absorption of nutrients as well as provide a pleasant sensory perception for acceptability and enjoyment for consumers (Lutz et al., 2019).

The design of healthy foods, which must be soft, safe and easy to swallow as well as have nutritive properties and attractive sensory attributes, is needed to help overcome physiological dysfunctions and specific nutritional requirements occurring during ageing. However, the ability of TMF to meet all these characteristics is often a challenge. This review aims to provide an overview about common and novel ingredients and techniques used to obtain TMF with desired textural, nutritional and sensory characteristics. Moreover, some digestibility aspects of TMF, particularly the influence of food structure and material properties on nutrient digestion, as well as current gaps and future directions in the design and formulation of TMF are addressed.

2. TMF types

TMF refer to food with soft textures and/or reduced particle size, which can be easily mixed and disintegrated in the mouth by a tongue-palate compression without mastication (Ishihara et al., 2013). In case of liquids, their viscosity can be modified by adding a thickening agent in order to flow more slowly and reduce the risk of fluid penetration into the airway (Newman, Vilardell, Clavé, & Speyer, 2016). Until recently, there has been international variation in terms of nomenclature for TMF, mostly used in dysphagia management, so that several countries such as USA, Japan, Australia, and United Kingdom had their own national descriptors and classifications (Cichero et al., 2013). Among them, the National Dysphagia Diet from the American Dietetic Association is a widely used guide that sets ranges for foods according to four viscosity categories, including: thin (1-50 mPa·s), nectar-thick (50-350 mPa·s), honey-thick (350-1750 mPa·s), and pudding-thick (>1750 mPa·s), when measured at the shear rate of 50 s^{-1} at 25 ºC (Force, 2002). In 2013, the International Dysphagia Diet Standardisation Initiative (IDDSI) was founded with the aim to develop international and standardised terminology and definitions to describe food textures and drink thickness for people suffering chewing and swallowing difficulties. Main reasons to develop a standardised framework were to promote patient safety, interprofessional communication, and facilitate evolution of the field to get better treatment outcomes (Cichero et al., 2017). The IDDSI framework comprises a continuum of 8 levels (0-7) with foods and liquids displayed on a single scale using a twin-pyramid design (Figure 1). Classification is based on their textural and rheological properties from foods that are modified to be soft by processing, minced, pureed or liquidised, to liquids that are thickened at different levels. However, certain foods shared texture properties with thickened liquids creating an overlap zone (levels 3 and 4) in the middle of the framework (Cichero et al., 2017; IDDSI, 2019). Hardness, cohesiveness, adhesiveness, and particle size are main parameters evaluated in the classification of TMF, whereas drinks would be characterised based on the rate of flow (Cichero et al., 2017). Nevertheless, the suitability of TMF is not only related to an adequate food texture but they should also offer nutritional value and satisfactory palatability and acceptability for consumers.

3. Design of TMF

3.1. Macronutrients as structuring ingredients of TMF

Proteins, lipids, and carbohydrates provide the energy and nutrients needed to maintain body functions but are also basic ingredients in the design of TMF. These macronutrients are assembled into hierarchical structures that influence sensory and textural properties as well as the bioavailability of some nutrients during digestion (Aguilera, 2016). Figure 2 shows typical structuring molecules used for the design of TMF. Proteins and carbohydrates are the most effective ingredients in structuring foods and drinks. Nevertheless, combinations of macronutrients with other food ingredients, having determined microstructures provided by nature or modified by processing conditions, are mainly used as building-blocks to obtain TMF.

Proteins are major constituents of foods and participate in the formation of food structures that can act as regulators in nutrient release or texture modifiers. In this regard, proteins can provide different polymers with structural and functional properties such as thickening, gelling, emulsification and foaming, resulting from applied temperature treatments, changes in pH or ionic strength, high pressure processing, or enzymatic hydrolysis, among others (Ritzoulis & Karayannakidis, 2015). Gelation is one of the most important properties of food proteins. This mechanism involves the thermal denaturation or conformational changes of globular molecules, which may increase viscosity of solutions, followed by a gradual association or aggregation of denatured proteins into a network. The conditions of gelation and type of proteins affect the aggregation process, yielding different structures (microparticles, fibrils, flexible strands, fractal clusters, gels or precipitates) with diverse functionalities in food systems (Brodkorb, Croguennec, Bouhallab, & Kehoe, 2016). However, some protein solutions denature when heated but conditions of the medium lead to a limited aggregation and formation of soluble aggregates instead of gels. In these cases, gelation can be induced by pH changes or addition of salts in a process denominated as cold gelation, which can be used for preparation of products with desirable texture or in encapsulation of sensitive ingredients (Cheng et al., 2017; Liu et al., 2020). Proteins can be also involved in the formation and stabilisation of emulsions and foams due to their amphiphilic nature. These functions are determined by the structure, properties, and composition of proteins in the adsorbed layers at air-water and oil-water interfaces (Yan et al., 2020). Aerated food systems may facilitate mastication and digestibility, enhance flavour and mouthfeel sensation, and weaken gel structure (Zúñiga, Kulozik, & Aguilera, 2011), which offer a great potential for the development of TMF. The most widely used texture-modifying proteins in food applications are those derived from milk and eggs, which are commonly used as emulsifiers, as well as the animal-derived gelatin that is mainly employed as colloid stabiliser and gelling agent.

Carbohydrates are the major sources of energy in human diets and have a wide variety of functions in foods. They provide structural, textural, and sensory properties, impact on the release of nutrients during digestion and absorption, as well as may have effect on satiety. Polysaccharides are mainly used as thickening and gelling agents, but they can also act as emulsifiers, stabilisers of emulsions, foams and dispersions, or delivery systems. All these properties are determined by the type of hydrocolloid used and its characteristics (solubility, hydrodynamic volume, associative interactions), concentration, food system, and conditions (pH, salts, temperature) (Nakauma et al., 2008; Saha & Bhattacharya, 2010). Typically, starch, xanthan gum and cellulose derivatives are used to increase viscosity of solutions; alginate, pectin, agar, gellan gum, or carrageenan to form gels; and arabic gum and modified starches as emulsifying agents. Nevertheless, they can offer high number of functions to variety of foods. For instance, blends of starch/non-starch hydrocolloids can be used as texture modifiers (emulsifier, stabiliser, gelling, and thickening agent), fat replacers, as well as for high fibre nutritional claim, stability to processing conditions (high temperature, shear, low pH), or encapsulation of flavours (Mahmood et al., 2017). Furthermore, polysaccharides and proteins can be mixed and form complexes, joined by covalent or non-covalent interactions, with enhanced mechanical properties and stability. Protein-polysaccharides self-assembled structures can be used in foods as emulsifiers, stabilisers, texture modifiers or potential nutrient delivery systems, although this complex behaviour would be determined by several factors such as concentration, ionic strength, pH, heat, and mechanical treatments (Gentile, 2020).

Lipids have several structural and textural properties in food systems. Triacylglycerols are commonly present as crystals that are grouped offering a fat network that determine texture and sensory attributes of foods (Narine & Marangoni, 2002). Monoglycerides, diglycerides and phospholipids can spontaneously self-assemble into micelles and liposomes that may act as vehicles of compounds such as vitamins, antioxidants, and flavours. Moreover, lipid molecules are usually used as emulsifiers due to their amphiphilic character. Oleogels and different types of emulsions, including nanoemulsions, Pickering emulsions, multilayer emulsions, high internal phase emulsions, and multiple emulsions, can improve or extend food functionalities,, enhance oral bioavailability, reduce fat and salt contents, or encapsulate micronutrients and bioactives. These functions are determined by the physical properties of the fat, droplet size, interfacial properties, and stability of emulsions. (Farjami, & Madadlou, 2019; Yan et al., 2020; Gao et al., 2021).

3.2. Processing techniques to obtain TMF

Different techniques can be used in order to obtain TMF. They can be divided in those applied to produce from regular to minced foods, corresponding to transitional foods (levels 5 to 7) of the IDDSI framework, and those for drinks and semi-solid foods (levels 0 to 4), although some technologies can be applied indistinctly.

3.2.1 Processes for obtaining regular, soft and minced foods

The simplest processing techniques would involve pureed, minced or softened of foods for facilitating oral processing; however, the lack sensory or taste appeal of these products can result in refusal and reduced intake (Cichero, 2015). For that, treatments that soften textures but maintain appearance, colour and flavour of foods and meals are preferred. Easy-to-do culinary processes such as blade tenderisation, marinade and cooking may improve meat tenderness and juiciness, and thus, facilitate the formation of food bolus, texture perception, and oral comfort while eating meat (Vandenberghe-Descamps et al., 2018). Impregnation of foods with enzymes is also used for texture softening, particularly for tenderisation of meats. Fruit-derived proteolytic enzymes such as bromelain and papain have shown effects on integrity and fibre structure of meat by producing degradation of myofibrillar proteins and collagen, which would reduce mastication effort (Eom, Lee, Chun, Kim, & Park, 2015; Botinestean et al., 2018). Enzymatic treatments can be also used in combination with freeze-thawing for obtaining TMF. Besides texture-softening effects of freeze-thawing processes due to destruction of cellular tissues, a slow freeze-thaw treatment in vacuum would facilitate the infiltration of enzyme solutions, which soften the whole sample more uniformly. This method has been commonly used in vegetables such as carrots and lotus roots (Eom et al., 2018; Park & Lee, 2020), which might retain appearance, nutrients and flavours because softening is produced by enzymatic reaction and not by heating (Nakatsu, Shibata, & Sakamoto, 2010). Other technologies using high-pressure, pulsed electric fields, plasma, ultrasounds, and irradiation have been applied for texture modification of meat, fish, cereals, fruits, vegetables or seaweeds, having minimal effects on colour, taste, and nutritional characteristics in comparison to thermal processes (Sungsinchai, Niamnuy, Wattanapan, Charoenchaitrakool, & Devahastin, 2019). Some examples of applications of these techniques, used alone or in combination, to soften foods as well as the effects on textural, physicochemical, and functional characteristics of the products are shown in Table 1.

3D printing is an emerging technology that can offer personalised and specially textured food to meet the needs and demands of specifics populations such as the elderly. This technique is characterised by building physical structures through the deposition of materials layer by layer, providing food with desired texture and nutritional attributes, taste, and visually appealing (Liu, Zhang, Bhandari, & Wang, 2017). 3D printing has been applied to simulate several foods, although few studies to date have aimed to develop special foods for people which chewing and swallowing difficulties. Some recent works combined the addition of hydrocolloids and 3D printing to obtain cooked pork meat (Dick, Bhandari, Dong, & Prakash, 2020) and vegetables (Pant et al., 2021), which may be categorised as transitional foods in the IDDSI framework.

3.2.2 Processes for drinks and semi-solid foods

In liquid foods, changes in their texture commonly implies the use of thickening agents such as starches and gums. These hydrocolloids can give desired textural properties and flow characteristics to fluids, including increased viscosity, water retention, firmness, and smoothness. The use of different types and concentrations of hydrocolloids will lead to different rheological profiles depending on molecular weight and conformation (Ross, Tyler, Borgognone, & Eriksen, 2019). A wide range of hydrocolloids including modified starch, xanthan gum, carrageenan, carboxymethyl cellulose, pectin, or gellan gum, among others, can be used to thicken products such as beverages (Moret-Tatay, Rodríguez-García, Martí-Bonmatí, Hernando, & Hernández, 2015), carrot purees (Sharma, Kristo, Corredig, & Duizer, 2017) and pea creams (Talens, Castells, Verdú, Barat, & Grau, 2021).

