Critical Reviews in Food Science and Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

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To cite this article: Camila de Souza Paglarini , Vitor Andre Silva Vidal , Silvana Martini , Rosiane Lopes Cunha & Marise Aparecida Rodrigues Pollonio (2020): Protein-based hydrogelled emulsions and their application as fat replacers in meat products: A review, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2020.1825322

To link to this article: https://doi.org/10.1080/10408398.2020.1825322

Published online: 01 Oct 2020.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2020.1825322

REVIEW

Protein-based hydrogelled emulsions and their application as fat replacers in meat products: A review

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ABSTRACT
Recent consumers' concerns about diet and its health benefits has triggered a reduction in consumption of foods rich in sugar, fat, salt, and chemical additives. As a result, an expanded market for functional foods has arisen. In particular, high-fat foods normally composed by saturated fatty acids, cholesterol and *trans*-fatty acids have been reformulated to be healthier. The primary source of saturated fat ingested by humans includes meats and their by-products that have animal fat as lipid source. The reformulation of these products therefore represents an important strategy to make them healthier for human consumption. Substituting solid fat by unsaturated oils usually affects the texture of the products, and therefore, new structuring methods must be developed to provide vegetable oils a similar characteristic to solid fats and improve their functional and health-related properties. Among these structural models, gelled emulsions (GE) show great potential to be used as healthier lipid ingredients in low-calorie and reduced-fat products, including healthier meat products. This review addresses the GE properties to be used as structuring agent, their in vitro bioaccessibility in meat products and effect on technological, sensorial, microstructural and microbiological characteristics.

KEYWORDS
Fat reduction; gelled emulsion; healthier meat products; structured oils

Introduction

Saturated fat is commonly present in high levels in some products such as emulsified meats and fermented and restructured meat products. Its presence in these products comes from the raw materials used in their production such as fat cuts and pork back fat. These meat ingredients have excellent technological properties since they provide texture, mouthfeel, and flavor to the products. They are also associated with high production yield and high stability toward lipid oxidation. However, excessive intake of saturated fats has been associated with the rise of several chronic diseases, such as obesity, hypertension and, thus, an increased risk of cardiovascular diseases, leading consumers to be concerned about high consumption of saturated fat (Jiménez-Colmenero et al. 2015; Mao et al. 2018). Consequently, the food industry is shifting toward the production of fat-free or low-fat foods (Sandrou and Arvanitoyannis 2000) with addition of unsaturated fats that challenges food scientists because the simple replacement of conventional fats by healthier fats (i.e., vegetable oil) is not a simple task.

Numerous strategies to stabilize and structure liquid oils in semi-solid materials with high content of unsaturated fatty acids (UFA), reduced levels of saturated fatty acids (SFA), and zero *trans* fatty acids have been used by food scientists (Jiménez-Colmenero et al. 2015). According to recent studies structuring liquid oils also show a more feasible way of obtaining reformulated systems with characteristics similar to the formulations developed with saturated fat (Alejandre et al. 2016; Dickinson 2012; Jiménez-Colmenero et al. 2015). These systems also can carry functional ingredients such as minerals, vitamins, phenolic compounds, and carotenoids resulting in a healthier and interesting new multi-ingredient system to be used as a fat replacer in high fat foods such as cheese, ice cream, meat products, mayonnaise, and salad dressing, to name a few.

These structuring oil methods include interesterification, organogelation, and structured emulsions, such as gelled emulsions (Zetzl, Marangoni, and Barbut 2012). Interesterification is a conventional lipid modification process consisting in the rearrangement of the position of fatty acids in the triacylglycerol molecule without altering the overall amount of fatty acids. This process can be performed through chemical means or by using enzymes (Pokorný and Schmidt 2011) and has the disadvantage of being more prone to lipid oxidation, especially when the oil source used is rich in polyunsaturated fatty acids (Jiménez-Colmenero et al. 2015) such as palm, cottonseed, olive, and hazelnut (Cheong et al. 2010; Ospina-E et al. 2010; Vural and Javidipour 2002). Organogelation is a non-conventional

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technique used to modify lipid structure and can be defined as semi-solid systems where an organic solvent such as vegetable oil is entrapped by a three-dimensional network formed by a wide range of structuring agents (organogelator molecules) (Hughes et al. 2009). Recently, several studies have used organogels to elaborate healthier meat products (Alejandre, Astiasarán et al. 2019; Barbut and Marangoni 2019; Gómez-Estaca, Pintado et al. 2019; Wolfer et al. 2018), however the high temperature required to melt organogelator (up to 170 °C) may increase lipid oxidation and depending on structuring agent concentration the hardness of meat products is strongly affected (Barbut, Wood, and Marangoni 2016; Gómez-Estaca, Herrero et al. 2019).

