Chapter 12
Replacement of Fat or Starch

Cuixia Sun and Yapeng Fang

Abstract A growing public demand for low-calorie foods is stimulating the researchers and food manufacturers to develop reduced-calorie products due to the recognized adverse effects of high energy diet on human health. Fat and starch are two condensed sources of energy, and reducing their intake is a major dietary goal for the consumer. Currently a variety of available technological options have been applied to decrease the content of fat or starch in foods. The development of food hydrocolloids-based fat or starch replacers is one of the most important approaches for fat or starch reduction because their functionalities allow them to mimic the oral and flow properties of fat or starch. However, the replacement of fat or starch is not trivial because both of them play important roles in determining the nutritional, physical, chemical, and sensory characteristics of foods. How to achieve the replacement of fat while matching as close as possible all the characteristics of full-fat foods remains a major challenge. This chapter describes the main challenges for the reduction of fat from the viewpoint of flavour perception and texture quality. Two strategies for fat replacement are involved, including food formulation optimization and food structure design. Various hydrocolloids-based formulations created for the purpose of starch replacement are introduced and the associated principles discussed. The commercially available fat replacers and their applications in different food products are presented.

Keywords Fat · Starch · Replacement · Challenges · Strategies

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C. Sun · Y. Fang (✉)
Department of Food Science and Technology, School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai, China
e-mail: ypfang@sjtu.edu.cn

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1 Introduction

High calorie food intake is associated with the increased prevalence of numerous chronic diseases, including obesity, type 2 diabetes, hypertension, cancers, gall bladder disease, and coronary heart disease. Fat and starch are two major sources of calories in many processed food products. High levels of certain types of triacylglycerols in the blood have been related to coronary heart disease and obesity (Bray et al. 2004; Han et al. 2016). Rapid digestion of starch causes a sudden rise in blood glucose level, which has been linked to diabetes and obesity (Lustig et al. 2012; Svihus and Hervik 2016). Based on the growing awareness about the adverse effects of high caloric products through nutrition and health claims, reducing fat or starch intake is becoming a major dietary goal for the consumer. In addition, our ever more sedentary life styles serve as a driving force to decline the consumption of high-energy foods.

The World Health Organization (2003) recommends a daily intake of total fat no more than 30% of dietary energy, of which <10% should be saturated fatty acids. The UK Food Standards Agency (2008) published its Saturated Fat and Energy Intake Programme and recommends that the saturated fat consumption should be reduced from 13.3% of dietary energy to 11%. The 2015–2020 Dietary Guidelines for Americans emphasize the restriction of trans and saturated fats intake and recommend the consumption of low-fat or fat-free foods (DeSalvo et al. 2016). Food reformulation to reduce the content of fat was included in nutrition action plans of many European countries (Belc et al. 2019). The United States Code of Federal Regulations (2014) defines low-fat food as: 'The food has a reference amount customarily consumed >30 g and contains 3 g or less of fat per reference amount customarily consumed (RACC); or the food has a reference amount customarily consumed of 30 g or less and contains 3 g or less of fat per RACC and per 50 g of food'. In the USA, a low-fat cheese must contain 6 g or less of fat per 100 g of cheese, while a reduced-fat cheese requires at least a 25% reduction in fat level from the traditional fat level of the referenced variety. Fat-free cheese is defined as that with <0.5 g fat per 100 g of cheese (Johnson 2011).

In such a context, researchers and the food industry are highly sensitive to consumer perceptions and demands for low-calorie foods. However, the replacement of fat or starch is not trivial because both of them play important roles in determining the nutritional, physical, chemical, and sensory characteristics of foods. For example, as shown in Fig. 12.1, fat not only provides a concentrated source of energy, but also supplies essential fatty acids and fat-soluble vitamins (A, D, E, and K). Fat reduction would result in loss of nutritional benefits or even an unbalanced diet (Colmenero 2000). Besides, fat provides structure in baked goods, influences the storage stability, and affects the observed lightness of food products owing to the impact of the fat droplets on light scattering (Chung et al. 2013a). A direct removal or simple replacement of fat without compensation for specific functions would cause a considerable change in the organoleptic characteristics of foods, leading to a poor food quality. For instance, inulin addition at levels of 100% in cake

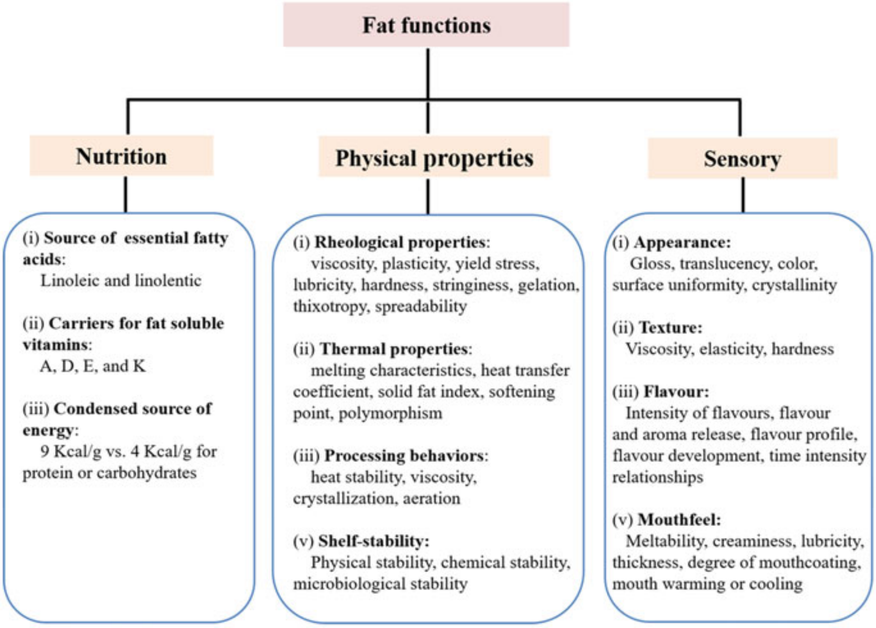

Fig. 12.1 Functions of fat in food products

formulations resulted in remarkable loss of different quality attributes, including higher water activity and baking loss, lower volume, harder texture, darker colour, and highly asymmetrical shape (Majzoobi et al. 2018). Starch granules are often used in food products to provide desirable texture attributes, such as ‘thickness’, and contribute to the physicochemical properties of foods, including the volume, viscosity, gelation, and stability (Ai and Jane 2015). Any ingredients to replace starch granules should be able to simulate such characteristics normally provided by conventional starch granules and meanwhile should contribute less calories and lower glycemic index (McClements et al. 2017).

Consequently, a number of considerations need to be taken into account for the feasibility of fat- or starch-reduced products in order to maintain the desired physicochemical and sensory attributes of original foods. In this chapter, major challenges for the development of low-fat or low-starch foods are discussed from the aspects of scientific problems and technical limitations. A variety of hydrocolloids-based formulations developed for the purpose of fat or starch replacement are introduced and the associated principles discussed. The commercially available fat replacers and their applications in different food products are presented.

2 Challenges for Fat or Starch Replacement

Based on either omission or replacement of fat or starch, a variety of available technological options have been involved to quantitatively reduce fat or starch content and qualitatively modify the fatty acid profiles. For example, food reformulation is one of the most important approaches to remove, reduce, and/or replace different components in order to develop healthy products. However, food is a typically complex colloid system with common characteristics of multiphase, multicomponent, and multiscale. Fat droplets and starch granules vary considerably in their size, shape, charge, and behaviour and endow foods with many desirable functions. Therefore, they are difficult to replace.

2.1 Challenges for Fat Replacement

The elimination or reduction of fat in foods evidently modifies its composition and structure and also the expected interactions among components, giving rise in most cases to clearly perceptible changes in flavour and/or texture. Moreover, although most taste compounds do not dissolve in fats, when fat content is reduced, the salty, sweet, sour, and umami tastes will be weakened and the bitter taste enhanced (Metcalf and Vickers 2002).

2.1.1 Flavour Concerns

Sensory preference for fat appears to be a universal human trait because fat contributes to numerous sensory characteristics of fatty products, including appearance, texture, flavour and aroma, and mouthfeel. Flavour as one of the most-important attributes determines consumer selection and satisfaction with fat-reduced foods. Reduction or elimination of fat directly affects the processes of flavour release and perception, modifies the signals received by the brain on consuming a particular food, and may partially determine its acceptance or rejection.

Flavour Distribution and Release

The term ‘flavour’ refers to volatile components that are sensed by aroma receptors in the nose and non-volatile components that are sensed by taste receptors in the mouth (Taylor and Linforth 1996). The overall perceived flavour of a food product usually involves the integration of information from mouthfeel, taste, and aroma during mastication (González-Tomás et al. 2008). As an extremely complicated process, flavour perception is dependent on a combination of physicochemical, biological, and psychological phenomenon, which is perhaps the most multisensory of our everyday experiences (Spence 2015). Fat functions as flavour precursors, and reducing fat content influences both the distribution of the flavour and the kinetics of flavour release (McClements and Demetriades 1998). The type and concentration of flavour molecules mainly determine the perceived flavour. For nonpolar flavour, decreasing fat content would increase in the aqueous phase flavour concentration, leading to an intense initial taste perception (Roberts et al. 2003). Even if the amount of flavour compounds is rebalanced in fat-reduced foods to provide the same maximum aroma intensity as the full-fat products, the low-fat alternatives still fail to match the same perception. The major reason is that fat has an impact on time-intensity profile of lipophilic flavour release. The sustained aroma release relies on the hydrophobicity and fat content of the product, that is, the higher the hydrophobicity and fat content, the slow the aroma release into the aqueous phase (de Roos 2006). In full-fat products, a rich flavour sensation is perceived because flavour compounds with various degrees of hydrophobicity are released at different rates. On the contrary, in reduced-fat products, lower amount of fat is insufficient to retain the aroma compounds and thus causes quick flavour disappearance and lack of richness (van Ruth et al. 2002).

Flavour–Ingredients Interactions

Food matrix ingredients such as proteins, polysaccharides, and lipids can interact with flavour compounds (Guichard 2002). Modification of the food formulation by using fat replacers would change such interaction and thus alter the flavour perception. The development of fat-reduced products with desired flavour will be only possible if the knowledge of flavour-ingredients interactions has been well understood (Plug and Haring 1994). Flavour-binding behaviour of fat replacers results in lower volatilities in aqueous systems, which may explain the decreased flavour intensity in fat-reduced foods (Godshall 1997; Fischer and Widder 1997). For example, proteins like β-lactoglobulin, casein, gelatin, and egg albumin can interact with flavour compounds by reversible or irreversible binding, causing lower volatilities in water phase (Maier 1970). More research is required to explore the mechanisms of flavour–ingredients interactions and the location of the binding sites, which can provide the necessary information for the selection of suitable fat replacers in the development of fat-reduced food products.

2.1.2 Texture Concerns

Texture is another important sensory attribute to assess food quality, such as being hard or soft, cold or warm, oily or juicy, elastic or flaky, heavy, viscous, or smooth. If the texture attribute fails to meet our expectations, we may reject the food regardless of the quality of flavour (Engelen and de Wijk 2012). Fat is an important contributor to texture in different types of foods, such as thickness of liquid foods (Villegas and Costell 2007), consistency of semisolids (Tárrega and Costell 2006), and firmness of solids (Kavas et al. 2004). Fat content has obvious impacts on the food texture in different ways because fat droplets impart many textural characteristics such as the viscosity, afterfeel, lubrication, and melting or cooling mouthfeel. Fat reduction usually results in a dramatic decrease in viscosity, leading to the lower perceived thickness. The common approach is to add biopolymer or biopolymer mixture to the aqueous phase to enhance its viscosity. However, biopolymer molecules are not able to mimic all of the textural characteristics. Particularly, fat has distinctive thermal properties because of its unique melting point, which contributes the creamy mouthfeel after the melting of fat crystals at room temperature (Weenen 2005). It was reported that heat transfer between foods and the oral surface may be an important factor for fat perception. The perceived food temperature is associated with fat content, for example, high fat products were perceived as warmer than low-fat products (Weenen et al. 2003). Therefore, the sensory difference of foods with different fat contents can be detected based on the fact that lips and tongue are highly sensitive with the temperature changes (Prinz et al. 2007).

Moreover, numerous sensory characteristics of food emulsions are related to their rheological properties such as elasticity, viscosity, and viscoelasticity. For example, the fatty, creamy, smooth, and thick texture of full-fat products is related to the bulk rheology, thin-film rheology, and colloidal interaction between food and oral surface (Malone et al. 2003). Removal of fat causes textural problems in reduced or low-fat ice creams, such as coarseness and iciness, crumbly body, shrinkage, and flavour defects (Akalın et al. 2008). Cakes presented significantly increased hardness, elasticity, and decreased specific volume as fat replacement increased above 65%, leading to lower scores on taste and flavour (Psimouli and Oreopoulou 2013). Fat reduction is likely to reduce the degree of shear-thinning behaviour, which may have important implications for the mouthfeel and texture of the product. Therefore, a thorough understanding of the rheological behaviours and colloidal properties of foods would provide guidelines for the design of products with the replacement of fat or starch but without quality loss.

Overall, the functional properties of lipids that must be reproduced include organoleptic properties, the ability to dissolve lipid-soluble flavours, aeration, aroma, emulsification, flavour, heat stability, and spreadability. Translating idea into reality is not a simple task. Hydrocolloids-based fat replacers are generally polar water-soluble compounds, so it is difficult for them to replace some of the nonpolar functional characteristics of fats, such as lipid-soluble flavour-carrying capacity.

2.2 Challenges for Starch Replacement

Starch granules are widely used in foods to create desirable textural attributes because of its preferable characteristics such as gelling, thickening, and aqueous solubility. The viscosity is a determining factor for the application of starch in food products to obtain desirable rheological characteristics (Sarkar et al. 2013).

Therefore, the challenge for starch replacement is how to develop a food ingredient with similar functional attributes as starch granules.