Techniques that produce small particles from natural polymers can also have wide applications in the design of TMF, as they can improve oral processing and provide desirable sensory characteristics and nutritional benefits. Thermal processing strongly influences food texture, resulting in physicochemical changes in cell walls, for example, solubilisation of pectin, gelatinisation of starch, and denaturation and aggregation of proteins. As mentioned previously, aggregation of denatured proteins can lead to the formation of different structures such as microparticles, fibrils, flexible strands, fractal clusters, or gels, with varied functions. Temperature, processing time, pressure and salt concentration can be modified to tune properties of foods, but also thermal processing can be used in combination with other techniques such as high pressure, impregnation of enzymes, or infusion of firming agents (calcium ions, phenolics, or hydrocolloids) to have synergistic effects (Kadam, Tiwari, & O'Donnell, 2015). For instance, the combination of heating and shearing can induce microparticulation of proteins or mixed biopolymer solutions. Microparticles are designed to obtain products with wanted particle size distribution and viscosity (Chung, Degner, & McClements, 2014), to induce gelling (Torres, Mutaf, Larsen, & Ipsen, 2016), and especially as fat replacers that would restore sensory and rheological properties of the product (Liu, Wang, Liu, Wu, & Zhang, 2018; Kew, Holmes, Stieger, & Sarkar, 2020). Gelation also plays a major role in the production of TMF, as the semi-solid structure of gels formed through the use of structuring hydrocolloids (proteins, polysaccharides, or mixtures) provides small particles with a variety of sizes, morphologies, and food textures (Stokes, 2012). So, gels can give soft and stable textures, be used as structuring agents and to strengthen dispersed phases, as well as have functions in fat replacement, satiety control, encapsulation and targeted delivery (Shewan & Stokes, 2013; Kew et al., 2020). Hydrocolloid gel particles can be formed by gelation of preformed droplets using techniques such as emulsion and extrusion, or by gelling and subsequent breaking up into smaller pieces by coacervation or shear processes. Moreover, spray drying could be used to produce intermediate particles before hydration in an appropriate liquid medium to form gel particles. This process has been proved to be very effective in the encapsulation of compounds (Drosou, Krokida, & Biliaderis, 2017). Electrospinning and electrospraying are simple and flexible methods for production of small fibres or particles, respectively, with many structural and functional advantages. They may be used in the design of TMF for the development of tailored structures, improvement of thermal or physicochemical stability, encapsulation of bioactive compounds for improving stability, bioavailability and controlled release, or mask unwanted odor and tastes of compounds (Drosou et al., 2017). Some examples of all these technologies and their applications in foods are shown in Table 2.

4. Improvement of nutritional quality and sensory perception of TMF

Deficiencies in energy and nutrients are common in elderly people due to a decrease in food intake resulting from physiological changes and reduced appetite during ageing. Furthermore, the need of some nutrients, such as proteins, vitamin C, or calcium, increases in elderly adults due to their important roles in functions like the maintenance of bone and muscle mass. A declining anabolic response to lower doses of protein intake and the need to offset the catabolic conditions associated with diseases commonly occurring in older adults also require higher protein intake (Lutz et al., 2019). The consumption of TMF may increase the risk of malnutrition. It has been reported that individuals fed with pureed diets can suffer malnutrition due to nutrient dilution during the texture modification process (Hotaling, 1992). Moreover, individuals receiving TMF could have a lower intake of energy and protein than those with a normal diet (Wright, Cotter, Hickson, & Frost, 2005). Several strategies including increased either meal frequency or energy density, use of oral nutritional supplements, or enrichment/fortification of foods can be used to accommodate nutritional needs and mitigate against malnutrition, sarcopenia or other diseases of older population (Bauer et al., 2015; Hébuterne et al., 2020). Indeed, enriching TMF may be the most suitable option for people with chewing and/or swallowing problems. Pritchard, Davidson, Jones, and Bannerman (2014) reported that texture modification reduced both food and energy intake, but energy enrichment of meals would increase short term energy intake without impacting on appetite responses or food intake. Thus, enriching TMF could have potential applications for enhancing energy content without increasing meal quantity in individuals with reduced appetites.. García et al. (2019) designed functional food products enriched with bioactive extracts from sea cucumbers to meet the nutritional needs of the elderly. The hydrolysates provided minerals, essential amino acids, antioxidant and antihypertensive compounds, and showed adequate sensory properties in terms of aspect, texture, and taste after incorporation into foods. Food properties such as taste or smell notably influence food intake, so they can be improved to make foods more palatable and stimulate appetite of consumers. Moreover, the poor appearance of meals or lack of menu variety also contribute to decrease food intake and thus nutrient deficiencies, particularly among individuals receiving TMF. A recent study formulated different protein-based beverages with viscous liquid behaviour for dysphagia diets of the elderly. Beverages containing pea and milk proteins presented faster proteolysis and good protein quality, and when flavoured with meat broth essence were more comfortable and easier to drink than beverages with mushroom flavour (Štreimikytė et al., 2020). Ott et al. (2019) proposed and innovative nutrition concept including enrichment and reshaping of food in addition to texture modification, resulting in increased body weight, energy and protein intakes of individuals with chewing and/or swallowing problems. Van Wymelbeke et al.

(2020) also reported that improving the sensory quality and/or providing variety of the meals increased meal enjoyment and food intake in older people.

In addition, the use of sensory stimulating products could have potential applications as vehicles for the delivery of nutrients and energy to the elderly. Spence, Navarra, and Youssef (2019) proposed the development of ice creams nutritionally enhanced by addition of fruit or vegetable purees while maintaining an appropriate texture and mouthfeel. Encapsulation of micronutrients or bioactive compounds could be also used for nutritional improvement of TMF. Carriers can increase the stability and solubility of active components such as vitamins, minerals, or antioxidants, and provide controlled delivery as well as they can be developed from a variety of sizes, materials and using different techniques (Garg, Sharma, Rath, & Goyal, 2017). For example, a recent work designed a double emulsion loaded of multiple bioactives (several vitamins and antioxidant anthocyanins) for fortification of diets for elderly people, showing a good stability and effective protection of the encapsulated compounds and their simultaneous deliver during digestion (Keršienė, Jasutienė, Eisinaitė, Venskutonis, & Leskauskaitė, 2020). In fact, the use of nanoscale delivery systems is undergoing a strong growth over the last decades, with a wide range of applications in food and beverages (Luo & Hu, 2017; Muhamad, Zaidel, Hashim, Mohammad, & Bakar, 2020).

Despite the advances in experimental research, the availability of TMF in the market is still scarce. Food and pharmaceutical companies have mostly commercialised thickeners to be added to liquids and foods for obtaining suitable rheological characteristics. Examples are starch- or gum-based thickeners such as Resource® ThickenUp® (Nestlé Health Science, Vevey, Switzerland), and Nutilis® (Nutricia, Milupa GmbH., Fulda, Germany). Some dysphagia-oriented products and TMF to meet specific nutritional needs are also available, for example, Boost® Nutritional Pudding, Resource® Instant Protein, and Boost® Very High Calorie Nutritional Drink developed from Nestlé Health Science. Nevertheless, this market segment should be expanded to increase the variety and supply of commercial TMF.

5. Digestibility of TMF

5.1 Digestion models

Digestion of food is a complex process that comprises the oral, gastric and intestinal phases, in which numerous mechanical, chemical and enzymatic processes take place. The oral processing is a dynamic process that includes the decomposition the food into smaller particles by mastication and formation of a cohesive and lubricated bolus by saliva incorporation, allowing a safe swallowing. It is a crucial phase specially for solid and semi-solid foods as it influences the following digestion steps. Food fragmentation facilitates transportation of the bolus to the stomach as well as increases surface area of food, maximising both the efficiency of further digestion and the release of aroma and taste compounds (Chen, 2015). Saliva is involved in several mechanisms including surface coating and particle clustering, destabilisation of colloidal systems, enzymatic breakdown, formation of aggregates and precipitates, and binding of aroma compounds (Mosca & Chen, 2017). The main salivary enzyme is α-amylase that initiate the hydrolysis of starch and would affect oral sensations; although lipase is also believed to be another salivary enzyme that may initiate lipid digestion in the mouth. Salivary proteins, particularly mucins, affect adsorption and/or lubrication properties of saliva and colloidal destabilisation of food structures such as emulsions (Mosca & Chen, 2017; Çelebioğlu, Lee, & Chronakis, 2020). Following oral processing, gastric digestion involves the disintegration of food structure in the stomach due to peristaltic movements and interaction with the gastric juice. Stomach secretions contain pepsin and gastric lipase enzymes, which participate in proteolytic and lipolytic reactions, respectively, as well as hydrochloric acid, mucins, and salts. The hydrolysis of food particles by the acidic environment and gastric enzymes is based on the diffusion of the gastric juice into the bolus, which depends on food structure and material properties (Singh, Ye, & Ferrua, 2015). Lastly, the environment of the small intestine has a neutral-alkaline pH and contains different enzymes, mainly trypsin, chymotrypsin, pancreatic lipase and pancreatic amylase, as well as coenzymes, bile salts and inorganic salts. The hydrolysis of macronutrients, initiated in the mouth for carbohydrates and in the stomach for proteins and lipids, is completed in this phase, whereas indigestible food materials can be fermented by bacterial microflora in the large intestine. A scheme of the main mechanical and biochemical processes occurring during gastrointestinal digestion is shown in Figure 3.

In vitro digestion models are simple and useful tools to evaluate the structural changes, digestibility and release of food compounds from the food matrix under simulated gastrointestinal conditions. These methods can show good correlations with *in vivo* models, which provide the most accurate results but are costly, time consuming and ethically disputable. Several types of *in vitro* gastrointestinal digestion models, including static and dynamic methods, are commonly used in foods, but differences in the experimental parameters such as the number and type of phases or the composition of digestive fluids difficult the comparison of results between studies. In this regard, the INFOGEST digestion protocol was proposed as a standardised and practical *in vitro* static method that sets the parameters (pH and digestion times, composition of simulated digestive fluids, activities of digestive enzymes, bile salt concentration) for the oral, gastric and intestinal digestion phases based on physiological data (Minekus et al., 2014, Brodkorb et al., 2019). Cell cultures can also be used as part of *in vitro* digestion models to improve the knowledge about intestinal absorption and bioavailability of nutrients or bioactive compounds. Furthermore, the use of *in silico* computational models is currently increasing as a promising tool to predict the digestion and absorption of foods compounds in the gastrointestinal tract. These models employ parameters obtained empirically and could help to investigate phenomena that are difficult to study *in vivo* and *in vitro* such as the kinetics of enzymatic hydrolysis or gastric emptying. The integration of the knowledge acquired by the different digestion models can serve to design food that is better adapted to meet the nutritional needs of specific populations such as the elderly (Dupont, Le Feunteun, Marze, & Souchon, 2018; Le Feunteun, Mackie, & Dupont, 2020).

5.2 Influence of food structure on digestion

Food structure is of great importance for food intake, digestion and absorption of nutrients, as well as to provide pleasant sensory attributes to consumers. As food passes through the gastrointestinal tract, its structure is broken down by different forces and mixing, temperatures, pH, and enzymes, which influence the rate and extent of digestion and thus the release and uptake of macronutrients and micronutrients (Norton, Espinosa, Watson, Spyropoulos, & Norton, 2015; Singh et al.,2015; Dupont et al., 2018).

5.2.1 Oral processing

In the oral phase, food-saliva interactions lead to the formation of new compounds, complexes and microstructures. Even soft foods that are disintegrated with minimal or no chewing effort and remain a short time in the mouth before swallowing, undergo important physical and biochemical changes during oral processing. For example, structures of food emulsions are modified in the mouth by heating or cooling to the body temperature, tongue-palate compression, and mixed with saliva, which can lead to destabilisation mechanisms such as droplet flocculation or coalescence that may influence texture and taste sensations (Mao & Miao, 2015). Mucin proteins play a key role in droplet flocculation of protein-stabilised emulsions, whose behaviour under oral conditions depends mostly on the charge on the surface of protein emulsion droplets (Singh & Sarkar, 2011; Çelebioğlu et al., 2020). The composition, structure and mechanical behaviour of foods also determine fragmentation mechanisms and bolus formation. Assad-Bustillos et al. (2019a) reported a similar chewing behaviour and in-mouth comfort but different bolus properties such as hydration or viscosity and oral mechanisms for two soft cereal products with different composition and structure. Indeed, soft aerated cereal foods stimulated the salivary flow rate, which would impact food bolus properties and perception of oral comfort in the elderly, independently of dental status. However, a further study considering particle size distribution of the bolus showed different fragmentation mechanisms (fragmentation/aggregation patterns) for the two soft cereal products varying in initial structure and mechanical properties during oral processing as well as evidenced the importance of the dental status in the fragmentation of both foods (Assad-Bustillos et al., 2019b). Modification of the physical properties of the bolus during eating also impacts on aroma and taste perception. Several studies in food gels showed that salt release or sweetness intensity depend on the total surface area of fragments formed upon chewing, which were affected by the structure and composition of the gel matrix (De Loubens et al. 2011; Mosca et al., 2015). Stokes, Boehm, and Baier, (2013) depicted the transition in film thickness of fluid/soft foods between oral surfaces as they are consumed, underlying that textural sensations would be dominated initially by bulk phase properties of food (rheology) and then by surface properties of food and/or the food-saliva mixture (oral tribology).