In particular, gelled emulsions or emulsion gel are alternatives with great potential for applications in food products, especially for their use in healthier meat products (Pintado et al. 2015). A gelled emulsion is a structured emulsion that can be defined as an emulsion where the continuous phase is characterized by a gel-like network structure and therefore presents solid-like properties (Dickinson 2012, 2013). Several reformulated meat products use non-gelled O/W emulsions with a healthier combination of fatty acids, but liquid emulsions are thermodynamically unstable systems. Thus, gelation of the continuous outer phase of the O/W emulsion may be of interest to improve product stability and texture. O/W hydrogelled emulsions or emulsion gels can be made in two simple steps. The first step is the formation of an O/W emulsion using protein as emulsifier. During or after emulsion formation, gums, fibers and other ingredients such as bioactive compounds can also be added to act as stabilizers. The second stage needed to form a hydrogelled emulsion consists of inducing the formation of a soft solid state by promoting aggregation of the emulsion's droplets or by inducing gelation of the continuous phase. The change from liquid to soft solid state of protein-based emulsions is caused by several different processing stages such as heating, acidification, or enzymatic treatment (Dickinson 2013).

Many components can be used to develop a hydrogelled emulsion, emphasizing plant-based ingredients (Dickinson and Casanova 1999; Freire, Cofrades et al. 2017; Herrero et al. 2018; Mao et al. 2018; Mao, Roos, and Miao 2014; Sato, Moraes, and Cunha 2014; Wang et al. 2017). Among the vegetable proteins used as emulsifiers, soybean and chia have exhibited good results, while gums (such as carrageenan), lecithin, inulin and some proteins have been used as stabilizers (Delgado-Pando et al. 2011; Herrero et al. 2012; Jiménez-Colmenero et al. 2010; López-López et al. 2010, 2011; Pintado, Herrero, Ruiz-Capillas et al. 2016; Pintado et al. 2015). The use of ingredients with functional properties, such as inulin or chia flour (high fiber content) or ingredients rich in bioactive compounds also represents a potential for structuring lipid systems (Freire, Cofrades et al. 2017; Herrero et al. 2018; Pintado et al. 2015; Wang et al. 2017). In addition, replacing saturated fats with gelled emulsion may be a suitable technology not only to produce healthier foods but also to protect lipids in food products (Cofrades et al. 2017; Poyato et al. 2015).

The objective of this review is to describe the properties of protein-based hydrogelled emulsion with added polysaccharides (carrageenan, pectin, inulin, etc) used as a major functional strategy in food products, depicting technological and nutritional advantages as well the most relevant methods to produce them. Emphasis is given on applying the gelled emulsions as fat replacers to improve the fat content (quantity and type) of meat products.

Reducing saturated fat in meat products

Processed meat products are widely consumed worldwide due to their sensorial and nutritional properties. In addition, these products are usually cheap which also appeals to consumers. However, products such as frankfurters, patties, and fermented sausages have high content of animal fat (20 to 30%) with pork back fat being the most widely used fat source. Animal fat has high content of saturated fatty acids and therefore various strategies to reduce fat levels and to replace these fats by heathier options have been explored (Alejandre et al. 2017). Fat content can be reduced in meat products by modifying product formulation. For example, fat chemical composition and content in meat products can be modified by using meats with lower fat content, by increasing the amount of water in the product, by using lipid sources from plants rather than animals, and by adding other ingredients such as fat replacers. In addition, processing conditions can be altered to aid in the reformulation, for example the functional properties of fibers added to meat products can be different if the materials are processed with a high shear continuous grinding system compared to when it is processed with a traditional bowl chopping process. Overall, reduction of fat content in finely ground meat products such as Bologna sausage and frankfurters is extremely challenging since various important consumer acceptance treats such as flavor, appearance, and texture are usually changed during the reformulation (Weiss et al. 2010).