2.2.1 Pasting and Gel Texture Properties Control

The replacement of starch with non-starch hydrocolloids influences the properties of a starch-based paste, gel, or food product. Mixing gelatin (0.5 wt%) with pectin (0.01 wt%) formed the hydrogel particles with similar dimensions to swollen starch granules, and these hydrogel microspheres were shown to have similar rheological attributes as starch pastes (Wu et al. 2014). However, the unsolved technical and scientific question is that the physicochemical properties of gelatin are highly susceptible to temperature because it forms a gel at low temperatures. By the increase of corn starch citrate (CSC) substitution level, the textural parameters of wheat starch gels were decreased, such as firmness, cohesiveness, springiness, gumminess, and chewiness (Hedayati and Niakousari 2018). Addition of glutamic acid or lysine increased gelatinization temperatures of the cross-linked potato starches and decreased the G' and G'' moduli of the modified starch gels while accelerated the retrogradation process (Gałkowska and Juszczak 2019), which may cause undesirable changes to food and mostly affect the bakery products. The substitution of kudzu and lotus starches with soybean soluble polysaccharide (SSPS) reduced the hardness of the starch/SSPS gels, and the mixtures of starch/SSPS yielded more liquid-like behaviour than the controls did (Liu et al. 2019). The modified pasting and gel texture properties may change the sensory properties of the end product. Therefore, how to control the stability and quality of starch-based foods is the key point for starch replacement. In addition, the amylose content positively correlated with its cohesiveness and stringiness (Zhang et al. 2019), and amylopectin molecular size significantly contributes to gel viscoelasticity (Li et al. 2019). Consequently, the pasting and gel texture properties of starch-based foods would be influenced after starch being replaced by the non-starch hydrocolloids.

2.2.2 Interactions Control

The compositions of starch-based foods are generally complicated, and the interactions of starch with various food components such as proteins and lipids have been extensively reported. The challenge of starch replacement lies in the understanding of the interaction mechanisms of starch and non-starch food constituents to achieve desirable quality of low-starch foods. Starch–protein interactions affect the rheological, pasting, gelatinization, textural, and physicochemical properties of food systems (Villanueva et al. 2015). In general, the inclusion of proteins increased water absorption capacity, water absorption index, water solubility index, and swelling power, decreased the viscosity of gels, and increased their stability, with the effect being more conspicuous for SPI incorporation (Villanueva et al. 2018). The interaction between starch and whey protein mainly through hydrogen bonds restricted the swelling process of starch granule while accelerated recrystallization after cold storage (Yang et al. 2019). Complexes between amylose and lipids may significantly modify the properties and functionality of starch. For example, the solubility of starch in water is reduced, and the gelatinization temperature is increased after the complexation with lipids (Copeland et al. 2009). Lipids may prevent gelatinization by inhibiting hydration of amylopectin chains and retard retrogradation, which affects starch digestibility (Henry 2009). Starch/carrageenan interactions are especially involved in dairy products where gelling properties are of primary importance (Huc et al. 2014). The lower carrageenan charge density, the higher the interaction between starch and carrageenan (Lascombes et al. 2017). Formation of starch gel is hindered by the presence of cationic polysaccharide and, therefore, the retrogradation of starch at very early stage can be delayed by addition of chitosan. However, long-term retrogradation was slightly increased (Raguzzoni et al. 2016).

Overall, a universal starch substitute does not exist. All of the macromolecule replacers contribute to distinct properties suitable for replicating a limited number of functions in particular food products.

3 Strategies for Fat Replacement

The traditional dietary advice is to replace fat with low-calorie fruits, vegetables, and grains, which has not been very effective for reducing fat consumption. Direct fat removal was evolved as the first strategy to comply with nutritional recommendations in the 1980s, which worked well for milk, some dairy products, certain processed meat, but not much else. The approach to fat replacement has changed in the twenty-first century. Formulation optimization emerged as the second strategy to reduce fat content in foods, which is one of the most important approaches to replace fat in modern food technology. The food reformulation refers to the development of a range of functional ingredients as fat replacers to reduce fat intake. There are two large groups of fat replacers: fat substitutes and fat mimetics. In general, lipid-based fat replacers are fat substitutes, and protein- or carbohydrate-based fat replacers are fat mimetics (Sandrou and Arvanitoyannis 2000). In addition, processing technology is the third fat replacement strategy by varying processing conditions (pH, pressure, ionic strength, time and temperature, mixing order, stirring speed, etc.) to cause interactions in ingredients or to modify functionalities.

3.1 Food Formulation Optimization

Ideally, fat mimetics should be safe, inexpensive, low calorie, suitable for cooking applications, yet provide the sensory equivalent of fat texture and flavour, and maintain the eating quality of foods. The majority of fat mimetics belong to the groups of polysaccharide and protein hydrocolloids because their functionalities allow them to mimic the oral and flow properties of fat. For example, viscosity enhancement potential is an important feature in the use of hydrocolloids as emulsifying, stabilizing, and bodying agents in low-fat foods. Hydrocolloids as fat mimetics are able to augment the lubrication of aqueous fluids through the three lubrication regimes via both viscosity modification and by adsorbing to hydrophobic substrates (Stokes et al. 2011). Hydrocolloids-based fat replacers are usually divided into protein-based, carbohydrate-based, and lipid-based.

3.1.1 Protein-Based Fat Replacers

Protein-based fat mimetics are typically produced from egg, milk, whey, soy, or wheat proteins. Using proteinaceous ingredients to replace fat in food emulsions is mainly because of their emulsifying and stabilizing capacities. The particle size of hydrocolloids is important in determining both the taste and mouthfeel of fats in fat-replaced products. Food particles <3 μm in diameter are not detected by the oral cavity, and instead the substance feels creamy and smooth. The minimum size of particles above which humans detect the grittiness depends on the hardness and the shape of particles (Engelen et al. 2005). Therefore, proteins are often microparticulated by applying a high shearing force during heating of the proteins. The obtained small spherical (0.1–2.0 μm diameter) protein gel particles are perceived in the mouth and taste buds as similar to fat with a creamy, smooth texture. Gelatin is commonly used in low-fat yoghurts due to its melting behaviour at body temperature, as it forms a thermoreversible gel (Alting et al. 2009). The representative microparticulated whey proteins (MWP) have been produced and applied in food systems as fat replacers since the 1980s due to its soft lubrication characteristics. MWP increases the lightness and viscosity of products, and almost all of the MWP-based systems have a creamy white appearance similar to sauces and dressings, indicating their potential application in the manufacture of reduced-fat foods (Chung and McClements 2014). For example, the improved texture and rheological properties of low-fat yoghurt were obtained when whey proteins were added as microparticles rather than conventional whey protein ingredients such as whey protein isolate (Torres et al. 2018). In addition, the complex of MWP and high-methoxyl pectin was prepared as a novel fat mimetic in low-fat mayonnaise (Fig. 12.2), and two possible hypotheses were proposed to explain the interaction and distribution of MWP, pectin, and droplets (Sun et al. 2018): (1) in low-fat mayonnaise (upper figure of Fig. 12.2), MWP particles were adsorbed on the surface of oil droplets by hydrophobic interaction and formed thick and viscous films, and pectin formed coatings around interfacial proteins to inhibit flocculation of oil droplets. (2) in non-fat mayonnaise (lower figure of Fig. 12.2), MWP evenly distributed among the stable three-dimensional network formed by pectin molecules, and the stable structure of fat mimetic was maintained by hydrogen bonding, electrostatic force, and van der Waals interactions (Gentès et al. 2010).

It was observed that the friction levels attained with MWP and dairy fat (DF) at typical speeds involved in oral processing were comparable, hence demonstrating

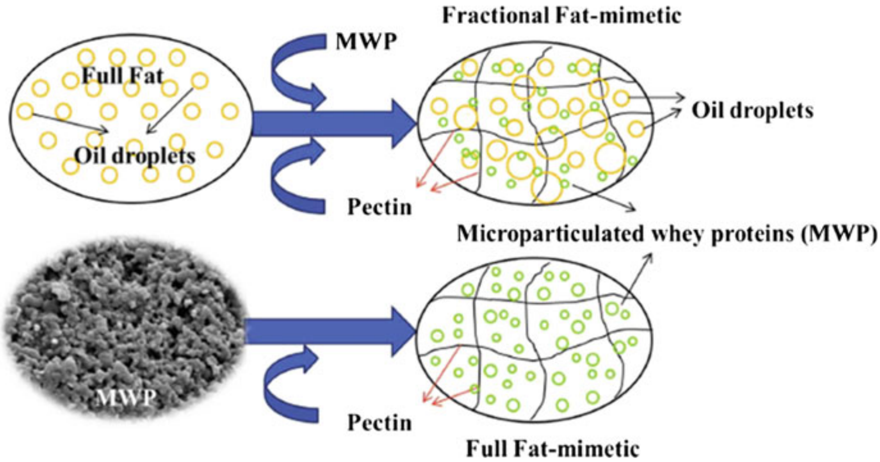

Fig. 12.2 Schematic representation of interaction among microparticulated whey protein, pectin, and oil in low-fat and non-fat mayonnaises. Reproduction with permission from (Sun et al. 2018), Copyright 2018 Elsevier

the capability of MWP in skim milk dispersions to imitate DF in fluid milk-based systems from a lubrication point of view (Olivares et al. 2019). Compared with MWP, superfine MWP (sMWP) exhibited more stable liquid behaviours (Sun et al. 2015a) and could maintain creamy mouthfeel better due to high dispersion stability of sMWP–pectin–xanthan gum gel mixtures (Sun et al. 2016). In addition, a novel group of fat globular mimetics (FGMs) was prepared by coating calcium carbonate particles with a layer of casein–maltodextrin conjugates. Such FGMs were stable in skim milk during 10-day storage at 5 °C, and increased the desirable turbidity and viscosity of skim milk, which can be used to simultaneously reduce fat and increase calcium contents of food products (Qu and Zhong 2017).

Animal proteins are rich in necessary nutrients, particularly the essential amino acids needed for human body. However, they may have a strong allergic effect and are not suitable to produce food requiring heat treatment, because high temperatures induce irreversible denaturation of protein, altering the structure of the final product (Jing et al. 2011). Besides, the consumption of animal proteins would cause problems associated with biodiversity, land use, water use, climate, human health, and animal welfare (Aiking 2011). Natural plant proteins show similar physicochemical properties to animal proteins like water binding capacity and can serve as fat substitutes in low-calorie food. Soy proteins are increasingly important in the human diet because of reported beneficial effects on nutrition and health, including lowering plasma cholesterol, prevention of cancer, diabetes, and obesity, and protection against bowel and kidney disease (Friedman and Brandon 2001). The addition of soy protein isolate improved the textural properties of chopped low-fat pork batters and lowered the cooking loss (Gao et al. 2015). Soy protein hydrolysates (SPH) and their blends with xanthan gum (SPH/XG) is an alternative choice as a fat replacer in the production of reduced-fat ice cream since 50% fat-substituted ice cream with

SPH/XG (96:4) had an appearance, taste, and texture similar to that of 10% full-fat ice cream (Liu et al. 2018a). The major limitation of proteins as fat replacers is the occurrence of molecular interactions between proteins and some volatile compounds, giving rise to unbalanced or even unacceptable sensory profiles (Kühn et al. 2006).

3.1.2 Carbohydrate-Based Fat Replacers

Carbohydrates are typical fat replacers due to their molecular diversity that gives rise to various structural and physicochemical properties. For example, carbohydrate-based fat replacers bind water into a gel-type structure, resulting in lubrication and flow properties similar to those of fat. Cookies prepared from wheat flour by 15% supplementation of carbohydrate-based fat replacers showed better attributes in terms of colour and texture, which were judged to be the best by the panellists (Majeed et al. 2017). Compared with the relatively limited available choices for protein-based fat replacers, carbohydrate-based fat replacers include a much larger family of materials, which can be categorized into digestible polysaccharides (starch) and non-digestible polysaccharides (gums and cellulose).

Digestible Starch

Among the carbohydrate-based fat replacers, starch is one of the most frequently used ingredients as it is relatively inexpensive and readily available and capable of replacing numerous attributes (O'Connor and O'Brien 2011). There are two hypotheses for starch-based fat replacer to mimic the mouthfeel and texture characteristics of fat. One is that starch would form a three-dimensional gel network structure, and the water trapped in the gel could provide a fat-like sensation (Alexander 1995). The other is that the starch could form spherulites with similar size to fat globules (2–10 μm) during heating and cooling treatment, which provide the lubricating mouthfeel of fat (Singh et al. 2010). Amylose plays an important role in the simulation mechanism of starch-based fat replacer because amylose contributed to the gel structure of starch-based fat replacer (Yang and Xu 2007). With the increasing amylose ratio, spherulites of 2–10 μm diameter, similar to fat globules in size, started to appear with the increasing amylose ratio, and the potato starch with 85% amylose ratio presented the better creamy texture (Hu et al. 2019). Starch-based fat replacers have been applied in a wide variety of low-fat food products including cheeses, sausages, yoghurt, mayonnaise, and frozen desserts (Peng and Yao 2017). The concentrations of starch frequently used as fat replacer in cheese normally ranges from 0.5 to 1.5% (Diamantino et al. 2014).

Different types of starches may present different behaviours as fat replacers. Compared to native starches, the modified starches produced high paste viscosity values and showed low retrogradation rates, which can be regarded as promising fat replacers in cheese (Diamantino et al. 2019). Starch granules remain even after heating the aqueous starch suspension, but heating at temperatures higher than 130 °C leads to complete molecular dissociation (Hanselmann et al. 1996). Starch–water systems can be classified into three states: the intact granular state, the melted state, and the solution state. When aqueous potato starch suspensions were heated and then cooled, spreadable particle gels were obtained with a spherulite morphology and a cream-like texture, which is currently applied as a fat mimetic (Steeneken and Woortman 2009). Citric acid treated sweet potato starch showed fat mimetic properties as its melting temperature (51.44 °C) was close to the melting point of fat (Surendra Babu et al. 2016). The pasting viscosity of the octenyl succinic anhydride (OSA) modified mung bean starches (OSA-MS) was found to be higher when compared with native starch, and cakes prepared from 30% OSA-MS were found to be highly acceptable by their overall quality score including the best texture, desirable colour, and mouthfeel (Punia et al. 2019). For acidified milk gels (yoghurt) with pregelatinized (PG), and both pregelatinized and chemically modified starches, viscosity/texture values were similar to or higher than those found for full-fat milk gel (Bravo-Núñez et al. 2019). The corn starch nanocrystals (CSNC) are regarded as a useful fat replacer/stabilizer for an O/W model emulsion because its addition resulted in a more solid-like behaviour of the emulsions due to the formation of nanocrystal network in the continuous phase (Javidi et al. 2019). However, one of the potential disadvantages of starch-based fat replacer is that it contains calories, so its overconsumption may lead to problems with overweight and diabetes (Lustig et al. 2012). Some of these problems may be overcome by using resistant starch (Parada and Aguilera 2011).