5.2.2 Gastric digestion

The properties of the food bolus formed at the oral stage would determine its disintegration in the stomach. Guo et al. (2015) reported that soft protein emulsion gels presented higher gastric disintegration rate and protein hydrolysis rate than hard emulsion gels which would result from both abrasion and fragmentation effects. In fact, the gastric emptying of the gels would be influenced by the combined effects of the original particle size of the bolus and the disintegration kinetics in the stomach. When protein solutions were compared with gelled systems having equal protein concentration, the material properties of gels provided greater resistance to hydrolysis due to the limited diffusion of enzymes into the gel structure, and consequently the hydrolysis progressed largely at the surface area of the gel particles (Luo, Boom, & Janssen, 2015; Luo, Borst, Westphal, Boom, & Janssen, 2017). Moreover, different structural pathways for gelation could lead to variances in kinetics of protein digestion. For instance, the microstructure of gels obtained by different heat-induced temperatures and protein sources would impact on simulated gastric digestion of protein gels. Lower gelation temperatures produced more compact structures that might result in slower gel disintegration and therefore slower protein digestion (Opazo-Navarrete, Altenburg, Boom, & Janssen, 2018). Nau et al. (2019) reported that egg white gels with the same macronutrient composition but differed in their pH, ionic strength, structure and texture led to changes in pH, structure and rheology of the gastric chyme. Smooth-rigid gels resulted in a slow gastric emptying, the largest particles and the most viscoelastic chyme, evidencing the effect of protein food structure on gastric chyme properties, and thus on the digestion process. Moreover, structuring emulsions with mixed protein-particle layers can tune and control interfacial barrier properties and delay gastric digestion (Sarkar, Zhang, Murray, Russell, & Boxal, 2017). The content of dietary fibres such as pectin and variable gastric pH can also interactively modify the microstructure of emulsions and therefore impact lipid digestibility and bioaccessibility (Lin & Wright, 2018). The extent of fat emulsification affects lipid digestion, so that lower oil droplet size provides larger surface area that facilitates the accessibility and action of lipases.

5.2.3 Intestinal digestion

The transit from stomach to intestine implies structural changes in the interface of food emulsions and droplet aggregation due to the increase in pH and ionic strength (Mao & Miao, 2015). Destabilisation of emulsions is also attributed to the extent of both the proteolysis of interfacial proteins, mainly by trypsin and chymotrypsin enzymes, and the lipolysis of the lipid hydrophobic core (Sarkar, Horne, & Singh, 2010). In fact, the rate and extend of lipolysis depend on the intestinal pH, fat and bile salts concentration due to the modulation of the fat globules size in the digestive media (Calvo-Lerma, Fornés-Ferrer, Heredia, & Andrés, 2019). Bile salts are surfactant compounds that play a key role in lipid digestion, since they can be absorbed onto the surface of oil droplets and displace proteins, emulsifiers and free fatty acids. This process facilitates the access and action of lipases and thus enhances the rate of lipid digestion in most systems (Hur, Lim, Decker, & McClements, 2011; Singh & Sarkar, 2011). Protein gel strength and microstructure would also impact lipid digestion. Softer gels presented a fast breakdown of protein gel network and then high lipolysis rate, whereas complex gel microstructures containing salts delayed lipid digestion (Guo, Bellissimo, & Rousseau, 2017). On the other hand, cell walls and tissue structures of plant-based food play a key role for digestion of starch, lipids, proteins and functional phytochemicals contained in their structures (Ogawa et al., 2018). For instance, the microstructure of legume cotyledon cells, consisting of starch granules entrapped on protein matrix and intact cell walls, restricts starch gelatinisation and hinders accessibility of amylolytic enzymes to intracellular starch, thus limiting the rate and extent of starch digestion. Indeed, cell walls remained predominantly intact throughout cooking and enzymatic digestion, so α-amylase may diffuse through the cell wall pores for hydrolysing starch and amylolytic products would be released for their absorption (Do, Singh, Oey, & Singh, 2019). Tamura, Singh, Kaur, and Ogawa (2016) evaluated the influence of structural characteristics of both intact and homogenised cooked rice grains on starch digestibility. The study revealed the degradation of starch granules within the first 5 min of small intestinal digestion and larger surface area in homogenised slurry sample, causing increased starch hydrolysis rate compared to intact cooked rice. In addition, endogenous proteins and lipids would impact starch digestion. The attachment of these compounds to the surfaces of starch granules and restriction of starch swelling as well as the formation of amylose-lipid complex would reduce the access of digestive enzymes and slow down starch hydrolysis in rice flour (Ye et al., 2018)

Recently, Golding (2019) provided an extensive context regarding the effects of food structure on digestion of proteins, lipids and carbohydrates, evidencing the impact of the structural assembly and interactions within a food system on the way the nutrients are digested. The term “food matrix” is increasingly used to refer to that part of the food microstructure that contains and/or interacts (physically or chemically) with specific food compounds, providing them behaviours and functionalities different than those when they are in isolated form. Food matrix influences structure and therefore the appearance, texture, oral processing, and flavour release, as well as the processes of digestion and absorption of food compounds in the gastrointestinal tract (Aguilera, 2019). In this context, Mat, Feunteun, Michon, and Souchon (2016) evaluated the impact of matrix structure on digestion of two emulsion-type foods with the same composition but different structures. The study reported slower rates of both lipolysis and proteolysis for solid emulsions (protein gels entrapping large fat droplets) than liquid emulsions (small oil droplets dispersed in a liquid continuous phase containing native proteins). The use of an *in vitro* digestion method based on the INFOGEST protocol combined with a pH-stat method allowed the monitorisation of the intestinal phase, suggesting that the physical state of the continuous phase as well as conformation of proteins would be the main factors influencing enzyme accessibility and thus digestion kinetics. Hiolle et al. (2020) also studied the influence of the food structure (from liquid to hard solid) on *in vitro* digestion of four micronutrient-enriched foods with identical compositions. Matrix disintegration, hydrolysis of macronutrients and release of micronutrients were evaluated, reporting different digestion pathways depending on the food matrix. This study highlights the global and complex process for which the food structure influences matrix disintegration and nutrient release.

5.3 Digestibility and bioaccessibility of nutrients

Processing and formulation of foods affect or partially remove the structural organisation in which the nutrients are embedded, modifying their liberation from the food matrix and thus influencing the processes of digestion and absorption. For example, thermal or mechanical processes on fruit- and vegetable-based products commonly disintegrate the structure and enhance the release of carotenoids by facilitating mechanical and enzymatic actions during digestion. However, high pressure or ultrasounds techniques can result in the formation of a strong fibre network that decreases the bioaccessibility of carotenoids (Lemmens et al., 2014). Many other studies using *in vitro* digestion methods have been conducted in order to evaluate the digestibility and bioaccessibility of nutrients, and some recent examples on texture modified or fortified food samples are shown in Table 3.

The digestibility of nutrients is also affected by the gastrointestinal conditions of consumers. For instance, the bioaccessibility of nutrients can be reduced in elderly population with oral deficiencies, in which case the bolus can be harder, more cohesive and elastic, and with greater proportion of large particles. The poorly formed food bolus would delay the digestion and assimilation of nutrients due to the difficult digestion of large particles and the limited contact surface between the food and the salivary enzymes and gastric fluids (Peyron, Santé-Lhoutellier, François, & Hennequin, 2018). Other gastrointestinal alterations in the elderly such as variation or reduction of enzyme activity, bile secretions, electrolyte composition or transit time, would also affect the digestibility of nutrients. In this regard, *in vitro* digestion studies revealed the impact of changes in intestinal conditions such as the pH or bile salts concentration on food matrix degradation (Asensio-Grau, Calvo-Lerma, Heredia, & Andrés, A., 2019) and fat globule size in the digestive media (Calvo-Lerma et al., 2019), which determined the extent of lipolysis. Hernández-Olivas, Muñoz-Pina, Andrés, and Heredia (2020) evaluated the role of elderly gastrointestinal alterations on the *in vitro* digestion of four cooked fishes, showing that the proteolysis and bioaccessibility of vitamins and calcium decreased, at different extent depending on the fish type, but the bioabsorbable lipids were not influenced. This study highlighted the impact of both individual gastrointestinal conditions and food matrix properties on the digestibility of macronutrients and bioaccessibility of micronutrients.

6. Gaps and future perspectives

TMF can be developed with different ingredients and processing conditions in order to allow a safe swallowing and enhance nutrient intake while giving pleasurable meal experiences in terms of taste, aroma, and visual aspect of foods. Obviously, the oral stage should be carefully considered when designing specific foods to meet the specific needs of the elderly population. However, the relationship between structural and mechanical properties of foods is still not fully understood, particularly for TMF, and further research is needed to link these properties to oral sensations (Munialo, Kontogiorgos, Euston, & Nyambayo, 2020). In this regard, tribology is an emerging field that considers lubrication by saliva and friction between surfaces that interact in relative motion (Stokes et al.,2013), deepening the understanding of food oral processing in terms of textural and sensory mouthfeel properties (Munialo et al., 2020; Shewan, Pradal, & Stokes, 2020). The knowledge of the eating capability of individuals regarding eating difficulty perception and oral processing behaviour is also needed for the design of personalised TMF. In fact, not only endogenous factors (oral capabilities) and exogenous factors (food texture) but also the heterogeneity of the food matrix affect oral processing behaviour. Thus, the optimisation of foods for people with limited eating capability should focus on both texture and structural heterogeneity (Sarkar, 2019).

The use of 3D printing is among promising strategies to develop TMF that enhance nutrient intake and eating pleasure. However, several challenges such as efficiency, printing precision and accuracy as well as production of foods with varying quality and nutritional attributes still need to be overcome. Moreover, the combination of 3D printing with non-thermal technologies that maintain heat-labile compounds and provide desirable rheological properties, or with materials that provide soft textures and desirable sensory and nutritional properties, could also be interesting to produce TMF based on individual physical conditions as well as energy and nutrition requirements (Liu et al., 2017; Sungsinchai et al., 2019). On the other hand, the use of nanotechnology can offer numerous applications in the design of TMF by providing nanostructured or nanotextured food constituents, new tastes, delivery systems for nutrients and food supplements, and advanced absorption of nutrients. Nevertheless, further studies are needed for the design of nanoparticles that maximise the bioavailability of active ingredients without comprising the food texture, taste, and appearance, as well as for elucidating their possible ecotoxicological effects (Kalita, & Baruah, 2019). Increasing the knowledge about food materials and mechanisms to produce TMF with desired textural and sensory characteristics as well as regarding the role of food structure in digestion and release of nutrients will help develop foods with enhanced functionalities in order to meet the needs of specific populations.

Author contributions

Conceptualization, M.G. and P.T.; Writing – Original Draft Preparation, M.G.; Writing – Review & Editing, M.G., J.M.B., R.G., and P.T.; Visualization, M.G.; Project Administration, R.G and P.T.; Funding Acquisition, J.M.B., R.G., and P.T.

Declaration of competing interest

The authors declare no conflict of interest.