Reformulation strategies are one of the most common approach to formulate healthy meat-based functional foods. The reformulation of the lipid fraction generally consists of replacing the animal fat (usually pork back fat) by a healthier fat that has fewer SFA, higher contents of MUFAs or PUFAs, better n-6/n-3 PUFA and PUFA/SFA ratios, and if possible is cholesterol-free. Several plant and marine lipid sources meet these nutritional characteristics (Jiménez-Colmenero 2007).

Direct substitution of animal fat by other types of fats is not an easy task since the new fat may affect some desired quality attributes in the reformulated product. For example, fat droplets from saturated lipid sources play important roles in functional attributes related to stability, chemical and sensory properties. In general, when saturated fat is totally replaced by vegetable oils that are richer in mono and polyunsaturated fatty acid, the products are more prone to lipid oxidation, are softer, have a loss in desired appearance and flavor, and have a reduced water holding capacity making

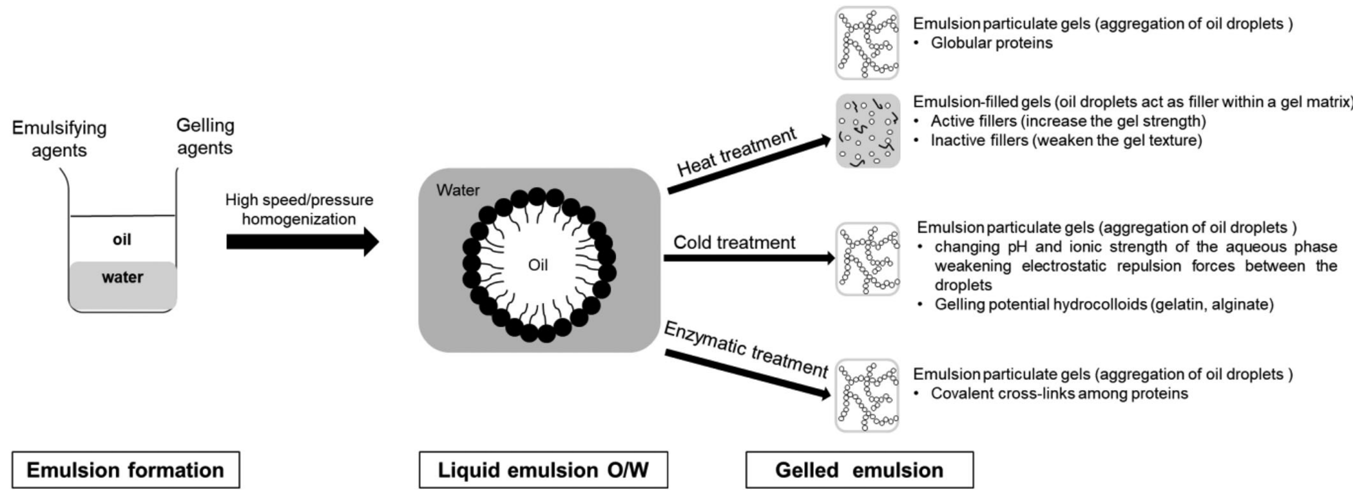

Figure 1. Schematic presentation to produce an O/W gelled emulsion and the characteristics of the final gel.

them more susceptible to microbiological contamination (Chung et al. 2013).

The use of structured oils such as hydrogelled emulsion in meat products emerges as one of the most promising strategies for reducing saturated fat content and improving the nutritional profile in these products (Herrero et al. 2017; Pintado et al. 2018; Poyato et al. 2015). In addition an improvement in fatty acids profile (lower content of saturated fatty acid, higher amount of mono- and polyunsaturated fatty acids) with the addition of gelled emulsion in meat products have shown reduced cooking loss, lower rate and extent of lipid oxidation, as well as good textural and sensorial properties (Paglarini, Martini, and Pollonio 2019; Pintado et al. 2018; Pintado, Herrero, Ruiz-Capillas et al. 2016). Studies have also shown that gelled emulsion systems may be a good strategy to increase bioaccessibility of some bioactive compounds such as docosahexaenoic acid (DHA) (Gayoso, Ansorena, and Astiasarán 2018).