Non-digestible Cellulose Derivatives

Cellulose derivatives show different solubility, emulsifying property, and gelation characteristics, and they can reassociate with each other to form aggregates that can be used as fat replacers. Typically, 60–70% of the cellulose microcrystals are <0.2 mm long, which can form an insoluble dispersion in water. Methylcellulose (MC) and hydroxypropyl methylcellulose (HPMC) have been used to stabilize air bubbles, provide lubricity and creaminess, and entrap moisture in a variety of foods, such as salad dressings and biscuits (Laguna et al. 2014). Microcrystalline cellulose (MCC) is an uncharged biopolymer with a crystalline structure and could form a filled particle gel network. Therefore, MCC provides a fat-like mouthfeel and a softer texture (Fig. 12.3a) when it is added to the ground beef without causing a disturbance of the protein network. Since carboxymethyl cellulose (CMC) at high concentrations (>0.5 wt%) is thermodynamically incompatible with meat proteins, it is not a suitable fat replacer because it weakened the connections within the protein network (Gibis et al. 2015). As shown in Fig. 12.3b, cellulose nanofibrils (CNFs) at concentrations of 0.15 and 0.3 wt% were incorporated into low-fat (5 wt%) and standard ice cream formulations (10 wt%), which improved the sensory properties of low-fat samples, even after heat shocking the specimens (Velásquez-Cock et al. 2019).

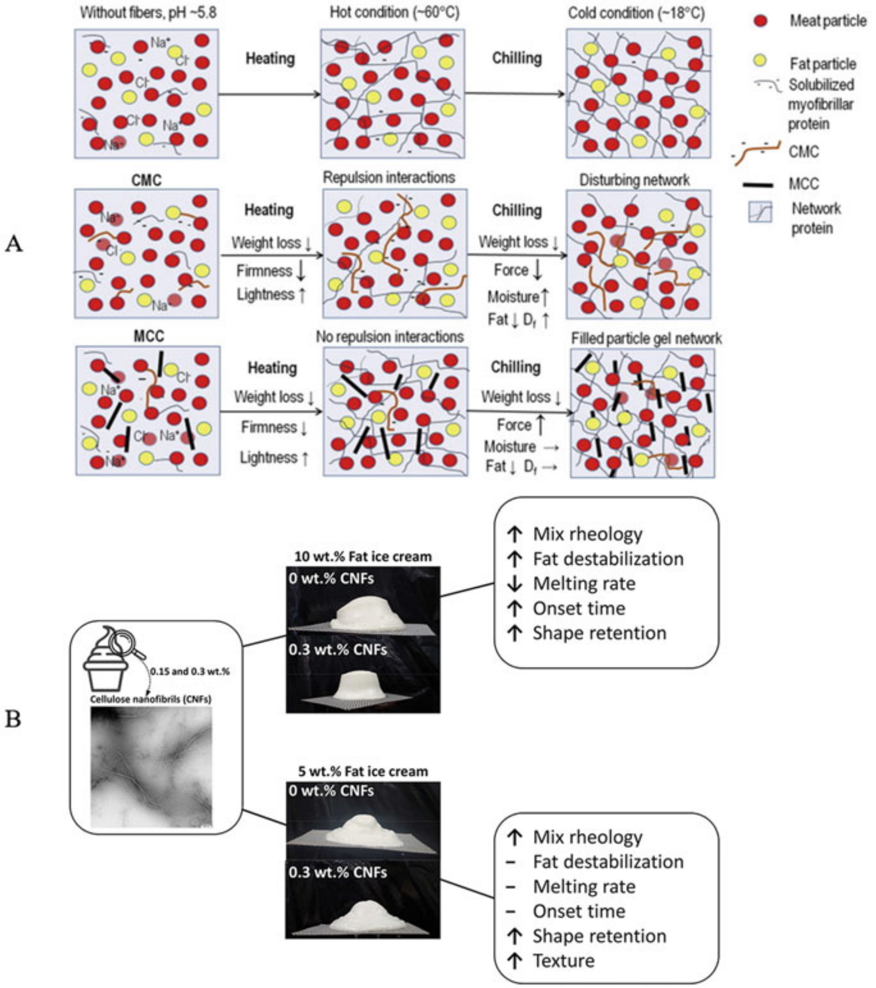

Fig. 12.3 (**a**) Suggested mechanisms of interaction of meat proteins with CMC and MCC () and (**b**) effect of cellulose nanofibrils (CNFs) at concentrations of 0.15 and 0.3 wt % on the physicochemical properties of low-fat (5 wt%) and standard ice cream formulations (10 wt%). (**a**) Reproduction with permission from (Gibis et al. 2015), Copyright 2015 Elsevier. (**b**) Reproduction with permission from (Velásquez-Cock et al. 2019), Copyright 2019 Elsevier

Non-digestible Inulin

Inulin, typically derived from chicory root, belongs to a class of carbohydrates known as fructans (Kaur and Gupta 2002). As a non-digestible dietary fibre, inulin can remain stable during processing and successive heat treatment. It is widely used in replacing dietary fat in baked products, providing nearly the same sensory characters as of full-fat products while giving only 25–35% energy as compared to digestible carbohydrates (Keenan et al. 2014). Such fat-substituting property is based on its ability to stabilize the structure of the aqueous phase, which creates an improved creaminess. A creamy mouthfeel is achieved when inulin is used as a fat replacer in dairy products due to its interactions with whey protein and caseinate (Karaca et al. 2009). Long chain inulin microcrystals could aggregate each other, interact with water, and eventually agglomerate creating a gel network, thus altering the product texture and providing a fat-like mouthfeel (Bayarri et al. 2011). The consumer study revealed that 15% fat replacement by inulin provided acceptable biscuits, but higher replacement decreased the overall acceptability (Laguna et al. 2014). Inulin addition (2–7%) to replace fat in fresh caprine milk cheese provided a creamier mouthfeel and added a reasonable flavour with softening effect (Salvatore et al. 2014). Fermented chicken sausages made with inulin as a partial oil replacement persisted stable without any significant loss of physicochemical, microbiological, and sensory characteristics during storage at 4 °C for 45 days (Menegas et al. 2013). It was found that inulin fortification of low-fat set yoghurt significantly reduced syneresis by 59% over full-fat control yoghurt (Rudra et al. 2017). What is more, inulin has promising gut health properties due to its prebiotic nature and may increase absorption of nutrients such as calcium. Therefore, it is recommended as a reasonably high-level fat replacer in crackers, cakes, biscuits, and muffins (Shoaib et al. 2016).

Other Non-digestible Gums

The performance of gums as fat replacers is determined mainly by their distinct chemical composition and structure (Saha and Bhattacharya 2010). The principles that are taken into account in applying gum as a fat mimetic include the rheological properties of the gel it forms, the effects of temperature and shearing forces on the functional properties of the gum, and its compatibility with other ingredients in the foods. Xanthan gum and carrageenan had large spheres of hydration, provided slipperiness and viscosity, and mimicked the continuous phase of mayonnaise (De Ruiter and Rudolph 1997). Locust bean gum (LBG) formed non-dissolved microparticles at relatively high concentrations ($\geq$0.4%), trapping fat droplets within its hydrogel particles and helping balance the flavour profile of reduced-fat products (Chung et al. 2013b). Water-extracted okra gum was found to be effective to make an ice cream comparable with full-fat ice cream and was used to replace the fat in ice cream at 0, 22, 44, 55, 88, and 100% to produce super premium (18% fat), premium (14% fat), regular (10% fat), economy (8% fat), low-fat (2% fat), and zero-fat (0% fat) ice cream (Aziz et al. 2018). The substitution of fat with okra gum increased the viscous modulus (G”) of the ice cream, and up to 55% replacement of fat was feasible to achieve satisfactory ice cream properties (Aziz et al. 2018). Addition of tragacanth gum (*A. gossypinus* and *A. compactus*) to sausage formulation effectively reduced cooking loss and enhanced oxidative stability, and 0.5% tragacanth (*A. gossypinus*) showed an acceptable sensory score of the sausage formulation, suggesting its potential to be a fat replacer in the reduced-fat sausages (Abbasi et al.

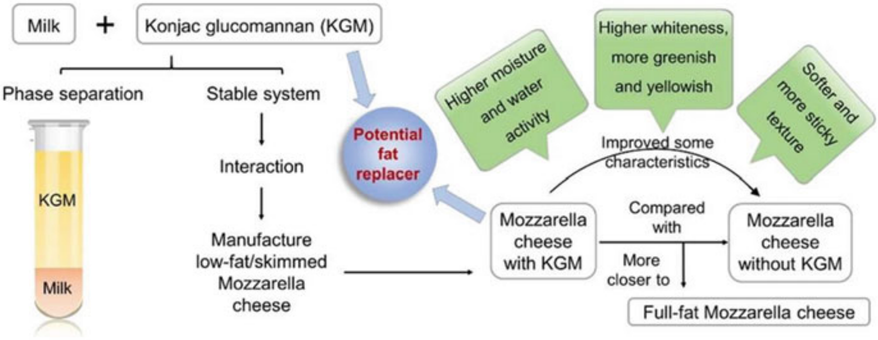

Fig. 12.4 Schematic representation of KGM addition as a potential replacer in Mozzarella cheese. Reproduction with permission from (Dai et al. 2018), Copyright 2018 Elsevier

2019). The addition of pectin in ice cream can cause an increase in viscosity, overrun, and hardness and a decrease in meltdown of the ice cream. When 0.72% pectin (w/w) was incorporated into ice cream, a prototype product of ice cream with 45% lower fat content compared to the control was prepared (Zhang et al. 2018). Konjac glucomannan (KGM) as a natural polysaccharide also exhibits functional properties as a potential fat replacer in dairy products. As shown in Fig. 12.4, KGM addition in cheese affected the lightness, increased the moisture, lowered firmness, and increased the stickiness, and such changes were closer to those of full-fat cheese, suggesting KGM could improve some characteristics of the fat-reduced Mozzarella cheeses (Dai et al. 2018). Mozzarella cheese with konjac had lower firmness but higher meltability and less scorching in pizza bake and exhibited a denser casein matrix with coalesced fat globules (Dai et al. 2019). Sodium alginate was used to modify the textural and microstructural properties of low-fat Cheddar cheese up to 91% fat reduction (Khanal et al. 2018).

3.1.3 Combination Systems

Individual fat mimetic has limitations in its ability to cover the full functions of fat. The combination of different fat replacers may show synergistic interactions and provide better fat-like qualities which are not easy to achieve by individual fat replacers (Sikora et al. 2008). For example, single carbohydrate-based and protein-based fat mimetics may suffer from several sensory and functional limitations such as poor stability and undesirable mouthfeel. The simultaneous addition of protein and polysaccharides may induce intermolecular interactions that modify or generate more desirable functional properties (Gulão et al. 2016).

Protein–Polysaccharide Combination

A combination of polydextrose with MWP is the most suitable fat replacers for soft-type cookies (Zoulias et al. 2000). The MWP in combination with either modified starch or locust bean gum (LBG), with or without fat droplets (5%), could be used as fat mimetics to modulate the texture, appearance, and stability of emulsion-based food products with reduced calorie such as sauces, mayonnaise, dressings, and dips (Chung et al. 2014). A nonheated whey protein–high methoxyl pectin mixture can be used as fat replacer in the skim milk formulations, which yielded a yoghurt texture resembling the full-fat counterpart because the associative interaction of whey proteins with pectin suppressed whey protein aggregation while maintaining the structuring effects of denatured whey protein in yoghurt (Krzeminski et al. 2014). Biopolymer-based hydrogel particles consisting of a protein-rich core and a pectin-rich shell were formed by using a segregation–aggregation phase separation method. Such particles may be suitable as texture modifiers and fat replacers since they scattered light strongly to give the hydrogel suspensions a milky white appearance and also led to an appreciable increase in viscosity or gel-like characteristics (Duval et al. 2015). The mixtures of soy protein isolate (SPI) and cellulose nanofibre (CNF) with a higher CNF proportion showed increased viscosity, storage modulus, and loss modulus and a higher tendency of gelation. The targeted low fat, low calorie, anti-melting, and similar textural taste were achieved when SPI–CNF complex gels with an SPI:CNF ratio of 7:1 were added to ice cream as a fat replacer (Fig. 12.5), in which 10% fat was replaced (Sun et al. 2015b).