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References

Aguilera, J. M. (2006). Seligman lecture 2005 food product engineering: building the right structures. *Journal of the Science of Food and Agriculture, 86*(8), 1147-1155. https://doi.org/10.1002/jsfa.2468

Aguilera, J. M. (2019). The food matrix: implications in processing, nutrition and health. *Critical Reviews in Food Science and Nutrition, 59*(22), 3612-3629. https://doi.org/10.1080/10408398.2018.1502743

Aguilera, J. M., & Park, D. J. (2016). Texture-modified foods for the elderly: Status, technology and opportunities. *Trends in Food Science & Technology, 57*, 156-164. https://doi.org/10.1016/j.tifs.2016.10.001

Alvarez-Ramirez, J., Vernon-Carter, E. J., Carrera-Tarela, Y., Garcia, A., & Roldan-Cruz, C. (2020). Effects of candelilla wax/canola oil oleogel on the rheology, texture, thermal properties and in vitro starch digestibility of wheat sponge cake bread. *LWT-Food Science and Technology*, 109701. https://doi.org/10.1016/j.lwt.2020.109701

Asensio-Grau, A., Calvo-Lerma, J., Heredia, A., & Andrés, A. (2019). Fat digestibility in meat products: influence of food structure and gastrointestinal conditions. *International Journal of Food Sciences and Nutrition, 70*(5), 530-539. https://doi.org/10.1080/09637486.2018.1542665

Assad-Bustillos, M., Tournier, C., Septier, C., Della Valle, G., & Feron, G. (2019a). Relationships of oral comfort perception and bolus properties in the elderly with salivary flow rate and oral health status for two soft cereal foods. *Food Research International, 118*, 13-21. https://doi.org/10.1016/j.foodres.2017.11.057

Assad-Bustillos, M., Tournier, C., Feron, G., Guessasma, S., Reguerre, A. L., & Della Valle, G. (2019b). Fragmentation of two soft cereal products during oral processing in the elderly: Impact of product properties and oral health status. *Food Hydrocolloids, 91*, 153-165. https://doi.org/10.1016/j.foodhyd.2019.01.009

Assad-Bustillos, M., Palier, J., Rabesona, H., Choiset, Y., Della Valle, G., & Feron, G. (2020). Role of the bolus degree of structure on the protein digestibility during in vitro digestion of a pea protein ‐ fortified sponge cake chewed by elderly. *Journal of Texture Studies, 51*(1), 134-143. https://doi.org/10.1111/jtxs.12486

Barekat, S., & Soltanizadeh, N. (2017). Improvement of meat tenderness by simultaneous application of high-intensity ultrasonic radiation and papain treatment. *Innovative Food Science & Emerging Technologies, 39*, 223-229. https://doi.org/10.1016/j.ifset.2016.12.009

Bashir, K., & Aggarwal, M. (2016). Effects of gamma irradiation on the physicochemical, thermal and functional properties of chickpea flour. *LWT-Food Science and Technology, 69*, 614-622. https://doi.org/10.1016/j.lwt.2016.02.022

Bauer, J. M., Verlaan, S., Bautmans, I., Brandt, K., Donini, L. M., Maggio, M., et al. (2015). Effects of a vitamin D and leucine-enriched whey protein nutritional supplement on measures of sarcopenia in older adults, the PROVIDE study: a randomized, double-blind, placebo-controlled trial. *Journal of the American Medical Directors Association, 16*(9), 740-747. https://doi.org/10.1016/j.jamda.2015.05.021

Baugreet, S., Gomez, C., Auty, M. A., Kerry, J. P., Hamill, R. M., & Brodkorb, A. (2019). In vitro digestion of protein-enriched restructured beef steaks with pea protein isolate, rice protein and lentil flour following sous vide processing. *Innovative Food Science & Emerging Technologies, 54*, 152-161. https://doi.org/10.1016/j.ifset.2019.04.005

Botinestean, C., Gomez, C., Nian, Y., Auty, M. A., Kerry, J. P., & Hamill, R. M. (2018). Possibilities for developing texture-modified beef steaks suitable for older consumers using fruit-derived proteolytic enzymes. *Journal of Texture Studies, 49*(3), 256-261. https://doi.org/10.1111/jtxs.12305

Brodkorb, A., Croguennec, T., Bouhallab, S., & Kehoe, J. J. (2016). Heat-induced denaturation, aggregation and gelation of whey proteins. In P. L. H. McSweeney & J. A. O'Mahony (Eds.). *Advanced Dairy Chemistry* (pp. 155-178). New York: Springer.

Brodkorb, A., Egger, L., Alminger, M., Alvito, P., Assunção, R., Ballance, S., et al. (2019). INFOGEST static in vitro simulation of gastrointestinal food digestion. *Nature Protocols, 14*(4), 991-1014. https://doi.org/10.1038/s41596-018-0119-1

Calvo-Lerma, J., Fornés-Ferrer, V., Heredia, A., & Andrés, A. (2019). In vitro digestion models to assess lipolysis: The impact of the simulated conditions of gastric and intestinal pH, bile salts and digestive fluids. *Food Research International, 125,* 108511. https://doi.org/10.1016/j.foodres.2019.108511

Çelebioğlu, H. Y., Lee, S., & Chronakis, I. S. (2020). Interactions of salivary mucins and saliva with food proteins: a review. *Critical Reviews in Food Science and Nutrition, 60*(1), 64-83. https://doi.org/10.1080/10408398.2018.1512950

Chen, J. (2015). Food oral processing: Mechanisms and implications of food oral destruction. *Trends in Food Science & Technology, 45*(2), 222-228. https://doi.org/10.1016/j.tifs.2015.06.012

Cheng, J., Xie, S., Yin, Y., Feng, X., Wang, S., Guo, M., & Ni, C. (2017). Physiochemical, texture properties, and the microstructure of set yogurt using whey protein–sodium tripolyphosphate aggregates as thickening agents. *Journal of the Science of Food and Agriculture, 97*(9), 2819-2825. https://doi.org/10.1002/jsfa.8110

Chian, F. M., Kaur, L., Oey, I., Astruc, T., Hodgkinson, S., & Boland, M. (2019). Effect of Pulsed Electric Fields (PEF) on the ultrastructure and in vitro protein digestibility of bovine longissimus thoracis. *LWT-Food Science and Technology,* 103, 253-259. https://doi.org/10.1016/j.lwt.2019.01.005

Chihi, M. L., Mession, J. L., Sok, N., & Saurel, R. (2016). Heat-induced soluble protein aggregates from mixed pea globulins and β-lactoglobulin. *Journal of Agricultural and Food Chemistry, 64*(13), 2780-2791. https://doi.org/10.1021/acs.jafc.6b00087

Chung, C., Degner, B., & McClements, D. J. (2014). Development of reduced-calorie foods: microparticulated whey proteins as fat mimetics in semi-solid food emulsions. *Food Research International, 56*, 136-145. https://doi.org/10.1016/j.foodres.2013.11.034

Cichero, J. A., Steele, C., Duivestein, J., Clavé, P., Chen, J., Kayashita, J., Dantas, R., Lecko, C., Speyer, R., Lam, P., & Murray, J. (2013). The need for international terminology and definitions for texture-modified foods and thickened liquids used in dysphagia management: foundations of a global initiative. *Current Physical Medicine and Rehabilitation Reports, 1*(4), 280-291. https://doi.org/10.1007/s40141-013-0024-z

Cichero, J. A. Y. (2015). Texture-modified meals for hospital patients. In J. Chen & A. Rosenthal (Eds.), *Modifying Food Texture, volume 2: Sensory analysis, consumer requirements and preferences* (pp. 135-162). Cambridge: Woodhead Publishing.

Cichero, J. A. Y. (2016). Adjustment of food textural properties for elderly patients. *Journal of Texture Studies, 47*(4), 277-283. https://doi.org/10.1111/jtxs.12200

Cichero, J. A., Lam, P., Steele, C. M., Hanson, B., Chen, J., Dantas, R. O., et al. (2017). Development of international terminology and definitions for texture-modified foods and thickened fluids used in dysphagia management: the IDDSI framework. *Dysphagia, 32*(2), 293-314. https://doi.org/10.1007/s00455-016-9758-y

De Loubens, C., Panouillé, M., Saint-Eve, A., Déléris, I., Tréléa, I. C., & Souchon, I. (2011). Mechanistic model of in vitro salt release from model dairy gels based on standardized breakdown test simulating mastication. *Journal of Food Engineering, 105*(1), 161-168. https://doi.org/10.1016/j.jfoodeng.2011.02.020

Dick, A., Bhandari, B., Dong, X., & Prakash, S. (2020). Feasibility study of hydrocolloid incorporated 3D printed pork as dysphagia food. *Food Hydrocolloids*, 105940. https://doi.org/10.1016/j.foodhyd.2020.105940

Do, D. T., Singh, J., Oey, I., & Singh, H. (2019). Modulating effect of cotyledon cell microstructure on in vitro digestion of starch in legumes. *Food Hydrocolloids, 96*, 112-122. https://doi.org/10.1016/j.foodhyd.2019.04.063

Dos Santos, T. P. R., Franco, C. M. L., do Carmo, E. L., Jane, J. L., & Leonel, M. (2019). Effect of spray-drying and extrusion on physicochemical characteristics of sweet potato starch. *Journal of Food Science and Technology, 56*(1), 376-383. https://doi.org/10.1007/s13197-018-3498-y

Drosou, C. G., Krokida, M. K., & Biliaderis, C. G. (2017). Encapsulation of bioactive compounds through electrospinning/electrospraying and spray drying: A comparative assessment of food-related applications. *Drying Technology, 35*(2), 139-162. https://doi.org/10.1080/07373937.2016.1162797

Dupont, D., Le Feunteun, S., Marze, S., & Souchon, I. (2018). Structuring food to control its disintegration in the gastrointestinal tract and optimize nutrient bioavailability. *Innovative Food Science & Emerging Technologies, 46*, 83-90. https://doi.org/10.1016/j.ifset.2017.10.005

Ellis, A. L., Mills, T. B., Norton, I. T., & Norton-Welch, A. B. (2019). The effect of sugars on agar fluid gels and the stabilisation of their foams. *Food Hydrocolloids, 87*, 371-381. https://doi.org/10.1016/j.foodhyd.2018.08.027

Eom, S. H., Lee, S. H., Chun, Y. G., Kim, B. K., & Park, D. J. (2015). Texture softening of beef and chicken by enzyme injection process. *Korean Journal for Food Science of Animal Resources, 35*(4), 486. https://doi.org/10.5851/kosfa.2015.35.4.486

Eom, S. H., Chun, Y. G., Park, C. E., Kim, B. K., Lee, S. H., & Park, D. J. (2018). Application of freeze–thaw enzyme impregnation to produce softened root vegetable foods for elderly consumers. *Journal of Texture Studies, 49*(4), 404-414. https://doi.org/10.1111/jtxs.12341

Falsafi, S. R., Maghsoudlou, Y., Rostamabadi, H., Rostamabadi, M. M., Hamedi, H., & Hosseini, S. M. H. (2019). Preparation of physically modified oat starch with different sonication treatments. *Food Hydrocolloids, 89,* 311-320. https://doi.org/10.1016/j.foodhyd.2018.10.046

Farjami, T., & Madadlou, A. (2019). An overview on preparation of emulsion-filled gels and emulsion particulate gels. *Trends in Food Science & Technology, 86,* 85-94. https://doi.org/10.1016/j.tifs.2019.02.043

Force, D.D.T., & AD Association. (2002). National dysphagia diet: Standardization for optimal care. Chicago: American Dietetic Association.

Gao, H., Ma, L., Cheng, C., Liu, J., Liang, R., Zou, L., Liu, W., & McClements, D.J. (2021). Review of recent advances in the preparation, properties, and applications of high internal phase emulsions. *Trends in Food Science & Technology, 112,* 36-49. https://doi.org/10.1016/j.tifs.2021.03.041García, J., Méndez, D., Álvarez, M., Sanmartin, B., Vázquez, R., Regueiro, L., & Atanassova, M. (2019). Design of novel functional food products enriched with bioactive extracts from holothurians for meeting the nutritional needs of the elderly. *LWT-Food Science and Technology, 109,* 55-62. https://doi.org/10.1016/j.lwt.2019.03.097

Garg, T., Sharma, G., Rath, G., & Goyal, A. K. (2017). Colloidal systems: An excellent carrier for nutrient delivery. In A. M. Grumezescu (Ed.), *Nutrient Delivery* (pp. 681-712). London: Academic Press.

Gentile, L. (2020). Protein-polysaccharide interactions and aggregates in food formulations. *Current Opinion in Colloid & Interface Science, 48,* 18-27. https://doi.org/10.1016/j.cocis.2020.03.002

Golding, M. (2019). Exploring and Exploiting the Role of Food Structure in Digestion. In O. Gouseti, G. M. Bornhorst, S. Bakalis, & A. Mackie (Eds.), *Interdisciplinary Approaches to Food* Digestion (pp. 81-128). Cham: Springer.