Non-conventional oil structuring methods: The hydrogelled emulsions or emulsion gels

Since the elimination of GRAS status of partially hydrogenated oils the food industry has sought for novel healthy lipids that are low in saturated fatty acids and free of trans-fats. Over the years, partial hydrogenation has been replaced by fully hydrogenation, interesterification, fractionation, and blending. In addition, oil structuring has emerged as non-conventional methods (Chaves, Barrera-Arellano, and Ribeiro 2018) that require simpler processing than some conventional techniques. One of these unconventional methods is the structuring of vegetable oils to create a semi-solid fat that has appropriate solid-like properties while maintaining the nutritional properties of a vegetable oils (low in SFA, high in MUFA and PUFA) (Jiménez-Colmenero et al. 2015). These structured oils show potential to create innovative food products, especially for those products that need fat reformulation such as processed meats. Non-conventional oil structuring methods include organogelation, oil bulking system (oil droplets trapped in hydrogels without emulsifier or stabilizing agents), and structured emulsion, such as hydrogelled and organogelled emulsions (Jiménez-Colmenero et al. 2015; Mao and Miao 2015). Among them, hydrogelled emulsions are a potential animal fat replacer especially because it can be developed with plant-based ingredients that contain healthy fatty acids, fiber, minerals, antioxidants or vitamins, among others (Pintado et al. 2018).

Protein-based hydrogelled emulsion

Hydrogelled emulsion (GE) can be described as a complex gel filled with emulsified fat in a matrix of protein network showing solid-like mechanical properties (Dickinson 2012; Jiménez-Colmenero et al. 2015; Matsumura, Sakamoto et al. 1993). Hydrogelled emulsions or emulsion gels are more stable than conventional liquid emulsions since gel-like or paste-like characteristics of the continuous phase can hinder gravitational separation (Chung and McClements 2014). The physical properties of the emulsion gels such as structure and rheological behavior are affected by whether the fat acts as active or inactive filler but also by the droplet sizes and oil content in the emulsion. In addition, processing conditions such as acidification, heating and enzyme action can affect these physical properties. Ultimately, protein-protein, protein-oil, and oil-oil interactions driven by hydrogen and covalent bonds, electrostatic, hydrophobic, and electrostatic interactions affect gel strength (protein-protein, protein-oil and oil-oil) (Guo et al. 2013). The addition of other ingredients such as polysaccharides as stabilizers and/or texturizers in the aqueous phase also contribute to the final properties of the gels due to their gelling/thickening properties (Dickinson 2013).

Traditional GE include cheeses, tofu, yoghurt, sausage, and some dairy desserts (Dickinson 2012; Mao et al. 2018). The soft-solid-like structure of GE can deliver novel functional properties that can be used for many industrial applications which makes GE interesting ingredients to be used as textural mimetic of saturated fat (Chung et al. 2013; Freire, Cofrades et al. 2017). In addition, studies have reported that volatile compounds within GE systems show lower release rates, which is important for designing semi-solid foods with desirable flavor (Hou et al. 2016; Lee, Choi, and Moon 2006; Mao et al. 2018; Mao, Roos, and Miao 2014).

Emulsion gels for food applications are usually made with natural ingredients and stabilized with proteins. These types of emulsions have been of great interest in the food industry due to the trend of moving toward "clean label" products (McClements and Gumus 2016). Protein-based emulsion gels are formed by oil droplets stabilized by a layer of protein adsorbed at the oil–water interface and entrapped in a protein gel network. GE formation involves firstly the production of a protein-stabilized emulsion followed by the gelation of this emulsion (Figure 1). The emulsion is formed by the addition of emulsifying agents (proteins, synthetic emulsifiers, or other hydrocolloids showing emulsifier properties) and the incorporation of a gelling agent (hydrocolloid or other gelling ingredients) transform the emulsion into a GE. The formation of a GE can occur by either inducing the aggregation of oil droplets and/or by gelling continuous phase (Dickinson 2013; Jiménez-Colmenero et al. 2015). The real structure of an oil-in-water (O/W) gelled emulsion has been defined as a complex network combining aggregated emulsion droplets and cross-linked biopolymer molecules (Dickinson 2012; Herrero et al. 2018).

Droplets within the emulsions can act as active or inactive fillers depending on their effect on the GE rheology and their interaction with the gel matrix (type, nature and concentration of emulsifier). As active filler particles, the oil droplets are encapsulated into the protein gel network and consequently the gel matrix is reinforced leading to an increase in gel firmness. If oil droplets interact with the gel matrix they can result in a lower elastic modulus of the GE and therefore act as inactive fillers (Dickinson 2012; Dickinson and Chen 1999; Hou et al. 2016).