Polysaccharide–Polysaccharide Combination

Polysaccharides such as pectin and alginates can interact with each other to form more or less permanent junction zones, providing yield stress and gel structure. Maltodextrin and xanthan gum yielded increased moisture, hardness, and chewiness in 66% FR (fat replacer) muffins (Khouryieh et al. 2005). The mixtures of guar gum

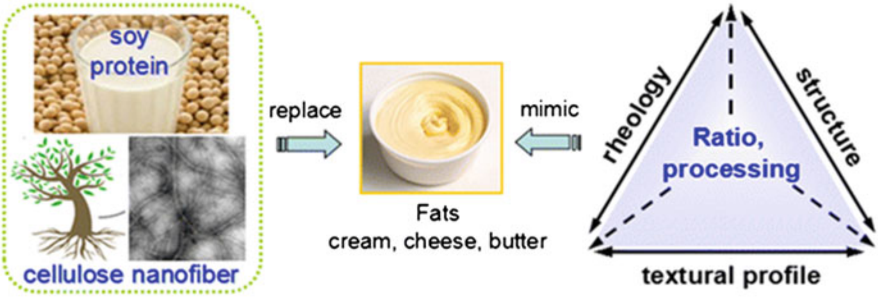

Fig. 12.5 Soy protein isolate/cellulose nanofibre complex gels as fat substitutes in dairy products. Reproduction with permission from (Sun et al. 2015b), Copyright 2015 Springer Nature

(GG) and xanthan gum or citrus fibre simulated the function of oil emulsions and made the low-fat mayonnaise score the same as the full-fat counterpart with sensory panels (Su et al. 2010). Synergistic interaction between xanthan and pregel corn starch and also between xanthan and GG was identified by data analysis (Rahmati et al. 2015). The addition of xanthan gum and GG in low-fat cheese softened the structure by interfering the casein–casein interaction and cellulose particles that function similar to fat globules (Murtaza et al. 2017). Polydextrose and GG were successful fat replacers in biscuits at a relatively high level of FR (70%), with an increase in perceived taste, flavour, and consumer acceptance (Chugh et al. 2013). The combination of gum arabic at concentrations of <75 ppm with GG in the concentration range of 75–170 ppm provided the softest texture of low-fat Iranian white cheese (Lashkari et al. 2014). The blend of GG and basil seed gum yielded better creaminess in low-fat ice cream than GG alone (Javidi et al. 2016). Four combination sets of carboxymethyl cellulose, gum arabic, carrageenan, and xanthan were used as fat replacers in Labneh (semi-solid yoghurt with high solid content 23–25%), suggesting Labneh water holding capacity in the following order: xanthan>gum arabic>carrageenan>carboxymethyl cellulose (Saleh et al. 2018). Mixture of κ-carrageenan, locust bean, and xanthan gums has been added to milk to make cheese. Majeed et al. (2017) explored the combined potential of pectin and banana powder as carbohydrate-based fat replacers in cookies, suggesting that the fat content was reduced from 29.82% to 17.07% by using 15% such complex fat replacers. Upon using different concentrations of hydrocolloids, low-fat cheese showed a significant increase in the physiochemical characteristics, yield, and moisture. Furthermore, organoleptic properties obtained were both highly acceptable and comparable to full-fat cheese (Alnemr et al. 2016). The hybrid hydrogel prepared from sodium alginate and pectin by combining both physical and chemical cross-linking methods using citric acid as the cross linker was proved to reduce up to 50 vol% fat content in chocolate with the highest melting resistance (80 °C) (Francis and Ramalingam 2019).

3.1.4 Lipid-Based Fat Replacers

Lipid-based fat replacers are either chemically synthesized or derived from conventional fats and oils by enzymatic modification. They are usually stable at cooking and frying temperatures.

Emulsions

Wheat gluten-stabilized high internal phase emulsions (HIPEs) could be promising substitutes for mayonnaise because HIPEs and mayonnaise might have similar sensory property and perceived texture such as creaminess, smoothness, and sliminess (Liu et al. 2018b). Concentrated emulsions prepared by adding a fish gelatin-gum arabic mixture at pH 5.0 and 3.6 to olive oil at W:O = 30:70 (w/w) were

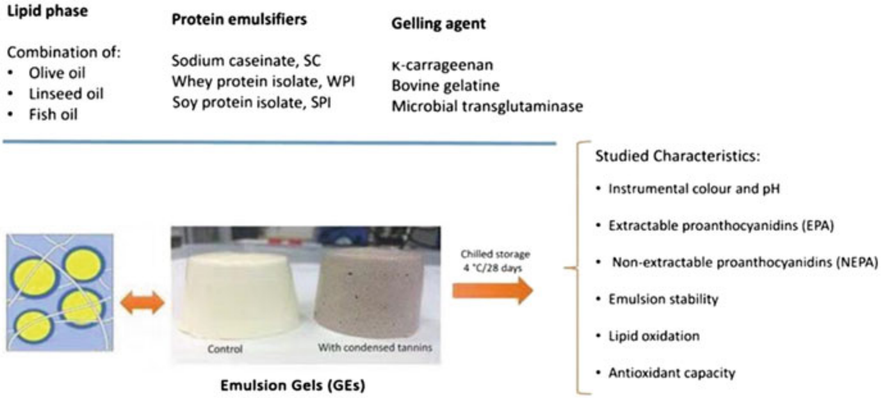

Fig. 12.6 Emulsion gels prepared with different protein emulsifiers and gelling agents. Reproduction with permission from (Freire et al. 2018), Copyright 2018 Elsevier

designed as novel fat replacers in reduced-fat (15% fat) and low-fat (6% fat) Cheddar cheeses (Anvari and Joyner 2018). Micron to nano-sized fat emulsions prepared from sodium caseinate and anhydrous butter were used as a source of fat in low-fat Cheddar without affecting much the texture, chemical and bio-chemical properties of cheese (Khanal et al. 2019). Food-grade emulsion (O/W) gels (Fig. 12.6) formulated with a lipid phase rich in n-3 fatty acids and different emulsifiers (sodium caseinate, whey protein isolate, and soy protein isolate) showed solid-like structure and their overall appearance is good enough to be used as animal fat replacers with a lower fat content (Freire et al. 2018). A multiple emulsion refers to the coexisting of water-in-oil and oil-in-water morphologies within the same system (Dickinson 2011). Multiple emulsions of water-in-oil-in-water (W/O/W) are particularly suitable for reducing the fat content of products because some of the fat within the droplets is replaced by water (Lobato-Calleros et al. 2008). However, it is difficult to ensure that the multiple emulsions have sufficient stability for commercial applications (Chung et al. 2016). Multiple emulsions (W/O/W) prepared with olive oil and sodium caseinate (SC) by two-step emulsification procedure resulted in reduced lipid, increased protein content, and modified fatty acid composition and were noted as promising constituents for beef fat replacement (Serdaroğlu et al. 2016). Multiple emulsions (W/O/W) with an average droplet size of 32 μm containing native beetroot juice as inner water phase, sunflower oil as oil phase, and 0.5% whey protein isolate as outer water phase were used to replace fat (11%) in meat products and also to enhance the product colour (Eisinaite et al. 2017). The emulsion gel (EG) prepared with gelling agents (chia flour and/or soy protein isolate, inulin, carrageenan, sodium caseinate, and sodium tripolyphosphate) resulted in a solid-like fat replacer, which was utilized as an animal fat replacer to prepare soft Bologna sausage (de Souza Paglarini et al. 2019).

Structured Oils

Unsaturated vegetable oils are often used to reduce saturated fats content in meat products, which improves the fatty acid profiles and also helps in product stability (Siraj et al. 2015). Oil structuring, or oleogelation, is the process in which edible liquid oil is immobilized in a three-dimensional gel network of gelators, conferring solid-fat functionality to liquid oils (Co and Marangoni 2012). This technology is relatively simple since it refers to the transformation of a liquid oil into a 'gel-like' structure with visco-elastic properties. The schematic representation is shown in Fig. 12.7 (Jiang et al. 2018). Unlike polymers used for hydrogels, such oleogels utilize small, amphiphilic molecules that self-assemble via non-covalent interactions forming fibrillar or platelet crystals (Patel and Dewettinck 2016). The interactions are responsible for gelation, including hydrogen bonding, π-π stacking, electrostatic and van der Waals interactions (Okesola et al. 2015).

Over the past decade, oleogels have made significant strides towards emulating desired sensory traits while maintaining healthy nutritional profile of the oil. In recent years, structuring techniques for liquid oils have received considerable attention in different fields including food science. Oleogel technology has shown strong potential as a way to replace hard-stock fats in meat products. Sunflower oil oleogels structured with monoglycerides and phytosterols at 15:5 weight ratio were used to replace 50% of the pork backfat in frankfurter sausages without significantly compromising their physicochemical, textural, and sensorial characteristics, at the same time providing an enriched polyunsaturated fatty acids lipid profile (Kouzounis

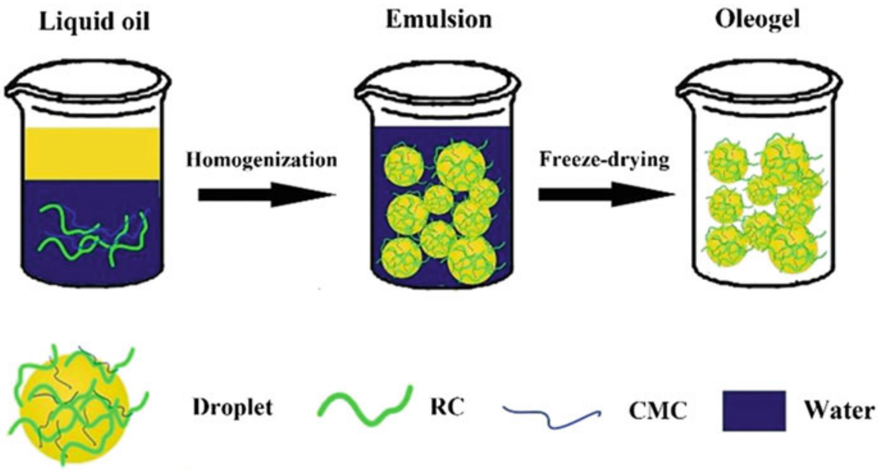

Fig. 12.7 Schematic representation of the process where liquid oil is first used to prepare an oil-in-water emulsion stabilized by regenerated cellulose (RC) and carboxymethyl cellulose (CMC), followed by freeze-drying to selectively evaporate the water phase, where further shearing of the dried oil results in the formation of an oleogel. Reproduction with permission from (Jiang et al. 2018), Copyright 2018 Elsevier

et al. 2017). Ethylcellulose (EC) oleogels have been used to replace colloidal fat crystal networks comprised of saturated fat of frankfurters (Zetzl et al. 2012). A lipid combination made with olive, linseed, and fish oils stabilized in a konjac gel matrix was created to reduce pork backfat in pork patties (Salcedo-Sandoval et al. 2015). Canola oil was structured with foam-structured hydroxypropyl methylcellulose (HPMC) into solid-like oleogels. Such an HPMC oleogel was used as an animal fat replacer for saturated fat-reduced meat patty, and the highest sensory acceptability was obtained at a 50% replacement level (Oh et al. 2019). Oleogels appeared to be the most successful fat replacer in cake, with no changes to the sensory qualities at 100% fat replacement (Kim et al. 2017). Overall, the novel approach of structuring liquid oils would be one of the most promising ways to develop healthy lipid meat products, which makes it possible to create a solid-like material rich in monounsaturated fatty acid (MUFA) and polyunsaturated fatty acid (PUFA) and with reduced saturated fatty acid (SFA) levels and zero *trans* fatty acids (Jimenez-Colmenero et al. 2015). In addition, as solid-fat replacer, the constructed structured oil systems can be used in both water-free (shortenings, chocolates, and chocolate pastes) and water-containing (cooked meat products, margarine, and spreads) products.

3.2 Food Structure Design

While fat replacers have been applied in the development of reduced-fat products, an attractive strategy for fat reduction is created based on the fundamental structure–function relationship of food ingredients (Fig. 12.8a) (Campbell et al. 2017). Structural design principles can be used to mimic some of the desirable physicochemical, sensory, and physiologic attributes normally associated with fat droplets. A variety of approaches based on structural design principles that can be used in emulsion-based products are highlighted in Fig. 12.8b (McClements 2015). For example, the control of microstructure and physical properties of biopolymer hydrogel particles can be achieved through modulation of electrostatic interactions, which could be used to manipulate food formulations to achieve desirable physicochemical or sensory properties (Chung and McClements 2015).

The potential of controlled aggregation has been used to improve texture properties for reduced-fat products since the aggregation of emulsion droplets forms a three-dimensional network that inhibits droplet movement and leads to increased viscosity and even gel-like structure (Mao and McClements 2011, 2012). The principle to control emulsion aggregation is through regulating interfacial properties of the emulsion droplets and induce electrostatic attraction between the colloidal particles (Mao and McClements 2013). By carefully controlling the pH below, above, or equal to the protein's isoelectric point (pI), respectively, the protein-stabilized emulsion droplets carry positive, negative, or neutral charges. Thus, droplets self-aggregation can be induced due to the oppositely charged biopolymers (Wu et al. 2013a). The interactions between negatively charged polysaccharide and positively charged protein interactions allow efficient approaches to construct food

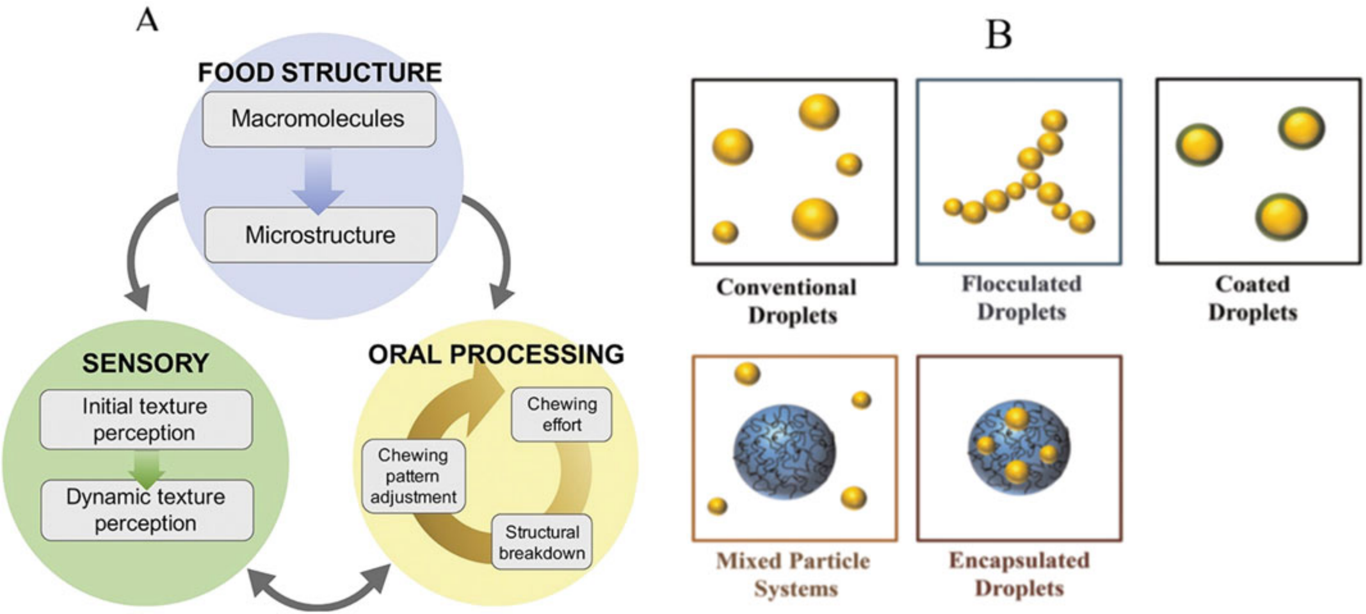

Fig. 12.8 (**a**) The relationships among food structure, oral processing, sensory perception and (**b**) structural design principles to create reduced-fat emulsion-based products with physicochemical attributes similar to conventional products. (**a**) Reproduction with permission from (Campbell et al. 2017), Copyright 2017 Elsevier. (**b**) Reproduction with permission from (McClements 2015), Copyright 2015 Oxford University Press

structures and improve the stability and textural properties of semi-solid food colloids (Le et al. 2017). Based on controlled aggregation, model reduced-calorie food emulsions consisting of fat droplets (5 wt%), starch granules (4 wt%), and xanthan gum (0–0.02 wt%) were developed with desirable textural and optical properties at pH 3, and the structural organization of the fat droplets could be regulated by altering xanthan levels (Wu and McClements 2015a). Alternatively, ions such as calcium can be added to induce aggregation of negatively charged droplets, and paste-like materials were produced when the fat droplets formed a three-dimensional network at a high calcium concentration (Wu et al. 2013b). Casein–maltodextrin conjugates produced smaller fat globule mimetics and increased the desirable turbidity and viscosity of skim milk (Qu and Zhong 2017).