Guo, Q., Ye, A., Lad, M., Ferrua, M., Dalgleish, D., & Singh, H. (2015). Disintegration kinetics of food gels during gastric digestion and its role on gastric emptying: an in vitro analysis. *Food & Function, 6*(3), 756-764. https://doi.org/10.1039/C4FO00700J

Guo, Q., Bellissimo, N., & Rousseau, D. (2017). Role of gel structure in controlling in vitro intestinal lipid digestion in whey protein emulsion gels. *Food Hydrocolloids, 69,* 264-272. https://doi.org/10.1016/j.foodhyd.2017.01.037

Guo, Q., Wijarnprecha, K., Sonwai, S., & Rousseau, D. (2019). Oleogelation of emulsified oil delays in vitro intestinal lipid digestion. *Food Research International, 119,* 805-812. https://doi.org/10.1016/j.foodres.2018.10.063

Hébuterne, X., Frin, G., Lefevere, S., Eyraud, E., Dorigny, B., & Schneider, S. (2020). Effectiveness and tolerance of an oral nutritional supplement highly concentrated in protein and energy in elderly subjects at risk of malnutrition. *Nutrition Clinique et Métabolisme, 34*(2), 156-160. https://doi.org/10.1016/j.nupar.2019.12.003

Hernández-Olivas, E., Muñoz-Pina, S., Andrés, A., & Heredia, A. (2020). Impact of elderly gastrointestinal alterations on in vitro digestion of salmon, sardine, sea bass and hake: proteolysis, lipolysis and bioaccesibility of calcium and vitamins. *Food Chemistry, 326*, 127024. https://doi.org/10.1016/j.foodchem.2020.127024

Hiolle, M., Lechevalier, V., Floury, J., Boulier-Monthéan, N., Prioul, C., Dupont, D., & Nau, F. (2020). In vitro digestion of complex foods: How microstructure influences food disintegration and micronutrient bioaccessibility. *Food Research International, 128,* 108817. https://doi.org/10.1016/j.foodres.2019.108817

Hotaling, D. I. (1992). Nutritional considerations for the pureed diet texture in dysphagic elderly. *Dysphagia 7*, 81–85. https://doi.org/10.1007/BF02493438

Hur, S. J., Lim, B. O., Decker, E. A., & McClements, D. J. (2011). In vitro human digestion models for food applications. *Food Chemistry, 125*(1), 1-12. https://doi.org/10.1016/j.foodchem.2010.08.036

IDDSI (2019). International Dysphagia Diet Standardisation Initiative Framework. (www.iddsi.org). Accessed March, 2021.

Ishihara, S., Nakao, S., Nakauma, M., Funami, T., Hori, K., Ono, T., Kohyama, K., & Nishinari, K. (2013). Compression test of food gels on artificial tongue and its comparison with human test. *Journal of Texture Studies, 44*(2), 104-114. https://doi.org/10.1111/jtxs.12002

Jayan, H., Leena, M. M., Sundari, S. S., Moses, J. A., & Anandharamakrishnan, C. (2019). Improvement of bioavailability for resveratrol through encapsulation in zein using electrospraying technique. *Journal of Functional Foods, 57,* 417-424. https://doi.org/10.1016/j.jff.2019.04.007

Jin, T. Z., Yu, Y., & Gurtler, J. B. (2017). Effects of pulsed electric field processing on microbial survival, quality change and nutritional characteristics of blueberries. *LWT-Food Science and Technology*, 77, 517-524. https://doi.org/10.1016/j.lwt.2016.12.009

Kadam, S. U., Tiwari, B. K., & O'Donnell, C. P. (2015). Improved thermal processing for food texture modification. In J. Chen & A. Rosenthal (Eds.), *Modifying Food Texture, volume 1: Novel Ingredients and Processing Techniques* (pp. 115-131). Cambridge: Woodhead Publishing.

Kalita, D., & Baruah, S. (2019). The Impact of Nanotechnology on Food. In R. F. Nascimento, O. P. Ferreira, A. J. De Paula, & V. O. S. Neto (Eds.), *Nanomaterials Applications for Environmental Matrices* (pp. 369-379). Oxford: Elsevier.

Kato, K., Hayashi, M., Umene, S., & Masunaga, H. (2016). A novel method for producing softened edible seaweed kombu. *LWT-Food Science and Technology, 65*, 618-623. https://doi.org/10.1016/j.lwt.2015.08.059

Keršienė, M., Jasutienė, I., Eisinaitė, V., Venskutonis, P. R., & Leskauskaitė, D. (2020). Designing multiple bioactives loaded emulsions for the formulations for diets of elderly. *Food & Function, 11*(3), 2195-2207. https://doi.org/10.1039/D0FO00021C

Kew, B., Holmes, M., Stieger, M., & Sarkar, A. (2020). Review on fat replacement using protein-based microparticulated powders or microgels: A textural perspective. *Trends in Food Science &* Technology, 106, 457-468. https://doi.org/10.1016/j.tifs.2020.10.032

Kirkhus, B., Afseth, N. K., Borge, G. I. A., Grimsby, S., Steppeler, C., Krona, A., & Langton, M. (2019). Increased release of carotenoids and delayed in vitro lipid digestion of high pressure homogenized tomato and pepper emulsions. *Food Chemistry, 285*, 282-289. https://doi.org/10.1016/j.foodchem.2019.01.124

Koo, C. K., Chung, C., Ogren, T., Mutilangi, W., & McClements, D. J. (2018). Extending protein functionality: Microfluidization of heat denatured whey protein fibrils. *Journal of Food Engineering, 223,* 189-196. https://doi.org/10.1016/j.jfoodeng.2017.10.020

Le Feunteun, S., Mackie, A. R., & Dupont, D. (2020). In silico trials of food digestion and absorption: How far are we?. *Current Opinion in Food Science, 31*, 121-125. https://doi.org/10.1016/j.cofs.2020.04.006

Lemmens, L., Colle, I., Van Buggenhout, S., Palmero, P., Van Loey, A., & Hendrickx, M. (2014). Carotenoid bioaccessibility in fruit-and vegetable-based food products as affected by product (micro) structural characteristics and the presence of lipids: A review.

Trends in Food Science & Technology, 38(2), 125-135. https://doi.org/10.1016/j.tifs.2014.05.005

Lin, X., & Wright, A. J. (2018). Pectin and gastric pH interactively affect DHA-rich emulsion in vitro digestion microstructure, digestibility and bioaccessibility. *Food Hydrocolloids, 76*, 49-59. https://doi.org/10.1016/j.foodhyd.2017.06.010

Liu, R., Wang, L., Liu, Y., Wu, T., & Zhang, M. (2018). Fabricating soy protein hydrolysate/xanthan gum as fat replacer in ice cream by combined enzymatic and heat-shearing treatment. *Food Hydrocolloids, 81*, 39-47. https://doi.org/10.1016/j.foodhyd.2018.01.031

Liu, Z., Zhang, M., Bhandari, B., & Wang, Y. (2017). 3D printing: Printing precision and application in food sector. *Trends in Food Science & Technology, 69*, 83-94. https://doi.org/10.1016/j.tifs.2017.08.018

Liu, Z., Liu, C., Sun, X., Zhang, S., Yuan, Y., Wang, D., & Xu, Y. (2020). Fabrication and characterization of cold-gelation whey protein-chitosan complex hydrogels for the controlled release of curcumin. *Food Hydrocolloids, 103*, 105619. https://doi.org/10.1016/j.foodhyd.2019.105619

Luo, Q., Boom, R. M., & Janssen, A. E. (2015). Digestion of protein and protein gels in simulated gastric environment. *LWT-Food Science and Technology, 63*(1), 161-168. https://doi.org/10.1016/j.lwt.2015.03.087

Luo, Y., & Hu, Q. (2017). Food-derived biopolymers for nutrient delivery. In A. M. Grumezescu (Ed.), *Nutrient Delivery* (pp. 251-291). London: Academic Press.

Luo, Q., Borst, J. W., Westphal, A. H., Boom, R. M., & Janssen, A. E. (2017). Pepsin diffusivity in whey protein gels and its effect on gastric digestion. *Food Hydrocolloids, 66*, 318-325. https://doi.org/10.1016/j.foodhyd.2016.11.046

Luo, N., Ye, A., Wolber, F. M., & Singh, H. (2019). Structure of whey protein emulsion gels containing capsaicinoids: Impact on in-mouth breakdown behaviour and sensory perception. *Food Hydrocolloids*, *92*, 19-29. https://doi.org/10.1016/j.foodhyd.2019.01.019

Lutz, M., Petzold, G., & Albala, C. (2019). Considerations for the development of innovative foods to improve nutrition in older adults. *Nutrients, 11*(6), 1275. https://doi.org/10.3390/nu11061275

Ma, Y., Yuan, Y., Bi, X., Zhang, L., Xing, Y., & Che, Z. (2019). Tenderization of Yak Meat by the Combination of Papain and High-Pressure Processing Treatments. *Food and Bioprocess Technology, 12*(4), 681-693. https://doi.org/10.1007/s11947-019-2245-3

Mahmood, K., Kamilah, H., Shang, P. L., Sulaiman, S., & Ariffin, F. (2017). A review: Interaction of starch/non-starch hydrocolloid blending and the recent food applications. *Food Bioscience*, *19*, 110-120. https://doi.org/10.1016/j.fbio.2017.05.006

Mao, L., & Miao, S. (2015). Structuring food emulsions to improve nutrient delivery during digestion. *Food Engineering Reviews, 7*(4), 439-451. https://doi.org/10.1007/s12393-015-9108-0

Mat, D. J., Le Feunteun, S., Michon, C., & Souchon, I. (2016). In vitro digestion of foods using pH-stat and the INFOGEST protocol: Impact of matrix structure on digestion kinetics of macronutrients, proteins and lipids. *Food Research International*, *88*, 226-233. https://doi.org/10.1016/j.foodres.2015.12.002

Minekus, M., Alminger, M., Alvito, P., Ballance, S., Bohn, Bourlieu, C., et al. (2014). A standardised static in vitro digestion method suitable for food–an international consensus. *Food & Function, 5*(6), 1113-1124. https://doi.org/10.1039/C3FO60702J

Moret-Tatay, A., Rodríguez-García, J., Martí-Bonmatí, E., Hernando, I., & Hernández, M. J. (2015). Commercial thickeners used by patients with dysphagia: Rheological and structural behaviour in different food matrices. *Food Hydrocolloids, 51*, 318-326. https://doi.org/10.1016/j.foodhyd.2015.05.019

Mosca, A. C., & Chen, J. (2017). Food-saliva interactions: Mechanisms and implications. *Trends in Food Science & Technology, 66,* 125-134. https://doi.org/10.1016/j.tifs.2017.06.005

Mosca, A. C., van de Velde, F., Bult, J. H., van Boekel, M. A., & Stieger, M. (2015). Taste enhancement in food gels: Effect of fracture properties on oral breakdown, bolus formation and sweetness intensity. *Food Hydrocolloids, 43*, 794-802. https://doi.org/10.1016/j.foodhyd.2014.08.009

Muhamad, I. I., Zaidel, D. N. A., Hashim, Z., Mohammad, N. A., & Bakar, N. F. A. (2020). Improving the Delivery System and Bioavailability of Beverages Through Nanoencapsulation. In A. M. Grumezescu & A. M. Holban (Eds.), *Nanoengineering in the Beverage Industry* (pp. 301-332). Duxford: Academic Press.