4 Strategies for Starch Replacement

High consumption of digestible starch is linked to a number of diet-related diseases. There is an increasing interest in the development of starch mimetics. Based on the important physicochemical properties and sensory attributes of foods, starch mimetics should have at least two essential attributes, being capable of effectively enhancing the viscosity of solutions and giving a desirable mouthfeel to foods such as thickness and creaminess (Rao 2014). Food hydrocolloids with a relatively low calorie density are suitable for creating reduced-calorie starch mimetics as they often contain large quantities of water, therefore increase the viscosity of starch pastes, influence the retrogradation rate, and prevent the syneresis of starch (Dolz et al. 2006).

4.1 Non-starch Polysaccharides

Non-starch polysaccharides can interact with starch and impart desired functionality to the resultant blend for oriented application (Yoshimura et al. 1999; Funami 2009; BeMiller 2011; Mahmood et al. 2017). *Mesona chinensis* polysaccharide (MCP) can improve the thermal stability in the early stage of pasting and enhance the rheological properties of wheat starch (Liu et al. 2018c). The addition of gums (xanthan gum, flaxseed gum, konjac glucomannan, or tamarind seed gum) to starch resulted in softer binary gels, which are effective in retarding retrogradation of starches (Pongsawatmanit et al. 2013; Liu and Xu 2019). The presence of basil seed gum (BSG) led to greater water binding capacity and greater water absorption index of the starch compared to the free-gum systems and also led to a rise in the viscoelasticity (G' and G'') and hardness of the final gels (Matia-Merino et al. 2019). The addition of pectin increased the storage modulus (G') and loss modulus (G'') of corn starch while resulted in a decrease in the starch susceptibility to α-amylase and promoted a remarkable reduction in the fraction of rapidly digested starch (Ma et al. 2019).

Modified starch can be replaced by inulin as prebiotic encapsulant matrix of lipophilic bioactive compounds (Zabot et al. 2016). Inulin at low concentrations can effectively restrain the retrogradation of wheat starch (Luo et al. 2017). Rice starch (RS) can be also partially replaced by inulin because it affects the pasting, thermal, and rheological properties of RS (Wang et al. 2019). Barley sourced beta glucan (βG) and microcrystalline cellulose (MCC) could replace starch in meat emulsions. The maximum inclusion level of MCC and βG that has been previously tested without detrimentally affecting colour and textural properties of meat emulsions was 2% (Schuh et al. 2013) and 3% (Mejia et al. 2018), respectively. The combination of βG (1.5%) and MCC (1.5%) to replace starch resulted in beef emulsions with less calories, greater insoluble fibre content, and appropriate technological properties (Mejia et al. 2019).

4.2 Hydrocolloid Microgels

Hydrocolloid microgels have been attracting much attention to produce low-calorie foods (Norton et al. 2006). Hydrocolloids microgels fabricated by complexation of cationic proteins and anionic polysaccharides through electrostatic attraction showed a strong potential to be starch mimetic. Gelatin-pectin-based starch mimetics have been developed, and the size and morphology of such starch mimetic could be controlled through manipulation of gelatin/pectin ratio. For example, gelatin at a fixed concentration of 0.5 wt% can form micro-sized translucent spheroids when interacting with 0.01 wt% pectin at pH 5, and these hydrogel particles showed similar dimensions, shape, and rheological properties as swollen starch granules (Wu et al. 2014). The ionic strength should also be controlled during gelatin–pectin complex formation, as a too high salt content perturbed the gelatin–pectin interactions through electrostatic screening and ion binding effects (Wu and McClements 2015b). The cross-linking altered the microstructure and rheology of the microgels under simulated oral processing conditions. The melt-in-the-mouth behaviour of the hydrocolloid microgels could be made to be similar to that of starch granules by controlling the degree of cross-linking (Wu and McClements 2015c). In addition, the gelatin–pectin microgels designed to dissociate around body temperature may be useful for imitating the melting properties and/or thickening properties of starch granules in the mouth, which is also particularly helpful for the development of elderly foods with improved swallowing ease under oral conditions. Electrostatic complexation of gelatin and modified (OSA) starch shows potential to modify texture of food products, suggesting their feasibility to replace starch granules in foods (Wu and McClements 2015d).

5 Commercially Available Fat Replacers

Limited studies have been specifically focused on the development of starch mimetics though there are lots of reports about the design of biopolymer-based hydrogel particles, so commercial starch mimetics are limited. As a result, commercial fat replacers are mainly introduced in this part.

Fat-reduction ingredients fall into three categories: carbohydrate-based, protein-based, and lipid-based, in which carbohydrate-based fat replacers are the most common. Examples of commercially available fat replacers and their applications and functional properties are shown in Table 12.1 (Mattes 1998). In some cases, the Food and Drug Administration (FDA) has approved fat-reduction ingredients as food additives, including carrageenan, olestra, and polydextrose. In other instances, fat-reduction ingredients are 'generally recognized as safe' (GRAS). Most carbohydrate-based fat replacers are GRAS substances. For example, oatrim gel made from whole oat flour behaves like shortening, being solid at room and body temperatures and liquid at cooking temperatures, and imparts fat-like qualities such as creaminess, moisture retention, bulking, and texture. Oatrim is heat stable in cooking and baking applications and can replace fat in foods such as frozen desserts, salad dressings, soups, cheeses, baked goods, meats, and skim milk. Besides, Oatrim also contains beta glucan, so it offers double health benefit by replacing the fat and increasing the soluble fibre content of foods (Hahn 1997).

Protein-based fat replacers are not as many as carbohydrate-based ingredients, but they have a wide range of applications. Commercially available protein-based fat replacers are Simplesse and Dairy Lois, which are derived from whey protein concentrates and are generally regarded as safe (Yazici and Akgun 2004). This category of fat mimetics is suitable for use in dairy products, salad dressings, frozen desserts, and table spreads. For instance, Dairy Lois incorporated at 5% by weight has been used to develop an ice cream containing 1% fat.

Lipid-based fat replacers often provide the closest taste and cooking properties of fat. Salatrim belongs to a group of structured triacylglycerols and has been used as a fat mimetic in reduced-calorie food products for many years because it provides approximately half of the calories and has similar physicochemical and organoleptic properties as those of conventional fats (Smith et al. 1994). A great concentration of undigested fat within the lower gastrointestinal tract (GIT) remained, indicating that Salatrim may be an effective fat replacer due to its ability to suppress hunger and increase fullness (Sørensen et al. 2008). Olestra is a sucrose polyester, in which the ester bonds are not hydrolysed by lipase in the human GIT because of steric hindrance effects. As a result, Olestra is not absorbed by the body and is specially designed to be a zero-calorie fat substitute to replace triglyceride oils in products such as fried foods, snacks, breads, and fillings (Bimal and Guonong 2006). However, Olestra may disturb the absorption of fat-soluble vitamins and may be linked to undesirable GIT symptoms, so its used amount is limited by FDA (Prince and Welschenbach 1998).

Table 12.1 Commercially available fat replacers and their applications

Fat replacer	Trade name	Applications	Functions
Protein-based (microparticulated protein, modified whey protein concentrate)	Simplesse, Dairy Lois, K-Blazer, Veri-lo, Power-pro, Versapro, Ultra-Baketm, Ultra-Freezetm, Lita	Dairy products, salad-dressing, margarine- and mayonnaise-type products, baked goods, coffee creamer, soups, and sauces	Mouthfeel, creaminess, viscosity
Lipid-based	Caprenin, Salatrim, Dur-Lo, ECT-25, Olestra	Confections, baked goods, dairy products	Mouthfeel, stability
Cellulose	Avicel cellulose gel, Methocel, Solka-Floc, Just Fiber	Dairy products, sauces, frozen desserts, salad dressings	Water retention, texturizer, stabilizer, mouthfeel, clouding agents
Dextrins	Amylum, N-Oil, Stadex	Salad dressings, puddings, spreads, dairy products, frozen desserts	Gelling, thickening, stabilizing, texturizer
Maltodextrins	CrystaLean, Lorelite, Lycadex, Malitrin, Oatrim, Stadex, nu-trim	Baked goods, dairy products, salad dressings, sauces, spreads, frostings, fillings, beverages	Gelling, thickening, stabilizing, texturizer
Gums (guar gum, gum arabic, locust bean gum, xanthan gum, carrageenan, pectin)	Kelcogel, Keltrol, Viscarin, Novagel, Jaguar, Fibrex, Slendid, Splendid, Grindsted	Salad dressings, formulated foods such as desserts and processed meats	Water retention, texturizer, thickener, mouthfeel, gelling, stabilizer
Inulin	Raftiline, Fruitafit, Fibruline	Yoghurt, cheese, frozen desserts, baked goods, fillings, whipped cream, fibre supplements	
Fibre	Opta TM, Oat Fiber, Snowite, Ultracel TM, Z-Trim	Baked goods, meats, spreads, extruded products	Heat stable
Starch and modified starch	Amalean I and II, N-Lite, Fairnex TMVA15 and VA 20, Instant StellarTM, Pure-Gel, Sta-SlimiTM, OptaGread	Dairy products, processed meats, salad dressings, baked goods, frozen desserts	Bodying agents, gelling, thickening, texture modifiers

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6 Future Perspective

Nowadays, healthiness and beauty are common interests among people. Reducing calorie consumption is a major goal for the consumer. Consequently, both food manufactures and researchers are sparing no effort to develop reduced-fat/starch food products. The key point is that the replacement of fat or starch should contribute low or even zero calorie to food products and should be nondetrimental to their organoleptic qualities.

Many low-fat products have been based on the use of a wide variety of biopolymers, especially hydrocolloids. More basic knowledge of physical, rheological, chemical, and sensory characteristics, functionality, and fat or starch interactions with other ingredients is required as to formulating these bases. Further studies are needed on new food-grade ingredients as potential replacers of fat or starch. Other approaches are available based upon the use of manufacturing and preparation procedures that can help to achieve desired product properties such as colour, texture, and water- and fat-holding abilities. A thorough understanding of the physicochemical properties and molecular interactions of food-grade ingredients is necessary for developing innovative fat reduction strategies such as utilizing structural design approach to control the macroscopic properties.

Currently, the consumer's unwillingness to give up high-energy foods suggests that there is a considerable potential market for frequently consumed foods such as meats which have been reformulated to produce health benefits. It is believed that in near future, people would adapt to a low-fat or low-starch diet based on the development of novel advanced technologies for the replacement of fat or starch.

References

Abbasi E, Amini Sarteshnizi R, Ahmadi Gavlighi H, Nikoo M, Azizi MH, Sadeghinejad N (2019) Effect of partial replacement of fat with added water and tragacanth gum (Astragalus gossypinus and Astragalus compactus) on the physicochemical, texture, oxidative stability, and sensory property of reduced fat emulsion type sausage. Meat Sci 147:135–143. https://doi.org/10.1016/j.meatsci.2018.09.007

Ai Y, Jane JL (2015) Gelatinization and rheological properties of starch. Starch-Stärke 67:213–224. https://doi.org/10.1002/star.201400201

Aiking H (2011) Future protein supply. Trends Food Sci Technol 22(2–3):112–120. https://doi.org/10.1016/j.tifs.2010.04.005

Akalın AS, Karagözlü C, Ünal G (2008) Rheological properties of reduced-fat and low-fat ice cream containing whey protein isolate and inulin. Eur Food Res Technol 227(3):889–895. https://doi.org/10.1007/s00217-007-0800-z

Alexander RJ (1995) Fat replacers based on starch. Cereal Foods World 40(5):249–262. https://doi.org/10.1021/bp00033a016

Alnemr T, Helal A, Hassan A, Elsaadany K (2016) Utilizing the functions of hydrocolloids as fat mimetic to enhance the properties of low-fat domiati cheese. J Food Process Technol 7(11):637. https://doi.org/10.4172/2157-7110.1000637

Alting AC, Van de Velde F, Kanning MW, Burgering M, Mulleners L, Sein A, Buwalda P (2009) Improved creaminess of low-fat yoghurt: the impact of amylomaltase-treated starch domains. Food Hydrocoll 23(3):980–987. https://doi.org/10.1016/j.foodhyd.2008.07.011

Anvari M, Joyner HS (2018) Concentrated emulsions as novel fat replacers in reduced-fat and low-fat Cheddar cheeses. Part 1. Rheological and microstructural characterization. Int Dairy J 86:76–85. https://doi.org/10.1016/j.idairyj.2018.06.017

Aziz NS, Sofian-Seng N-S, Yusop SM, Kasim KF, Mohd Razali NS (2018) Functionality of okra gum as a novel carbohydrate-based fat replacer in ice cream. Food Sci Technol Res 24(3):519–530. https://doi.org/10.3136/fstr.24.519

Bayarri S, González-Tomás LU, Hernando I, Lluch MA, Costell E (2011) Texture perceived on inulin-enriched low-fat semisolid dairy desserts. Rheological and structural basis. J Texture Stud 42(3):174–184. https://doi.org/10.1111/j.1745-4603.2010.00280.x

Belc N, Smeu I, Macri A, Vallauri D, Flynn K (2019) Reformulating foods to meet current scientific knowledge about salt, sugar and fats. Trends Food Sci Technol 84:25–28. https://doi.org/10.1016/j.tifs.2018.11.002

BeMiller JN (2011) Pasting, paste, and gel properties of starch–hydrocolloid combinations. Carbohydr Polym 86(2):386–423. https://doi.org/10.1016/j.carbpol.2011.05.064

Bimal C, Guonong Z (2006) Olestra: a solution to food fat? Food Rev Intl 22(3):245–258. https://doi.org/10.1080/87559120600694705

Bravo-Núñez Á, Pando V, Gómez M (2019) Physically and chemically modified starches as texturisers of low-fat milk gels. Int Dairy J 92:21–27. https://doi.org/10.1016/j.idairyj.2019.01.007

Bray GA, Paeratakul S, Popkin BM (2004) Dietary fat and obesity: a review of animal, clinical and epidemiological studies. Physiol Behav 83(4):549–555. https://doi.org/10.1016/j.physbeh.2004.08.039

Campbell CL, Wagoner TB, Foegeding EA (2017) Designing foods for satiety: the roles of food structure and oral processing in satiation and satiety. Food Struct 13:1–12. https://doi.org/10.1016/j.foostr.2016.08.002

Chugh B, Singh G, Kumbhar BK (2013) Development of low-fat soft dough biscuits using carbohydrate-based fat replacers. Int J Food Sci 2013:1–12. https://doi.org/10.1155/2013/576153

Chung C, McClements DJ (2014) Structure–function relationships in food emulsions: improving food quality and sensory perception. Food Struct 1(2):106–126. https://doi.org/10.1016/j.foostr.2013.11.002

Chung C, McClements DJ (2015) Controlling microstructure and physical properties of biopolymer hydrogel particles through modulation of electrostatic interactions. J Food Eng 158:13–21. https://doi.org/10.1016/j.jfoodeng.2015.02.028

Chung C, Degner B, McClements DJ (2013a) Physicochemical characteristics of mixed colloidal dispersions: models for foods containing fat and starch. Food Hydrocoll 30(1):281–291. https://doi.org/10.1016/j.foodhyd.2012.06.008

Chung C, Degner B, McClements DJ (2013b) Designing reduced-fat food emulsions: locust bean gum–fat droplet interactions. Food Hydrocoll 32(2):263–270. https://doi.org/10.1016/j.foodhyd.2013.01.008

Chung C, Degner B, McClements DJ (2014) Development of reduced-calorie foods: microparticulated whey proteins as fat mimetics in semi-solid food emulsions. Food Res Int 56:136–145

Chung C, Smith G, Degner B, McClements DJ (2016) Reduced fat food emulsions: physicochemical, sensory, and biological aspects. Crit Rev Food Sci Nutr 56(4):650–685. https://doi.org/10.1080/10408398.2013.792236

Co ED, Marangoni AG (2012) Organogels: an alternative edible oil-structuring method. J Am Oil Chem Soc 89(5):749–780. https://doi.org/10.1007/s11746-012-2049-3

Colmenero FJ (2000) Relevant factors in strategies for fat reduction in meat products. Trends Food Sci Technol 11(2):56–66. https://doi.org/10.1016/S0924-2244(00)00042-X

Copeland L, Blazek J, Salman H, Tang MC (2009) Form and functionality of starch. Food Hydrocoll 23(6):1527–1534. https://doi.org/10.1016/j.foodhyd.2008.09.016

Dai S, Jiang F, Corke H, Shah NP (2018) Physicochemical and textural properties of mozzarella cheese made with konjac glucomannan as a fat replacer. Food Res Int 107:691–699. https://doi.org/10.1016/j.foodres.2018.02.069

Dai S, Jiang F, Shah NP, Corke H (2019) Functional and pizza bake properties of Mozzarella cheese made with konjac glucomannan as a fat replacer. Food Hydrocoll 92:125–134. https://doi.org/10.1016/j.foodhyd.2019.01.045

de Roos KB (2006) How lipids influence flavor perception. In: Food lipids, vol 920. American Chemical Society Publications, Washington, DC, pp 145–158. https://doi.org/10.1021/bk-2005-0920.ch012

De Ruiter GA, Rudolph B (1997) Carrageenan biotechnology. Trends Food Sci Technol 8 (12):389–395. https://doi.org/10.1016/s0924-2244(97)01091-1

de Souza Paglarini C, de Figueiredo Furtado G, Honório AR, Mokarzel L, da Silva Vidal VA, Ribeiro APB, Cunha RL, Pollonio MAR (2019) Functional emulsion gels as pork back fat replacers in Bologna sausage. Food Struct 20:100105. https://doi.org/10.1016/j.foostr.2019.100105

DeSalvo KB, Olson R, Casavale KO (2016) Dietary guidelines for Americans. JAMA 315 (5):457–458. https://doi.org/10.1001/jama.2015.18396

Diamantino VR, Beraldo FA, Sunakozawa TN, Penna ALB (2014) Effect of octenyl succinylated waxy starch as a fat mimetic on texture, microstructure and physicochemical properties of Minas fresh cheese. LWT Food Sci Technol 56(2):356–362. https://doi.org/10.1016/j.lwt.2013.12.001

Diamantino VR, Costa MS, Taboga SR, Vilamaior PSL, Franco CML, Penna ALB (2019) Starch as a potential fat replacer for application in cheese: behaviour of different starches in casein/starch mixtures and in the casein matrix. Int Dairy J 89:129–138. https://doi.org/10.1016/j.idairyj.2018.08.015

Dickinson E (2011) Double emulsions stabilized by food biopolymers. Food Biophys 6(1):1–11. https://doi.org/10.1007/s11483-010-9188-6

Dolz M, Hernandez MJ, Delegido J (2006) Oscillatory measurements for salad dressings stabilized with modified starch, xanthan gum, and locust bean gum. J Appl Polym Sci 102(1):897–903. https://doi.org/10.1002/app.24125

Duval S, Chung C, McClements DJ (2015) Protein-polysaccharide hydrogel particles formed by biopolymer phase separation. Food Biophys 10(3):334–341. https://doi.org/10.1007/s11483-015-9396-1

Eisinaite V, Juraite D, Schroën K, Leskauskaite D (2017) Food-grade double emulsions as effective fat replacers in meat systems. J Food Eng 213:54–59. https://doi.org/10.1016/j.jfoodeng.2017.05.022

Engelen L, de Wijk RA (2012) Oral processing and texture perception. In: Food oral processing: fundamentals of eating and sensory perception. Wiley-Blackwell, Oxford, pp 159–176. https://doi.org/10.1002/9781444360943.ch8

Engelen L, Van Der Bilt A, Schipper M, Bosman F (2005) Oral size perception of particles: effect of size, type, viscosity and method. J Texture Stud 36(4):373–386. https://doi.org/10.1111/j.1745-4603.2005.00022.x

Fischer N, Widder S (1997) How proteins influence food flavor. Food Technol 51(1):68–70. https://doi.org/10.1177/108201329700300608

Food Standards Agency (2008) Saturated fat and energy intake programme. http://www.food.gov.uk/multimedia/pdfs/satfatprog

Francis FP, Ramalingam C (2019) Hybrid hydrogel dispersed low fat and heat resistant chocolate. J Food Eng 256:9–17. https://doi.org/10.1016/j.jfoodeng.2019.03.012

Freire M, Cofrades S, Pérez-Jiménez J, Gómez-Estaca J, Jiménez-Colmenero F, Bou R (2018) Emulsion gels containing n-3 fatty acids and condensed tannins designed as functional fat replacers. Food Res Int 113:465–473. https://doi.org/10.1016/j.foodres.2018.07.041

Friedman M, Brandon DL (2001) Nutritional and health benefits of soy proteins. J Agric Food Chem 49(3):1069–1086. https://doi.org/10.1021/jf0009246

Funami T (2009) Functions of food polysaccharides to control the gelatinization and retrogradation behaviors of starch in an aqueous system in relation to the macromolecular characteristics of food polysaccharides. Food Sci Technol Res 15:557–568. https://doi.org/10.3136/fstr.15.557

Gałkowska D, Juszczak L (2019) Effects of amino acids on gelatinization, pasting and rheological properties of modified potato starches. Food Hydrocoll 92:143–154. https://doi.org/10.1016/j.foodhyd.2019.01.063

Gao XQ, Kang ZL, Zhang WG, Li YP, Zhou GH (2015) Combination of κ-carrageenan and soy protein isolate effects on functional properties of chopped low-fat pork batters during heat-induced gelation. Food Bioprocess Technol 8(7):1524–1531. https://doi.org/10.1007/s11947-015-1516-x

Gentès MC, St-Gelais D, Turgeon SL (2010) Stabilization of whey protein isolate-pectin complexes by heat. J Agric Food Chem 58(11):7051–7058. https://doi.org/10.1021/jf100957b

Gibis M, Schuh V, Weiss J (2015) Effects of carboxymethyl cellulose (CMC) and microcrystalline cellulose (MCC) as fat replacers on the microstructure and sensory characteristics of fried beef patties. Food Hydrocoll 45:236–246. https://doi.org/10.1016/j.foodhyd.2014.11.021

Godshall MA (1997) How carbohydrates influence food flavor. Food Technol 51:63–67. https://doi.org/10.1177/108201329700300608

González-Tomás L, Bayarri S, Taylor AJ, Costell E (2008) Rheology, flavour release and perception of low-fat dairy desserts. Int Dairy J 18(8):858–866. https://doi.org/10.1016/j.idairyj.2007.09.010

Guichard E (2002) Interactions between flavor compounds and food ingredients and their influence on flavor perception. Food Rev Intl 18(1):49–70. https://doi.org/10.1081/FRI-120003417

Gulão EDS, de Souza CJ, Andrade CT, Garcia-Rojas EE (2016) Complex coacervates obtained from peptide leucine and gum arabic: formation and characterization. Food Chem 194:680–686. https://doi.org/10.1016/j.foodchem.2015.08.062

Hahn NI (1997) Replacing fat with food technology. J Acad Nutr Diet 97(1):15–16. https://doi.org/10.1016/S0002-8223(97)00007-2

Han SH, Nicholls SJ, Sakuma I, Zhao D, Koh KK (2016) Hypertriglyceridemia and cardiovascular diseases: revisited. Korean Circ J 46:135–144. https://doi.org/10.4070/kcj.2016.46.2.135

Hanselmann R, Burchard W, Ehrat M, Widmer HM (1996) Structural properties of fractionated starch polymers and their dependence on the dissolution process. Macromolecules 29:3277–3282. https://doi.org/10.1021/ma951452c

Hedayati S, Niakousari M (2018) Microstructure, pasting and textural properties of wheat starch-corn starch citrate composites. Food Hydrocoll 81:1–5. https://doi.org/10.1016/j.foodhyd.2018.02.024

Henry J (2009) Processing, manufacturing, uses and labeling of fats in the food supply. Ann Nutr Metab 55(1–3):273–300. https://doi.org/10.1159/000229006

Hu Y, Li C, Regenstein JM, Wang L (2019) Preparation and properties of potato amylose-based fat replacer using super-heated quenching. Carbohydr Polym 223:115020. https://doi.org/10.1016/j.carbpol.2019.115020

Huc D, Matignon A, Barey P, Desprairies M, Mauduit S, Sieffermann JM, Michon C (2014) Interactions between modified starch and carrageenan during pasting. Food Hydrocoll 36:355–361. https://doi.org/10.1016/j.foodhyd.2013.08.023

Javidi F, Razavi SMA, Behrouzian F, Alghooneh A (2016) The influence of basil seed gum, guar gum and their blend on the rheological, physical and sensory properties of low fat ice cream. Food Hydrocoll 52:625–633. https://doi.org/10.1016/j.foodhyd.2015.08.006

Javidi F, Razavi SMA, Mohammad Amini A (2019) Corn starch nanocrystals as a potential fat replacer in reduced fat O/W emulsions: a rheological and physical study. Food Hydrocoll 90:172–181. https://doi.org/10.1016/j.foodhyd.2018.12.003

Jiang Y, Liu L, Wang B, Sui X, Zhong Y, Zhang L, Mao Z, Xu H (2018) Cellulose-rich oleogels prepared with an emulsion-templated approach. Food Hydrocoll 77:460–464. https://doi.org/10.1016/j.foodhyd.2017.10.023

Jimenez-Colmenero F, Salcedo-Sandoval L, Bou R, Cofrades S, Herrero AM, Ruiz-Capillas C (2015) Novel applications of oil-structuring methods as a strategy to improve the fat content of meat products. Trends Food Sci Technol 44(2):177–188. https://doi.org/10.1016/j.tifs.2015.04.011

Jing H, Yap M, Wong PY, Kitts DD (2011) Comparison of physicochemical and antioxidant properties of egg-white proteins and fructose and inulin Maillard reaction products. Food Bioprocess Technol 4(8):1489–1496. https://doi.org/10.1007/s11947-009-0279-7

Johnson ME (2011) Cheese: low-fat and reduced-fat cheese. In: Encyclopedia of dairy science. Academic Press, New York, pp 833–842. https://doi.org/10.1016/B978-0-12-374407-4.00098-4

Karaca OB, Güven M, Yasar K, Kaya S, Kahyaoglu T (2009) The functional, rheological and sensory characteristics of ice creams with various fat replacers. Int J Dairy Technol 62(1):93–99. https://doi.org/10.1111/j.1471-0307.2008.00456.x

Kaur N, Gupta AK (2002) Applications of inulin and oligofructose in health and nutrition. J Biosci 27(7):703–714. https://doi.org/10.1007/BF02708379

Kavas G, Oysun G, Kinik O, Uysal H (2004) Effect of some fat replacers on chemical, physical and sensory attributes of low-fat white pickled cheese. Food Chem 88(3):381–388. https://doi.org/10.1016/j.foodchem.2004.01.054