Munialo, C. D., Kontogiorgos, V., Euston, S. R., & Nyambayo, I. (2020). Rheological, tribological and sensory attributes of texture ‐ modified foods for dysphagia patients and the elderly: A review. *International Journal of Food Science & Technology, 55*(5), 1862-1871. https://doi.org/10.1111/ijfs.14483

Nakatsu, S., Shibata, K., & Sakamoto, K. (2010). Digestibility of softened lotus roots treated with freeze-thaw infusion. *Nippon Shokuhin Kagaku Kogaku Kaishi, 57*(10), 434-440. https://doi.org/10.3136/nskkk.57.434

Nakauma, M., Funami, T., Noda, S., Ishihara, S., Al-Assaf, S., Nishinari, K., & Phillips, G. O. (2008). Comparison of sugar beet pectin, soybean soluble polysaccharide, and gum arabic as food emulsifiers. 1. Effect of concentration, pH, and salts on the emulsifying properties. *Food Hydrocolloids, 22*(7), 1254-1267. https://doi.org/10.1016/j.foodhyd.2007.09.004

Narine, S. S., & Marangoni, A.G. (2002). Structure and mechanical properties of fat crystal networks. *Advances in Food and Nutrition Research, 44*, 33-145. https://doi.org/10.1016/s1043-4526(02)44003-x

Nau, F., Nyemb-Diop, K., Lechevalier, V., Floury, J., Serrière, C., Stroebinger, N., ... & Rutherfurd, S. M. (2019). Spatial-temporal changes in pH, structure and rheology of the gastric chyme in pigs as influenced by egg white gel properties. *Food Chemistry, 280*, 210-220. https://doi.org/10.1016/j.foodchem.2018.12.042

Newman, R., Vilardell, N., Clavé, P., & Speyer, R. (2016). Effect of bolus viscosity on the safety and efficacy of swallowing and the kinematics of the swallow response in patients with oropharyngeal dysphagia: white paper by the European Society for Swallowing Disorders (ESSD). *Dysphagia, 31*(2), 232–249. https://doi.org/10.1007/s00455-016-9696-8

Norton, J. E., Espinosa, Y. G., Watson, R. L., Spyropoulos, F., & Norton, I. T. (2015). Functional food microstructures for macronutrient release and delivery. *Food & Function, 6*(3), 663-678. https://doi.org/10.1039/C4FO00965G

Ogawa, Y., Donlao, N., Thuengtung, S., Tian, J., Cai, Y., Reginio Jr, F. C., Ketnawa, S., Yamamoto, N., & Tamura, M. (2018). Impact of food structure and cell matrix on digestibility of plant-based food. *Current Opinion in Food Science, 19*, 36-41. https://doi.org/10.1016/j.cofs.2018.01.003

Opazo-Navarrete, M., Altenburg, M. D., Boom, R. M., & Janssen, A. E. (2018). The effect of gel microstructure on simulated gastric digestion of protein gels. *Food Biophysics*, *13*(2), 124-138. https://doi.org/10.1007/s11483-018-9518-7

Ott, A., Senger, M., Lötzbeyer, T., Gefeller, O., Sieber, C. C., & Volkert, D. (2019). Effects of a Texture-Modified, Enriched, and Reshaped Diet on Dietary Intake and Body Weight of Nursing Home Residents with Chewing and/or Swallowing Problems: An

Enable Study. *Journal of Nutrition in Gerontology and Geriatrics, 38*(4), 361-376. https://doi.org/10.1080/21551197.2019.1628158

Pant, A., Lee, A. Y., Karyappa, R., Lee, C. P., An, J., Hashimoto, M., ... & Zhang, Y. (2021). 3D food printing of fresh vegetables using food hydrocolloids for dysphagic patients. *Food Hydrocolloids, 114,* 106546. https://doi.org/10.1016/j.foodhyd.2020.106546

Park, E. Y., Kim, H. Y., Shin, H. Y., Jeon, Y. I., Kim, J. M., Kim, S., & Kim, J. Y. (2019). Change in textural properties, starch digestibility, and aroma of nonfried instant noodles by substitution of konjac glucomannan. *Cereal Chemistry, 96*(4), 784-791. https://doi.org/10.1002/cche.10180

Park, J. J., & Lee, W. Y. (2020). Softening of lotus root and carrot using freeze-thaw enzyme infusion for texture-modified foods. *Food Bioscience,* 100557. https://doi.org/10.1016/j.fbio.2020.100557

Pešić, M. B., Milinčić, D. D., Kostić, A. Ž., Stanisavljević, N. S., Vukotić, G. N., Kojić, M. O., et al. (2019). In vitro digestion of meat-and cereal-based food matrix enriched with grape extracts: How are polyphenol composition, bioaccessibility and antioxidant activity affected?. *Food Chemistry, 284,* 28-44. https://doi.org/10.1016/j.foodchem.2019.01.107

Peyron, M. A., Santé-Lhoutellier, V., François, O., & Hennequin, M. (2018). Oral declines and mastication deficiencies cause alteration of food bolus properties. *Food & Function, 9*(2), 1112-1122. https://doi.org/10.1039/C7FO01628J

Pritchard, S. J., Davidson, I., Jones, J., & Bannerman, E. (2014). A randomised trial of the impact of energy density and texture of a meal on food and energy intake, satiation, satiety, appetite and palatability responses in healthy adults. *Clinical Nutrition, 33*(5), 768-775. https://doi.org/10.1016/j.clnu.2013.10.014

Ritzoulis, C. & Karayannakidis, P. D. (2015). Proteins as texture modifiers. In J. Chen & A. Rosenthal (Eds.), *Modifying Food Texture, volume 1: Novel Ingredients and Processing Techniques* (pp. 51-69). Cambridge: Woodhead Publishing.

Roco, T., Torres, M. J., Briones-Labarca, V., Reyes, J. E., Tabilo-Munizaga, G., Stucken, K., Lemus-Mondaca, R., & Pérez-Won, M. (2018). Effect of high hydrostatic pressure treatment on physical parameters, ultrastructure and shelf life of pre-and post-rigor mortis palm ruff (Seriolella violacea) under chilled storage. *Food Research International*, *108*, 192-202. https://doi.org/10.1016/j.foodres.2018.03.009

Ross, A. I., Tyler, P., Borgognone, M. G., & Eriksen, B. M. (2019). Relationships between shear rheology and sensory attributes of hydrocolloid-thickened fluids designed to compensate for impairments in oral manipulation and swallowing. *Journal of Food Engineering, 263*, 123-131. https://doi.org/10.1016/j.jfoodeng.2019.05.040

Rutz, J. K., Borges, C. D., Zambiazi, R. C., Crizel-Cardozo, M. M., Kuck, L. S., & Noreña, C. P. (2017). Microencapsulation of palm oil by complex coacervation for application in food systems. *Food Chemistry*, *220,* 59-66. https://doi.org/10.1016/j.foodchem.2016.09.194

Saha, D., & Bhattacharya, S. (2010). Hydrocolloids as thickening and gelling agents in food: a critical review. *Journal of Food Science and Technology, 47*(6), 587-597. https://doi.org/10.1007/s13197-010-0162-6

Sánchez-Obando, J. D., Cabrera-Trujillo, M. A., Olivares-Tenorio, M. L., & Klotz, B. (2020). Use of optimized microparticulated whey protein in the process of reduced-fat spread and petit-suisse cheeses. *LWT-Food Science and Technology,* 120, 108933. https://doi.org/10.1016/j.lwt.2019.108933

Sarkar, A., Horne, D. S., & Singh, H. (2010). Pancreatin-induced coalescence of oil-in-water emulsions in an in vitro duodenal model. *International Dairy Journal, 20*(9), 589-597. https://doi.org/10.1016/j.idairyj.2009.12.007

Sarkar, A., Zhang, S., Murray, B., Russell, J. A., & Boxal, S. (2017). Modulating in vitro gastric digestion of emulsions using composite whey protein-cellulose nanocrystal interfaces. *Colloids and Surfaces B: Biointerfaces, 158*, 137-146. https://doi.org/10.1016/j.colsurfb.2017.06.037

Sarkar, A. (2019). Oral processing in elderly: understanding eating capability to drive future food texture modifications. *Proceedings of the Nutrition Society, 78*(3), 329-339. https://doi.org/10.1017/S0029665118002768

Sharma, M., Kristo, E., Corredig, M., & Duizer, L. (2017). Effect of hydrocolloid type on texture of pureed carrots: Rheological and sensory measures. *Food Hydrocolloids, 63*, 478-487. https://doi.org/10.1016/j.foodhyd.2016.09.040

Shekarforoush, E., Ajalloueian, F., Zeng, G., Mendes, A. C., & Chronakis, I. S. (2018). Electrospun xanthan gum-chitosan nanofibers as delivery carrier of hydrophobic bioactives. *Materials Letters*, *228*, 322-326. https://doi.org/10.1016/j.matlet.2018.06.033

Shewan, H. M., Pradal, C., & Stokes, J. R. (2020). Tribology and its growing use toward the study of food oral processing and sensory perception. *Journal of Texture Studies, 51*(1), 7-22. https://doi.org/10.1111/jtxs.12452

Shewan, H. M., & Stokes, J. R. (2013). Review of techniques to manufacture micro-hydrogel particles for the food industry and their applications. *Journal of Food Engineering, 119*(4), 781-792. https://doi.org/10.1016/j.jfoodeng.2013.06.046

Singh, H., & Sarkar, A. (2011). Behaviour of protein-stabilised emulsions under various physiological conditions. *Advances in Colloid and Interface Science*, *165*(1), 47-57. https://doi.org/10.1016/j.cis.2011.02.001

Singh, H., Ye, A., & Ferrua, M. J. (2015). Aspects of food structures in the digestive tract. *Current Opinion in Food Science, 3,* 85-93. https://doi.org/10.1016/j.cofs.2015.06.007

Stokes, J. R., Boehm, M. W., & Baier, S. K. (2013). Oral processing, texture and mouthfeel: From rheology to tribology and beyond. *Current Opinion in Colloid & Interface Science, 18*(4), 349-359. https://doi.org/10.1016/j.cocis.2013.04.010

Štreimikytė, P., Keršienė, M., Eisinaitė, V., Jasutienė, I., Lesauskaitė, V., Damulevičienė, G., Knašienė, J., & Leskauskaitė, D. (2020). Formulating protein‐based beverages used for the dysphagia diets of the elderly: Viscosity, protein quality, in vitro digestion and consumers' acceptability. *Journal of the Science of Food and Agriculture, 100*(10), 3895-3901. https://doi.org/10.1002/jsfa.10431

Spence, C., Navarra, J., & Youssef, J. (2019). Using ice-cream as an effective vehicle for energy/nutrient delivery in the elderly. *International Journal of Gastronomy and Food Science, 16*, 100140. https://doi.org/10.1016/j.ijgfs.2019.100140

Stokes, J. R. (2012). Food biopolymer gels, microgel and nanogel structures, formation and rheology. In B. Bhandari & Y. H. Roos (Eds.), *Food Materials Science and Engineering* (pp. 151-176). Chichester: Wiley-Blackwell.

Sungsinchai, S., Niamnuy, C., Wattanapan, P., Charoenchaitrakool, M., & Devahastin, S. (2019). Texture modification technologies and their opportunities for the production of dysphagia foods: A review. *Comprehensive Reviews in Food Science and Food Safety, 18*(6), 1898-1912. https://doi.org/10.1111/1541-4337.12495

Takei, R., Hayashi, M., Umene, S., Kobayashi, Y., & Masunaga, H. (2016). Texture and microstructure of enzyme‐treated chicken breast meat for people with difficulties in mastication. *Journal of Texture Studies, 47*(3), 231-238. https://doi.org/10.1111/jtxs.12178

Talens, P., Castells, M. L., Verdú, S., Barat, J. M., & Grau, R. (2021). Flow, viscoelastic and masticatory properties of tailor made thickened pea cream for people with swallowing problems. *Journal of Food Engineering, 292*, 110265. https://doi.org/10.1016/j.jfoodeng.2020.110265

Tamura, M., Singh, J., Kaur, L., & Ogawa, Y. (2016). Impact of structural characteristics on starch digestibility of cooked rice. *Food Chemistry, 191,* 91-97. https://doi.org/10.1016/j.foodchem.2015.04.019

Thirumdas, R., Saragapani, C., Ajinkya, M. T., Deshmukh, R. R., & Annapure, U. S. (2016). Influence of low pressure cold plasma on cooking and textural properties of brown rice. *Innovative Food Science & Emerging Technologies, 37*, 53-60. https://doi.org/10.1016/j.ifset.2016.08.009

Torres, I. C., Mutaf, G., Larsen, F. H., & Ipsen, R. (2016). Effect of hydration of microparticulated whey protein ingredients on their gelling behaviour in a non-fat milk system. *Journal of Food Engineering, 184,* 31-37. https://doi.org/10.1016/j.jfoodeng.2016.03.018

United Nations (2019). Department of Economic and Social Affairs, Population Division. *World Population Prospects 2019: Highlights.* ST/ESA/SER.A/423.