Keenan DF, Resconi V, Kerry JP, Hamill RM (2014) Modelling the influence of inulin as a fat substitute in comminuted meat products on their physico-chemical characteristics and eating quality using a mixture design approach. Meat Sci 96(3):1384–1394. https://doi.org/10.1016/j.meatsci.2013.11.025

Khanal BKS, Bhandari B, Prakash S, Liu D, Zhou P, Bansal N (2018) Modifying textural and microstructural properties of low fat Cheddar cheese using sodium alginate. Food Hydrocoll 83:97–108. https://doi.org/10.1016/j.foodhyd.2018.03.015

Khanal BKS, Budiman C, Hodson MP, Plan MR, Prakash S, Bhandari B, Bansal N (2019) Physicochemical and biochemical properties of low fat Cheddar cheese made from micron to nano sized milk fat emulsions. J Food Eng 242:94–105. https://doi.org/10.1016/j.jfoodeng.2018.08.019

Khouryieh HA, Aramouni FM, Herald TJ (2005) Physical and sensory characteristics of no-sugar-added/low-fat muffin. J Food Qual 28(5–6):439–451. https://doi.org/10.1111/j.1745-4557.2005.00047.x

Kim JY, Lim J, Lee J, Hwang HS, Lee S (2017) Utilization of oleogels as a replacement for solid fat in aerated baked goods: physicochemical, rheological, and tomographic characterization. J Food Sci 82(2):445–452. https://doi.org/10.1111/1750-3841.13583

Kouzounis D, Lazaridou A, Katsanidis E (2017) Partial replacement of animal fat by oleogels structured with monoglycerides and phytosterols in frankfurter sausages. Meat Sci 130:38–46. https://doi.org/10.1016/j.meatsci.2017.04.004

Krzeminski A, Prell KA, Busch-Stockfisch M, Weiss J, Hinrichs J (2014) Whey protein–pectin complexes as new texturising elements in fat-reduced yoghurt systems. Int Dairy J 36 (2):118–127. https://doi.org/10.1016/j.idairyj.2014.01.018

Kühn J, Considine T, Singh H (2006) Interactions of milk proteins and volatile flavor compounds: implications in the development of protein foods. J Food Sci 71(5):72–82. https://doi.org/10.1111/j.1750-3841.2006.00051.x

Laguna L, Primo-Martín C, Varela P, Salvador A, Sanz T (2014) HPMC and inulin as fat replacers in biscuits: sensory and instrumental evaluation. LWT Food Sci Technol 56(2):494–501. https://doi.org/10.1016/j.lwt.2013.12.025

Lascombes C, Agoda-Tandjawa G, Boulenguer P, Le Garnec C, Gilles M, Mauduit S, Barey P, Langendorff V (2017) Starch-carrageenan interactions in aqueous media: role of each polysaccharide chemical and macromolecular characteristics. Food Hydrocoll 66:176–189. https://doi.org/10.1016/j.foodhyd.2016.11.025

Lashkari H, Madadlou A, Alizadeh M (2014) Chemical composition and rheology of low-fat Iranian white cheese incorporated with guar gum and gum arabic as fat replacers. J Food Sci Technol 51(10):2584–2591. https://doi.org/10.1007/s13197-012-0768-y

Le XT, Rioux LE, Turgeon SL (2017) Formation and functional properties of protein-polysaccharide electrostatic hydrogels in comparison to protein or polysaccharide hydrogels. Adv Colloid Interf Sci 239:127–135. https://doi.org/10.1016/j.cis.2016.04.006

Li H, Lei N, Yan S, Yang J, Yu T, Wen Y, Wang J, Sun B (2019) The importance of amylopectin molecular size in determining the viscoelasticity of rice starch gels. Carbohydr Polym 212:112–118. https://doi.org/10.1016/j.carbpol.2019.02.043

Liu J, Xu B (2019) A comparative study on texture, gelatinisation, retrogradation and potential food application of binary gels made from selected starches and edible gums. Food Chem 296:100–108. https://doi.org/10.1016/j.foodchem.2019.05.193

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

Liu X, Guo J, Wan Z-L, Liu Y-Y, Ruan Q-J, Yang X-Q (2018b) Wheat gluten-stabilized high internal phase emulsions as mayonnaise replacers. Food Hydrocoll 77:168–175. https://doi.org/10.1016/j.foodhyd.2017.09.032

Liu S, Lin L, Shen M, Wang W, Xiao Y, Xie J (2018c) Effect of Mesona chinensis polysaccharide on the pasting, thermal and rheological properties of wheat starch. Int J Biol Macromol 118:945–951. https://doi.org/10.1016/j.ijbiomac.2018.06.178

Liu D, Li Z, Fan Z, Zhang X, Zhong G (2019) Effect of soybean soluble polysaccharide on the pasting, gels, and rheological properties of kudzu and lotus starches. Food Hydrocoll 89:443–452. https://doi.org/10.1016/j.foodhyd.2018.11.003

Lobato-Calleros C, Sosa-Perez A, Rodriquez-Tafoya J, Sandoval-Castilla O, Perez-Alonso C, Vernon-Carter EJ (2008) Structural and textural characteristics of reduced-fat cheese-like products made from W1/O/W2 emulsions and skim milk. LWT Food Sci Technol 41:1847–1856. https://doi.org/10.1016/j.lwt.2008.01.006

Luo D, Li Y, Xu B, Ren G, Li P, Li X, Ren G, Li P, Li X, Han S, Liu J (2017) Effects of inulin with different degree of polymerization on gelatinization and retrogradation of wheat starch. Food Chem 229:35–43. https://doi.org/10.1016/j.foodchem.2017.02.058

Lustig RH, Schmidt LA, Brindis CD (2012) Public health: the toxic truth about sugar. Nature 482:27–29. https://doi.org/10.1038/482027a

Ma S, Zhu P, Wang M (2019) Effects of konjac glucomannan on pasting and rheological properties of corn starch. Food Hydrocoll 89:234–240. https://doi.org/10.1016/j.foodhyd.2018.10.045

Mahmood K, Kamilah H, Shang PL, Sulaiman S, Ariffin F, Alias AK (2017) A review: interaction of starch/non-starch hydrocolloid blending and the recent food applications. Food Biosci 19:110–120. https://doi.org/10.1016/j.fbio.2017.05.006

Maier HG (1970) Volatile flavoring substances in foodstuffs. Angew Chem Int Ed Engl 9 (12):917–926. https://doi.org/10.1002/anie.197009171

Majeed M, Anwar S, Khan MU, Asghar A, Shariati MA, Semykin V, Fazel M (2017) Study of the combined effect of pectin and banana powder as carbohydrate based fat replacers to develop low fat cookies. Foods Raw Mater 5(2):62–69. https://doi.org/10.21603/2308-4057-2017-2-62-69

Majzoobi M, Mohammadi M, Mesbahi G, Farahnaky A (2018) Feasibility study of sucrose and fat replacement using inulin and rebaudioside A in cake formulations. J Texture Stud 49 (5):468–475. https://doi.org/10.1111/jtxs.12330

Malone M, Appelqvist I, Norton I (2003) Oral behaviour of food hydrocolloids and emulsions. Part 1. Lubrication and deposition considerations. Food Hydrocoll 17(6):763–773. https://doi.org/10.1016/S0268-005X(03)00097-3

Mao Y, McClements DJ (2011) Modulation of bulk physicochemical properties of emulsions by hetero-aggregation of oppositely charged protein-coated lipid droplets. Food Hydrocoll 25 (5):1201–1209. https://doi.org/10.1016/j.foodhyd.2010.11.007

Mao Y, McClements DJ (2012) Modulation of emulsion rheology through electrostatic heteroaggregation of oppositely charged lipid droplets: influence of particle size and emulsifier content. J Colloid Interface Sci 380:60–66. https://doi.org/10.1016/j.jcis.2012.05.007

Mao Y, McClements DJ (2013) Modulation of food texture using controlled heteroaggregation of lipid droplets: principles and applications. J Appl Polym Sci 130(6):3833–3841. https://doi.org/10.1002/app.39631

Matia-Merino L, Prieto M, Roman L, Gómez M (2019) The impact of basil seed gum on native and pregelatinized corn flour and starch gel properties. Food Hydrocoll 89:122–130. https://doi.org/10.1016/j.foodhyd.2018.10.005

Mattes RD (1998) Position of the American Dietetic Association: fat replacers. J Am Diet Assoc 98:463–468. https://doi.org/10.1016/s0002-8223(98)00105-9

McClements DJ (2015) Reduced-fat foods: the complex science of developing diet-based strategies for tackling overweight and obesity. Adv Nutr 6(3):338S–352S. https://doi.org/10.3945/an.114.006999

McClements DJ, Demetriades K (1998) An integrated approach to the development of reduced-fat food emulsions. Crit Rev Food Sci Nutr 38(6):511–536. https://doi.org/10.1080/10408699891274291

McClements DJ, Chung C, Wu BC (2017) Structural design approaches for creating fat droplet and starch granule mimetics. Food Funct 8(2):498–510. https://doi.org/10.1039/c6fo00764c

Mejia SMV, de Francisco A, Barreto PLM, Damian C, Zibetti AW, Mahecha HS, Bohrer BM (2018) Incorporation of β-glucans in meat emulsions through an optimal mixture modeling systems. Meat Sci 143:210–218. https://doi.org/10.1016/j.meatsci.2018.05.007

Mejia SMV, de Francisco A, Bohrer BM (2019) Replacing starch in beef emulsion models with β-glucan, microcrystalline cellulose, or a combination of β-glucan and microcrystalline cellulose. Meat Sci 153:58–65. https://doi.org/10.1016/j.meatsci.2019.03.012

Menegas LZ, Pimentel TC, Garcia S, Prudencio SH (2013) Dry-fermented chicken sausage produced with inulin and corn oil: physicochemical, microbiological, and textural characteristics and acceptability during storage. Meat Sci 93(3):501–506. https://doi.org/10.1016/j.meatsci.2012.11.003

Metcalf KL, Vickers ZM (2002) Taste intensities of oil-in-water emulsions with varying fat content. J Sens Stud 17:379–390. https://doi.org/10.1111/j.1745-459X.2002.tb00354.x

Murtaza MS, Sameen A, Huma N, Hussain F (2017) Influence of hydrocolloid gums on textural, functional and sensory properties of low fat cheddar cheese from buffalo milk. Pak J Zool 49 (1):27–34. https://doi.org/10.17582/journal.pjz/2017.49.1.27.34

Norton IT, Frith WJ, Ablett S (2006) Fluid gels, mixed fluid gels and satiety. Food Hydrocoll 20:229–239. https://doi.org/10.1016/j.foodhyd.2004.03.011

O'Connor TP, O'Brien NM (2011) Butter and other milk fat products fat replacers. In: Encyclopedia of dairy science. Academic Press, New York, pp 528–532. https://doi.org/10.1016/B978-0-12-374407-4.00330-7

Oh I, Lee J, Lee HG, Lee S (2019) Feasibility of hydroxypropyl methylcellulose oleogel as an animal fat replacer for meat patties. Food Res Int 122:566–572. https://doi.org/10.1016/j.foodres.2019.01.012

Okesola BO, Vieira VM, Cornwell DJ, Whitelaw NK, Smith DK (2015) 1,3:2,4-Dibenzylidene-D-sorbitol (DBS) and its derivatives-efficient, versatile and industrially-relevant low-molecular-weight gelators with over 100 years of history and a bright future. Soft Matter 11 (24):4768–4787. https://doi.org/10.1039/C5SM00845J

Olivares ML, Shahrivar K, de Vicente J (2019) Soft lubrication characteristics of microparticulated whey proteins used as fat replacers in dairy systems. J Food Eng 245:157–165. https://doi.org/10.1016/j.jfoodeng.2018.10.015

Parada J, Aguilera JM (2011) Starch matrices and the glycemic response. Food Sci Technol Int 17 (3):187–204. https://doi.org/10.1177/1082013210387712

Patel AR, Dewettinck K (2016) Edible oil structuring: an overview and recent updates. Food Funct 7(1):20–29. https://doi.org/10.1039/c5fo01006c

Peng X, Yao Y (2017) Carbohydrates as fat replacers. Annu Rev Food Sci Technol 8(1):331–351. https://doi.org/10.1146/annurev-food-030216-030034

Plug H, Haring P (1994) The influence of flavour-ingredient interactions on flavour perception. Food Qual Prefer 5:95–102. https://doi.org/10.1016/0950-3293(94)90013-2

Pongsawatmanit R, Chantaro P, Nishinari K (2013) Thermal and rheological properties of tapioca starch gels with and without xanthan gum under cold storage. J Food Eng 117:333–341. https://doi.org/10.1016/j.jfoodeng.2013.03.010

Prince DM, Welschenbach MA (1998) Olestra: a new food additive. J Am Diet Assoc 98:565–569. https://doi.org/10.1016/S0002-8223(98)00126-6

Prinz JF, Huntjens LAH, de Wijk RA, Engelen L, Polet IA (2007) Is fat perception a thermal effect? Percept Mot Skills 104(2):381–386. https://doi.org/10.2466/PMS.104.2.381-386

Psimouli V, Oreopoulou V (2013) The effect of fat replacers on batter and cake properties. J Food Sci 78(10):C1495–C1502. https://doi.org/10.1111/1750-3841.12235

Punia S, Siroha AK, Sandhu KS, Kaur M (2019) Rheological and pasting behavior of OSA modified mungbean starches and its utilization in cake formulation as fat replacer. Int J Biol Macromol 128:230–236. https://doi.org/10.1016/j.ijbiomac.2019.01.107

Qu B, Zhong Q (2017) Casein-maltodextrin conjugate as an emulsifier for fabrication of structured calcium carbonate particles as dispersible fat globule mimetics. Food Hydrocoll 66:61–70. https://doi.org/10.1016/j.foodhyd.2016.12.022

Raguzzoni JC, Delgadillo I, da Silva JAL (2016) Influence of a cationic polysaccharide on starch functionality. Carbohydr Polym 150:369–377. https://doi.org/10.1016/j.carbpol.2016.05.024

Rahmati NF, Tehrani MM, Daneshvar K, Koocheki A (2015) Influence of selected gums and pregelatinized corn starch on reduced fat mayonnaise: modeling of properties by central composite design. Food Biophys 10(1):39–50. https://doi.org/10.1007/s11483-014-9356-1