United Nations (2020). Department of Economic and Social Affairs, Population Division. *World Population Ageing 2020 Highlights: Living arrangements of older persons*. ST/ESA/SER.A/451.

Vandenberghe-Descamps, M., Sulmont-Rossé, C., Septier, C., Follot, C., Feron, G., & Labouré, H. (2018). Impact of blade tenderization, marinade and cooking temperature on oral comfort when eating meat in an elderly population. *Meat Science, 145*, 86-93. https://doi.org/10.1016/j.meatsci.2018.06.004

Van Wymelbeke, V., Sulmont-Rossé, C., Feyen, V., Issanchou, S., Manckoundia, P., & Maître, I. (2020). Optimizing sensory quality and variety: An effective strategy for increasing meal enjoyment and food intake in older nursing home residents. *Appetite, 153,* 104749. https://doi.org/10.1016/j.appet.2020.104749

Ye, J., Hu, X., Luo, S., McClements, D. J., Liang, L., & Liu, C. (2018). Effect of endogenous proteins and lipids on starch digestibility in rice flour. *Food Research International, 106,* 404-409. https://doi.org/10.1016/j.foodres.2018.01.008

Ye, J., Liu, C., Luo, S., Wu, J., Hu, X., & McClements, D. J. (2019). A simulated gastrointestinal tract study of texturized rice grains: Impact of texturization on starch digestibility. *Journal of Cereal Science, 89,* 102800. https://doi.org/10.1016/j.jcs.2019.102800

Wright, L., Cotter, D., Hickson, M., & Frost, G. (2005). Comparison of energy and protein intakes of older people consuming a texture modified diet with a normal hospital diet. *Journal of Human Nutrition and Dietetics, 18*(3), 213-219. https://doi.org/10.1111/j.1365-277X.2005.00605.x

Xue, S., Wang, C., Kim, Y. H. B., Bian, G., Han, M., Xu, X., & Zhou, G. (2020). Application of high-pressure treatment improves the in vitro protein digestibility of gel-based meat product. *Food Chemistry, 306,* 125602. https://doi.org/10.1016/j.foodchem.2019.125602

Yan, X., Ma, C., Cui, F., McClements, D. J., Liu, X., & Liu, F. (2020). Protein-stabilized pickering emulsions: Formation, stability, properties, and applications in foods. *Trends in Food Science & Technology, 103,* 293-303. https://doi.org/10.1016/j.tifs.2020.07.005

Zhou, H., Tan, Y., Lv, S., Liu, J., Mundo, J. L. M., Bai, L., Rojas, O. J., & McClements, D. J. (2020). Nanochitin-stabilized pickering emulsions: Influence of nanochitin on lipid digestibility and vitamin bioaccessibility. *Food Hydrocolloids*, 105878. https://doi.org/10.1016/j.foodhyd.2020.105878

Zúñiga, R. N., Kulozik, U., & Aguilera, J. M. (2011). Ultrasonic generation of aerated gelatin gels stabilized by whey protein β-lactoglobulin. *Food Hydrocolloids*, *25*(5), 958-967. https://doi.org/10.1016/j.foodhyd.2010.09.010

FIGURE CAPTIONS

Figure 1. The IDDSI framework. Terminology for describing food textures and drink thicknesses to improve safety for individuals with swallowing difficulties.

Figure 2. Typical structuring molecules used for the design of texture-modified foods (created with Biorender.com).

Figure 3. Main mechanical and biochemical processes occurring during gastrointestinal digestion.

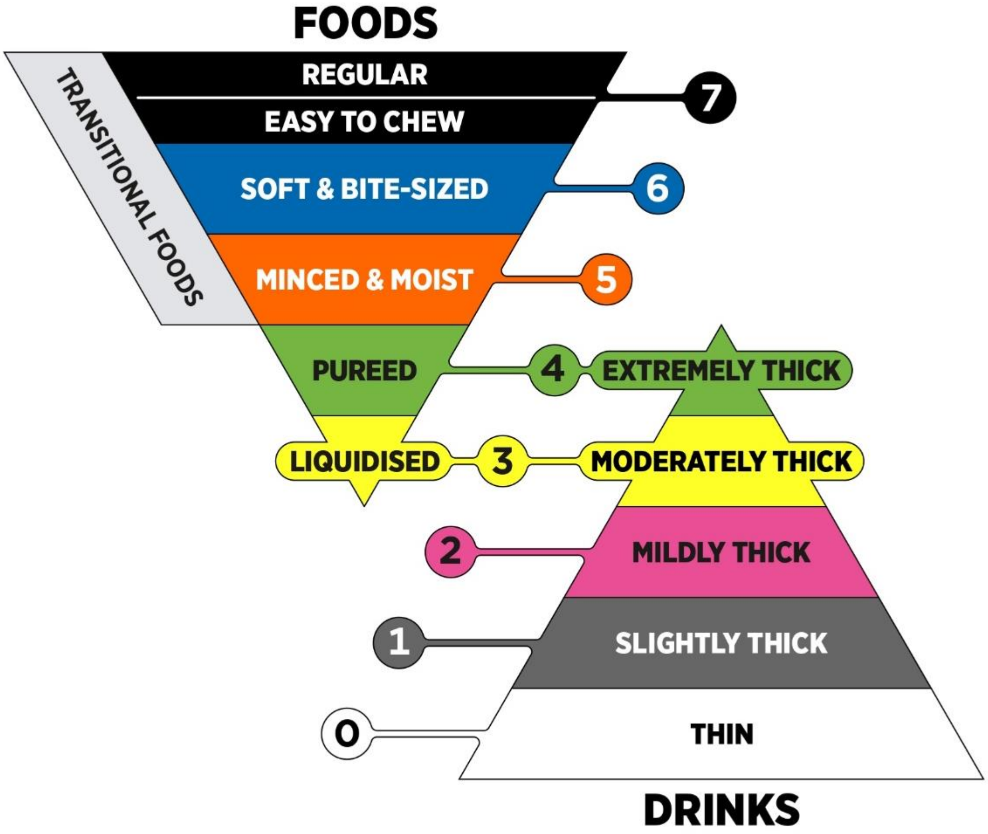

FOODS
REGULAR
EASY TO CHEW
7
TRANSITIONAL FOODS
SOFT & BITE-SIZED
6
MINCED & MOIST
5
PUREED
4
EXTREMELY THICK
LIQUIDISED
3
MODERATELY THICK
2
MILDLY THICK
1
SLIGHTLY THICK
0
THIN
DRINKS

Figure 1.

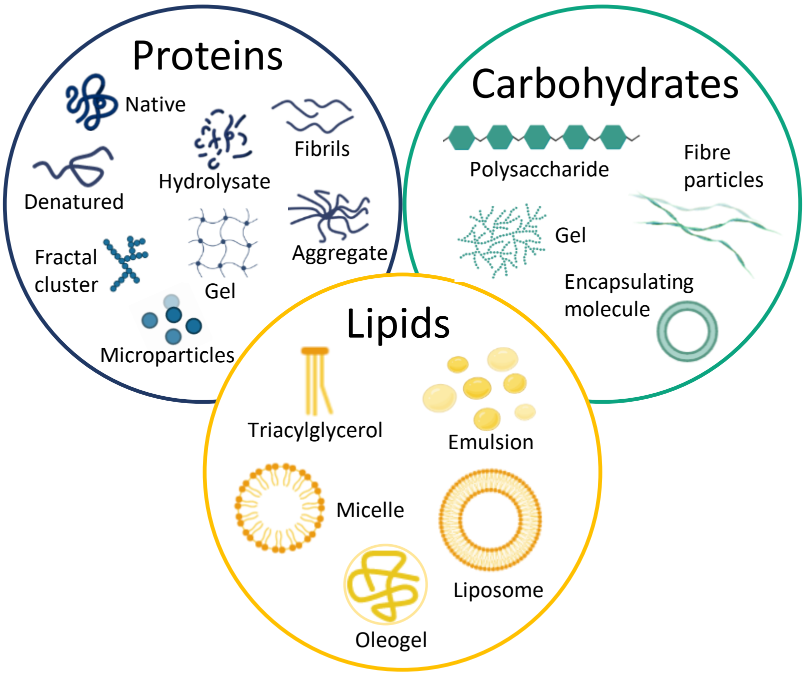
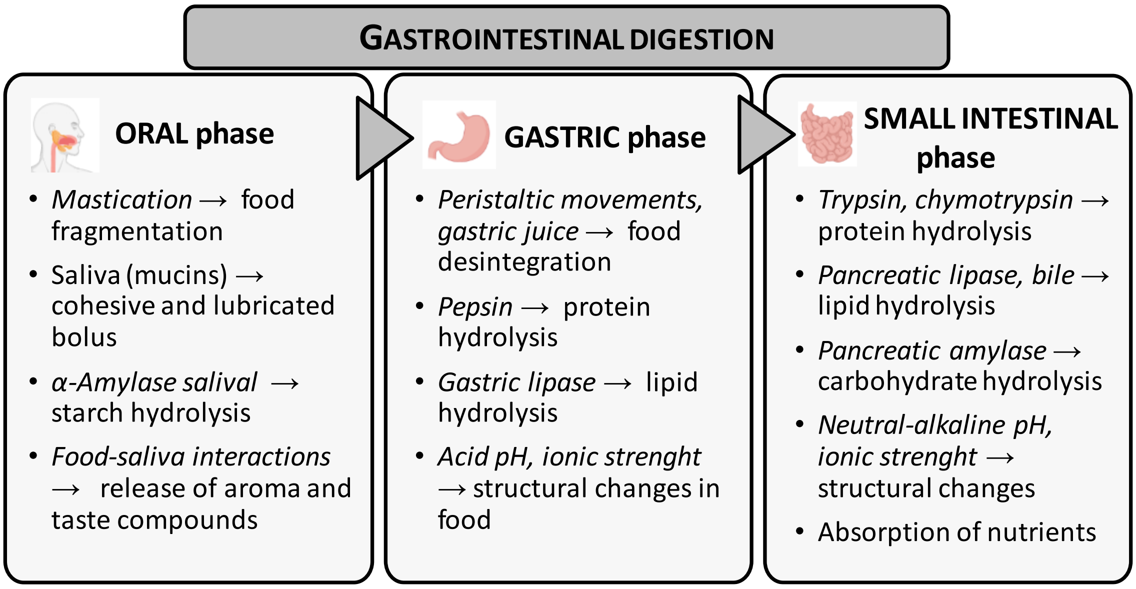

Proteins
Native
Hydrolysate
Fibrils
Denatured
Aggregate
Fractal cluster
Gel
Microparticles
Carbohydrates
Polysaccharide
Fibre particles
Gel
Encapsulating molecule
Lipids
Triacylglycerol
Emulsion
Micelle
Liposome
Oleogel

Figure 2.



GASTROINTESTINAL DIGESTION

ORAL phase

- *Mastication* → food fragmentation
- Saliva (mucins) → cohesive and lubricated bolus
- *α-Amylase salival* → starch hydrolysis
- *Food-saliva interactions* → release of aroma and taste compounds

GASTRIC phase

- *Peristaltic movements, gastric juice* → food desintegration
- *Pepsin* → protein hydrolysis
- *Gastric lipase* → lipid hydrolysis
- *Acid pH, ionic strenght* → structural changes in food

SMALL INTESTINAL phase

- *Trypsin, chymotrypsin* → protein hydrolysis
- *Pancreatic lipase, bile* → lipid hydrolysis
- *Pancreatic amylase* → carbohydrate hydrolysis
- *Neutral-alkaline pH, ionic strenght* → structural changes
- Absorption of nutrients

Figure 3.

Table 1. Application of processing technologies for softening foods and effects on food properties.

Technology	Treatment conditions*	Food sample	Effects on food properties	Reference
Enzymatic hydrolysis	Papain (0.002%) and bromelain (0.0003%)	Chicken meat	Original fibrous texture and appearance were maintained, firmness decreased, and texture is softened.	Takei, Hayashi, Umene, Kobayashi, and Masunaga (2016)
	Protease (1%) and phosphate buffer (4°C, 15h)	Seaweed kombu	Appearance and taste were maintained, firmness and stickiness decreased. It enabled to be mashed with the tongue and upper jaw.	Kato, Hayashi, Umene, and Masunaga (2016)
Freeze-thaw enzyme impregnation	Freeze-thawing (-20°C overnight / 25°C, 2h) + impregnation in vacuum (20 kPa, 10 min) with Viscozyme L (0.1-2%, 40-65°C, 1h)	Root vegetables	Marked softening effect (decreased hardness) without changing original shapes of the products.	Eom et al. (2018)
	Freeze-thawing (-20°C >12h / 25°C, 5h) + impregnation in vacuum (0-0.05 MPa, 5-30 min) with cellulase (0.25%, 50°C, 1h) + restoration (25°C, 0-120 min)	Lotus root and carrot	Long restoration times and vacuum times led to an increase in tissue softening and enzyme infusion. As vacuum time increased, texture softening rate of lotus root increased, and residual texture of carrot decreased. Further cooking of samples increased softness.	Park and Lee (2020)
High hydrostatic pressure	550 MPa, 3 min	Palm ruff fish	Hardness and water retention decreased in post-rigor fillets, increased cohesiveness and whitening effect.	Roco et al. (2018)
Enzymatic hydrolysis + High pressure	Papain (80 U/mL, 55°C, 30 min) + high pressure (50 MPa, 15 min)	Yak meat	Tenderness and water-holding capacity of raw meat decreased with no change in colour. Improvement of tenderness and aroma in cooked meat.	Ma et al. (2019)
Pulsed electric fields	2 kV/cm, 1 µs pulse width, 100 pulses/s, 4 min + sanitizer solution	Blueberries	Texture softening (decreased hardness), increased extraction of antioxidant compounds (anthocyanins and phenolic compounds), no changes in colour and appearance.	Jin, Yu, and Gurtler (2017)

Low-pressure cold plasma	50 W, 10 min	Brown rice	Shortened cooking time, soft texture (reduced hardness, gumminess and chewiness), negligible effect on nutritional value.	Thirumdas, Saragapani, Ajinkya, Deshmukh, and Annapure (2016)
Ultrasounds	Probe sonication: 350 W, 63 W/cm^2 density, 20 min	Oat starch	Increased amylose content, swelling power, solubility, transmittance, water and oil absorption capacity, and gelatinisation temperature, reduction in gel hardness.	Falsafi et al. (2019)
Ultrasounds + Enzymatic hydrolysis	Ultrasounds (100 W, 20 min) + papain (0.1%, 65°C, 30 min)	Beef meat	Decreased hardness, cohesiveness, gumminess, springiness and chewiness, providing the highest proteolytic activity and tenderness.	Barekat and Soltanizadeh (2017)
Gamma irradiation	0.5 - 10 kGy	Chickpea flour	Increased irradiation dose reduced pasting and textural properties (hardness, adhesiveness, cohesiveness, gumminess, and springiness), and increased swelling, solubility, transmittance, syneresis, gelatinisation temperature, and water and oil absorption.	Bashir and Aggarwal (2016)

* The studies consider different conditions in the treatments, but the specific or optimal ones to provide the mentioned results are indicated.

Table 2. Processing technologies used to obtain texture-modified foods, applications and effects on food properties.

Technology	**Material**	**Application**	**Effect on food properties**	**Reference**
Heat-induced aggregation	Soluble protein aggregates from mixed pea globulins and β-lactoglobulin	Control food texture	Formation of new disulfide bonds and noncovalent interactions. Higher particle size distribution and molecular weight of aggregates.	Chihi, Mession, Sok, and Saurel (2016)
Microparticulation	Microparticulated whey protein	Fat replacement in cheeses	Good sensory properties and higher nutritional value, no changes in textural characteristics in petit-suisse cheese.	Sánchez-Obando, Cabrera-Trujillo, Olivares-Tenorio, and Klotz, (2020)
Cold gelation	Whey protein–sodium tripolyphosphate aggregates	Thickening agent in yogurt	Formation of strong and firm gels, improved hardness, adhesiveness, gumminess, and springiness.	Cheng et al. (2017)
Emulsification - gelation	Whey protein emulsion gel	Delivery systems for bioactive compounds	Greater gel hardness led to smaller bolus particle size and lower mouth burn perception.	Luo, Ye, Wolber, and Singh (2019)
Complex coacervation	Chitosan/xanthan microparticles in yogurt	Microencapsulation of bioactive compounds	Good and gradual release of carotenoids under gastrointestinal conditions, no degradation of the released compounds.	Rutz et al. (2017)
Shearing	Agar fluid gel with added sugars	Foam stabilisation	Reduction in fluid gel particle size through changes in solution viscosity during gelation, good foaming properties where foam half-life increased with sugar concentration.	Ellis, Mills, Norton, and Norton-Welch (2019)
Extrusion	Sweet potato extrudate starch	Use in products that require rapid solubility and low viscosity	Complete gelatinisation of starch: reduction in molecular weight of amylopectin, decrease in swelling power, increase in solubility, formation of dispersed paste with low viscosity.	Dos Santos, Franco, do Carmo, Jane, and Leonel (2019)
Spray-drying	Sweet potato starch	Thickening agent	Partial gelatinisation of starch: increased viscosity and swelling power, decreased granular size of native starch and molecular weight of amylopectin.	Dos Santos et al. (2019)
Thermal-microfluidisation	Whey protein fibrils	Modulation of functional attributes	Protein fibrils decreased in length. Clear fluids were formed at high and low pH, whereas cloudy gels were formed at intermediate pH.	Koo, Chung, Ogren, Mutilangi, and McClements (2018)

Electrospinning	Xanthan gum-chitosan nanofibres	Delivery systems for hydrophobic bioactives	Encapsulation of curcumin with high encapsulation efficiency, physical stability in aqueous media, and long-term pH-stimulated release properties.	Shekarforoush, Ajalloueian, Zeng, Mendes, and Chronakis (2018)
Electrospraying	Resveratrol encapsulated in zein nanoparticles	Nanoencapsulation of bioactives	Improved antioxidant activity and bioaccesibility of resveratrol.	Jayan, Leena, Sundari, Moses, and Anandharamakrishnan (2019)

Table 3. Recent studies on texture modified or fortified foods evaluating the digestibility and bioaccessibility of nutrients by *in vitro* gastrointestinal digestion.

Food sample	***In vitro* gastrointestinal digestion***	**Parameter**	**Digestibility results**	**Reference**
Pea protein-fortified sponge cake	O: SSF, α-amylase (2min) / *Ex vivo* chewed bolus G: SGF, pepsin (2h) I: SIF, pancreatin (2h)	Protein digestion	Gradual protein hydrolysis during digestion. Bioaccesibility of pea proteins, the degree of structure of the bolus did not influence protein digestibility	Assad-Bustillos et al. (2020)
Gel-based rabbit meat product treated with high pressure	O: SSF, α-amylase (2min) G: SGF, pepsin (2h) I: SIF, trypsin, chymotrypsin (2h)	Protein digestion	High pressure treatment reduced solubility of proteins, induced alterations in myofibrillar proteins and led to the generation of less types but more abundant peptides. Protein digestion was improved.	Xue et al. (2020)
Bovine meat treated with pulsed electric fields	O: SSF, α-amylase (2min) G: SGF, pepsin (1h) I: SIF, pancreatin, bile extract (2h)	Protein digestion	Disruption of the muscle fibres that may enhance accessibility of digestive enzyme, improving protein digestibility.	Chian et al. (2019)
Plant protein-enriched restructured beef steaks processed *sous vide*	O: *ex vivo* "chew and spit" G: SGF, pepsin (2h) I: SIF, bile salt, pancreatin (2h)	Protein digestion	Fibre separation during gastric digestion; fibre breakdown and protein re-aggregation during intestinal digestion. Significant protein hydrolysis during digestion, mainly producing peptides smaller than 500 Da. Higher amounts of free amino acids in lentil-enriched meats.	Baugreet et al. (2019)
Wheat sponge cake bread with candelilla wax/canola oil oleogel	I: pancreatic α-amylase, amyloglucosidase (2h)	Starch digestion	Oleogel addition increased starch digestibility and decreased the formation of amylose-lipid complexes. Rapidly digestible starch fraction increased with the oleogel content while slowly digestible starch fraction remained unchanged.	Alvarez-Ramirez, Vernon-Carter, Carrera-Tarela, Garcia, and Roldan-Cruz (2020)

Cooked nonfried instant noodles substituted by glucomannan	I: amyloglucosidase, pancreatin (2h)	Starch digestion	No significant changes in rapidly digestible starch and slowly digestible starch contents, but resistant starch content increased probably because of the strong interaction between amylose and glucomannan.	Park et al. (2019)
Cooked texturised rice grains	O: SSF, α-amylase (3min) G: SGF, pepsin (2h) I: SIF, pancreatin, amyloglucosidase, bile extract (2.5h)	Starch digestion	Lower starch hydrolysis than cooked ordinary rice due to the higher resistant starch content in the texturised rice. Slow break down during digestion, reducing surface area of starch exposed to the digestive enzymes and thus starch digestibility.	Ye et al. (2019)
Emulsified soybean oil with rice bran wax oleogelator	O: artificial saliva (1min) G: SGF, pepsin (1h) I: SIF, pancreatin, bile salt (2h)	Lipid digestion	Oleogelation delayed intestinal lipid digestion mainly due to wax crystal network entrapped liquid oil and protected it against lipolysis. Oleogelation that balances oil droplet rigidity and emulsion stability best delayed lipolysis, regardless of rice bran wax concentration.	Guo, Wijarnprecha, Sonwai, and Rousseau (2019)
High pressure homogenised tomato and pepper emulsions	O: SSF, α-amylase (2min) G: SGF, pepsin (2h) I: SIF, pancreatin, bile extract (2.3h)	Lipid digestion/ Bioaccessibility of carotenoids	Delayed intestinal lipid digestion due to the structures or constituents originating from tomato that would reduce lipase activity. The release of carotenoids depended on the type and can be improved by increasing the homogenization pressure and oil content.	Kirkhus et al. (2019)
Nanochitin-emulsions fortified with vitamin D_3	O: mucin (10min) G: SGF, pepsin (2h) I: bile extract, lipase, salts (2h)	Lipid digestion/ Bioaccessibility of vitamin D_3	Nanochitin reduced the initial digestion rate and total extent of lipid digestion of emulsions as well as vitamin bioaccessibility.	Zhou et al. (2020)
Resveratrol encapsulated in zein nanoparticles	O: SSF, α-amylase (2min) G: SGF, pepsin (2h) I: SIF, pancreatin, bile salts / Dynamic (2h)	Bioavailability of resveratrol	Effective protection of resveratrol under stomach conditions and controlled release at intestinal region. Increased intestinal permeability of encapsulated resveratrol.	Jayan et al. (2019)
	O: SSF, α-amylase (2min) G: SGF, pepsin (2h)	Bioaccessibility of polyphenols	Grape skin and seed extracts exhibited different patterns of behaviour during digestion. *In vitro* digestion elevated the	Pešić et al. (2019)

Meat- and cereal-based food matrix enriched with grape extracts	I: SIF, pancreatin, bile salts (2h)		total phenolic content of the grape extracts in the presence of food matrix, and increased antioxidant activity.	
Multiple bioactives loaded emulsions	O: SSF, α-amylase (2min) G: pepsin (2h) I: pancreatin, lipase, bile salts (2h)	Release of vitamins B_9, B_{12}, C, D_3 and A, and anthocyanins	Poor release of vitamins B_9 and B_{12} and moderate release of vitamins C, D_3 and A during the gastric stage, but total release of vitamins during the intestinal stage. Restricted release of antioxidant anthocyanins during the gastric phase and moderate during the intestinal stage.	Keršienė et al. (2020)

[*] O: oral phase, G: gastric phase, I: intestinal phase. SSF: simulated saliva fluid; SGF: simulated gastric fluid; SIF: simulated intestinal fluid.