Rao MA (2014) Rheology of fluid, semisolid, and solid foods. Springer, Boston, MA, pp 161–229. https://doi.org/10.1021/jf025646k

Roberts DD, Pollien P, Watzke B (2003) Experimental and modeling studies showing the effect of lipid type and level on flavor release from milk-base liquid emulsions. J Agric Food Chem 51:189–195. https://doi.org/10.1021/jf025646k

Rudra SG, Nath P, Kaur C, Basu S (2017) Rheological, storage stability and sensory profiling of low-fat yoghurt fortified with red capsicum carotenoids and inulin. J Food Process Preserv 41 (4):e13067–e13076. https://doi.org/10.1111/jfpp.13067

Saha D, Bhattacharya S (2010) Hydrocolloids as thickening and gelling agents in food: a critical review. J Food Sci Technol 47(6):587–597. https://doi.org/10.1007/s13197-010-0162-6

Salcedo-Sandoval L, Cofrades S, Ruiz-Capillas C, Carballo J, Jiménez-Colmenero F (2015) Konjac-based oil bulking system for development of improved-lipid pork patties: technological, microbiological and sensory assessment. Meat Sci 101:95–102. https://doi.org/10.1016/j.meatsci.2014.11.010

Saleh M, Al-Baz F, Al-Ismail K (2018) Effects of hydrocolloids as fat replacers on the physicochemical properties of produced Labneh. J Texture Stud 49(1):113–120. https://doi.org/10.1111/jtxs.12296

Salvatore E, Pes M, Mazzarello V, Pirisi A (2014) Replacement of fat with long-chain inulin in a fresh cheese made from caprine milk. Int Dairy J 34(1):1–5. https://doi.org/10.1016/j.idairyj.2013.07.007

Sandrou DK, Arvanitoyannis IS (2000) Low-fat/calorie foods: current state and perspectives. Crit Rev Food Sci Nutr 40(5):427–447. https://doi.org/10.1080/10408690091189211

Sarkar S, Gupta S, Variyar PS, Sharma A, Singhal RS (2013) Hydrophobic derivatives of guar gum hydrolyzate and gum arabic as matrices for microencapsulation of mint oil. Carbohydr Polym 95 (1):177–182. https://doi.org/10.1016/j.carbpol.2013.02.070

Schuh V, Allard K, Herrmann K, Gibis M, Kohlus R, Weiss J (2013) Impact of carboxymethyl cellulose (CMC) and microcrystalline cellulose (MCC) on functional characteristics of emulsified sausages. Meat Sci 93(2):240–247. https://doi.org/10.1016/j.meatsci.2012.08.025

Serdaroğlu M, Öztürk B, Urgu M (2016) Emulsion characteristics, chemical and textural properties of meat systems produced with double emulsions as beef fat replacers. Meat Sci 117:187–195. https://doi.org/10.1016/j.meatsci.2016.03.012

Shoaib M, Shehzad A, Omar M, Rakha A, Raza H, Sharif HR, Shakeel A, Ansari A, Niazi S (2016) Inulin: properties, health benefits and food applications. Carbohydr Polym 147:444–454. https://doi.org/10.1016/j.carbpol.2016.04.020

Sikora M, Badrie N, Deisingh AK, Kowalski S (2008) Sauces and dressings: a review of properties and applications. Crit Rev Food Sci Nutr 48(1):50–77. https://doi.org/10.1080/10408390601079934

Singh J, Lelane C, Stewart RB, Singh H (2010) Formation of starch spherulites: role of amylose content and thermal events. Food Chem 121(4):980–989. https://doi.org/10.1016/j.foodchem.2010.01.032

Siraj N, Shabbir MA, Ahmad T, Sajjad A, Khan MR, Khan MI, Butt MS (2015) Organogelators as a saturated fat replacer for structuring edible oils. Int J Food Prop 18(9):1973–1989. https://doi.org/10.1080/10942912.2014.951891

Smith RE, Finley JW, Leveille GA (1994) Overview of SALATRIM: a family of low-calorie fats. J Agric Food Chem 42(2):432–434. https://doi.org/10.1021/jf00038a036

Sørensen LB, Cueto HT, Andersen MT, Bitz C, Holst JJ, Rehfeld JF, Astrup A (2008) The effect of salatrim, a low-calorie modified triacylglycerol, on appetite and energy intake. Am J Clin Nutr 87(5):1163–1169. https://doi.org/10.1039/b518127e

Spence C (2015) Multisensory flavor perception. Cell 161(1):24–35. https://doi.org/10.1016/j.cell.2015.03.007

Steeneken PA, Woortman AJ (2009) Superheated starch: a novel approach towards spreadable particle gels. Food Hydrocoll 23(2):394–405. https://doi.org/10.1016/j.foodhyd.2008.01.006

Stokes JR, Macakova L, Chojnicka-Paszu A, de Kruif CG, de Jongh HHJ (2011) Lubrication, adsorption, and rheology of aqueous polysaccharide solutions. Langmuir 27:3474–3484. https://doi.org/10.1021/la104040d

Su HP, Lien CP, Lee TA, Ho JH (2010) Development of low-fat mayonnaise containing polysaccharide gums as functional ingredients. J Sci Food Agric 90(5):806–812. https://doi.org/10.1002/jsfa.3888

Sun C, Wu T, Liu R, Liang B, Tian Z, Zhang E, Zhang M (2015a) Effects of superfine grinding and microparticulation on the surface hydrophobicity of whey protein concentrate and its relation to emulsions stability. Food Hydrocoll 51:512–518. https://doi.org/10.1016/j.foodhyd.2015.05.027

Sun L, Chen W, Liu Y, Li J, Yu H (2015b) Soy protein isolate/cellulose nanofiber complex gels as fat substitutes: rheological and textural properties and extent of cream imitation. Cellulose 22(4):2619–2627. https://doi.org/10.1007/s10570-015-0681-4

Sun C, Liu R, Wu T, Liang B, Shi C, Cong X, Hou T, Zhang M (2016) Combined superfine grinding and heat-shearing treatment for the microparticulation of whey proteins. Food Bioprocess Technol 9(2):1–9. https://doi.org/10.1007/s11947-015-1629-2

Sun C, Liu R, Liang B, Wu T, Sui W, Zhang M (2018) Microparticulated whey protein-pectin complex: a texture-controllable gel for low-fat mayonnaise. Food Res Int 108:151–160. https://doi.org/10.1016/j.foodres.2018.01.036

Surendra Babu A, Parimalavalli R, Jagannadham K, Sudhakara Rao J, Shalini Gaur R (2016) Fat mimicking properties of citric acid treated sweet potato starch. Int J Food Prop 19(1):139–153. https://doi.org/10.1080/10942912.2015.1020390

Svihus B, Hervik AK (2016) Digestion and metabolic fates of starch, and its relation to major nutrition-related health problems: a review. Starch-Stärke 68:302–313. https://doi.org/10.1002/star.201500295

Tárrega A, Costell E (2006) Effect of inulin addition on rheological and sensory properties of fat-free starch-based dairy desserts. Int Dairy J 16(9):1104–1112. https://doi.org/10.1016/j.idairyj.2005.09.002

Taylor AJ, Linforth RST (1996) Flavour release in the mouth. Trends Food Sci Technol 7(12):444–448. https://doi.org/10.1016/S0924-2244(96)10046-7

Torres IC, Amigo JM, Knudsen JC, Tolkach A, Mikkelsen BØ, Ipsen R (2018) Rheology and microstructure of low-fat yoghurt produced with whey protein microparticles as fat replacer. Int Dairy J 81:62–71. https://doi.org/10.1016/j.idairyj.2018.01.004

United States Code of Federal Regulations (2014) Title 21. Nutrient content claims for fat, fatty acid, and cholesterol content of foods. 101.62. http://www.gpo.gov/fdsys/pkg/CFR-2014-title21-vol2/pdf/CFR-2014-title21-vol2-chapI.pdf van Ruth SM, de Vries G, Geary M, Giannouli P (2002) Influence of composition and structure of oil-in-water emulsions on retention of aroma compounds. J Sci Food Agric 82:1028–1035. https://doi.org/10.1002/jsfa.1137

Velásquez-Cock J, Serpa A, Vélez L, Gañán P, Hoyos CG, Castro C, Duizer L, Goff HD, Zuluaga R (2019) Influence of cellulose nanofibrils on the structural elements of ice cream. Food Hydrocoll 87:204–213. https://doi.org/10.1016/j.foodhyd.2018.07.035

Villanueva M, Mauro RR, Collar C, Ronda F (2015) Acidification of protein-enriched rice starch doughs: effects on breadmaking. Eur Food Res Technol 240(4):783–794. https://doi.org/10.1007/s00217-014-2384-8

Villanueva M, De Lamo B, Harasym J, Ronda F (2018) Microwave radiation and protein addition modulate hydration, pasting and gel rheological characteristics of rice and potato starches. Carbohydr Polym 201:374–381. https://doi.org/10.1016/j.carbpol.2018.08.052

Villegas B, Costell E (2007) Flow behaviour of inulin–milk beverages. Influence of inulin average chain length and of milk fat content. Int Dairy J 17(7):776–781. https://doi.org/10.1016/j.idairyj.2006.09.007

Wang R, Wan J, Liu C, Xia X, Ding Y (2019) Pasting, thermal, and rheological properties of rice starch partially replaced by inulin with different degrees of polymerization. Food Hydrocoll 92:228–232. https://doi.org/10.1016/j.foodhyd.2019.02.008

Weenen H (2005) Effects of structure breakdown on creaminess in semisolid foods. Food Lipids 920:119–132. https://doi.org/10.1021/bk-2005-0920.ch010

Weenen H, Van Gemert LJ, Van Doorn JM, Dijksterhuis GB, De Wijk RA (2003) Texture and mouthfeel of semisolid foods: commercial mayonnaises, dressings, custard desserts and warm sauces. J Texture Stud 34(2):159–179. https://doi.org/10.1111/j.1745-4603.2003.tb01373.x

WHO (2003) Diet, nutrition and the prevention of chronic diseases: report of a joint WHO. World Health Organization. https://doi.org/10.1046/j.1365-2648.2003.02792.x

Wu BC, McClements DJ (2015a) Design of reduced-fat food emulsions: manipulating microstructure and rheology through controlled aggregation of colloidal particles and biopolymers. Food Res Int 76:777–786. https://doi.org/10.1016/j.foodres.2015.06.034

Wu BC, McClements DJ (2015b) Functional hydrogel microspheres: parameters affecting electrostatic assembly of biopolymer particles fabricated from gelatin and pectin. Food Res Int 72:231–240. https://doi.org/10.1016/j.foodres.2015.02.028

Wu BC, McClements DJ (2015c) Development of hydrocolloid microgels as starch granule mimetics: hydrogel particles fabricated from gelatin and pectin. Food Res Int 78:177–185. https://doi.org/10.1016/j.foodres.2015.10.020

Wu BC, McClements DJ (2015d) Microgels formed by electrostatic complexation of gelatin and OSA starch: potential fat or starch mimetics. Food Hydrocoll 47:87–93. https://doi.org/10.1016/j.foodhyd.2015.01.021

Wu BC, Degner B, McClements DJ (2013a) Microstructure & rheology of mixed colloidal dispersions: influence of pH-induced droplet aggregation on starch granule–fat droplet mixtures. J Food Eng 116(2):462–471. https://doi.org/10.1016/j.jfoodeng.2012.12.020

Wu BC, Degner B, McClements DJ (2013b) Creation of reduced fat foods: influence of calcium-induced droplet aggregation on microstructure and rheology of mixed food dispersions. Food Chem 141(4):3393–3401. https://doi.org/10.1016/j.foodchem.2013.06.044

Wu BC, Degner B, McClements DJ (2014) Soft matter strategies for controlling food texture: formation of hydrogel particles by biopolymer complex coacervation. J Phys Condens Matter 26 (46):464104. https://doi.org/10.1088/0953-8984/26/46/464104

Yang Y, Xu S (2007) Roles of components of rice-based fat substitute in gelation. Food Res Int 40 (9):1155–1160. https://doi.org/10.1016/j.foodres.2007.06.010

Yang C, Zhong F, Douglas Goff H, Li Y (2019) Study on starch-protein interactions and their effects on physicochemical and digestible properties of the blends. Food Chem 280:51–58. https://doi.org/10.1016/j.foodchem.2018.12.028

Yazici F, Akgun A (2004) Effect of some protein based fat replacers on physical, chemical, textural, and sensory properties of strained yoghurt. J Food Eng 62(3):245–254. https://doi.org/10.1016/s0260-8774(03)00237-1

Yoshimura M, Takaya T, Nishinari K (1999) Effects of xyloglucan on the gelatinization and retrogradation of corn starch as studied by rheology and differential scanning calorimetry. Food Hydrocoll 13:101–111. https://doi.org/10.1016/S0268-005X(98)00075-7

Zabot GL, Silva EK, Azevedo VM, Meireles MAA (2016) Replacing modified starch by inulin as prebiotic encapsulant matrix of lipophilic bioactive compounds. Food Res Int 85:26–35. https://doi.org/10.1016/j.foodres.2016.04.005

Zetzl AK, Marangoni AG, Barbut S (2012) Mechanical properties of ethylcellulose oleogels and their potential for saturated fat reduction in frankfurters. Food Funct 3(3):327–337. https://doi.org/10.1039/c2fo10202a

Zhang H, Chen J, Li J, Wei C, Ye X, Shi J, Chen S (2018) Pectin from citrus canning wastewater as potential fat replacer in ice cream. Molecules 23(4):925–936. https://doi.org/10.3390/molecules23040925

Zhang M, Sun C, Li Q (2019) Interaction between the polysaccharides and proteins in semisolid food systems. In: Varelis P, Melton L, Shahidi F (eds) Encyclopedia of food chemistry. Elsevier, Oxford, pp 439–445. https://doi.org/10.1016/b978-0-08-100596-5.21474-1

Zoulias EI, Oreopoulou V, Tzia C (2000) Effect of fat mimetics on physical, textural and sensory properties of cookies. Int J Food Prop 3(3):385–397. https://doi.org/10.1080/10942910009524643