Emulsion formation

The first stage to form a GE involves forming a liquid emulsion by using conventional methods such as high-speed blenders, colloidal mills, or high-pressure valve homogenizers. These methods are used generate small droplets of the dispersed phase that are suspended in the continuous phase (Schultz et al. 2004).

There are two types of emulsions: oil-in water (O/W) emulsions where the dispersed phase is formed by oil (oil droplets) and the continuous phase is formed by an aqueous media (e.g., milk and mayonnaise), or water-in-oil (W/O) when emulsions are dispersions of water droplets in a continuous oil phase (e.g., butter, spreads, and margarines). (Chung and McClements 2014; McClements 2016). Emulsions are thermodynamically unstable systems meaning that they become unstable over time. The mechanisms involved in emulsion destabilization include gravitational separation, flocculation, coalescence and Ostwald ripening (Chung and McClements 2014; Dalgleish 1997; Dickinson 2010; Mao and Miao 2015). However, stable emulsions can be made through the use of surfactants or amphiphilic ingredients (emulsifiers) such as proteins, phospholipids, and fatty acid esters. Emulsifiers adsorb to the surface of the newly formed droplets after disruption caused by mechanical forces, lower the interfacial tension, and hinder or delay the destabilization processes (Dickinson 2009; McClements 2016). The kinetic stability of an emulsion results from the balance between repulsion forces (electrostatic repulsion, and steric hindrance) and attractive forces (hydrophobic attraction, hydrogen bonding, and electrostatic attraction) between neighboring droplets (Mao and Miao 2015).

Several factors control the final properties of the emulsion such as emulsifier characteristics (type and concentration), bulk phase properties (interfacial tension and viscosity), and applied forces (pressure/shear rate and mechanical forces type). All these processes affect the size, charge, interactions, and organization of the oil droplets produced and in turn affect the bulk physicochemical properties of the emulsions such as rheology, appearance, flavor, and physical and chemical stability (Chung and McClements 2014).

Oil properties exert a minor effect on emulsions properties and on gelled emulsions more emphasis has been placed on the use of healthier oil composed by unsaturated fatty acids, such as sunflower, soybean, olive, perilla, algae, and chia oil have been reported in the literature (Freire, Cofrades et al. 2017; Herrero et al. 2018; Mao et al. 2018; Mao, Roos, and Miao 2014; Pintado et al. 2015; Wang et al. 2017).

Plant-proteins and/or polysaccharides as natural emulsifiers and gelling agents in gelled emulsion

Ideal emulsifiers used in oil-in-water emulsions are those that are soluble or that can form a suspension in water, they should be relatively small in size to rapidly adsorb to droplet surfaces during processing, and they should form a thick hydrophilic layer to provide appropriate steric stabilization (McClements 2016; McClements and Gumus 2016). In food applications the most used emulsifiers for oil-in-water emulsions are proteins, phospholipids, some polysaccharides, and small-molecule surfactants (Wilde et al. 2004). The efficiency of the emulsifier is dependent on product formulation, processing conditions, and the expected functional properties in final products. Other ingredients such as thickeners and gelling agents can be added to food emulsions to improve their stability, texture, and flavor (Chung and McClements 2014).

The most commonly used emulsifier in the food industry are proteins since they are natural, nontoxic, cheap, and widely available, making them ideal ingredients. Proteins can easily form an interfacial film on the surface of the oil droplets. The properties of this film are affected by the surface charge and hydrophobicity of the amino acids and their three-dimensional reorganization after the protein has been adsorbed to the interface (Wilde et al. 2004). Proteins used as emulsifiers have been isolated from various plant sources such as peas, soy, lentils, corn, and chickpea. These protein sources have been used since they provide a clean label, they are free of allergens and have appropriate functional properties (Lam and Nickerson 2013).

Protein and/or polysaccharides as emulsion stabilizers can also be used as replacers for synthetic emulsifiers. In addition, protein and/or polysaccharide emulsifiers increase the viscosity of the continuous phase reducing oxygen diffusion and therefore preventing lipid oxidation (Paraskevopoulou, Boskou, and Paraskevopoulou 2007). The oxidation reaction can also be inhibited by forming complexes between proteins and transition metals (McClements and Gumus 2016). At pH values below the isoelectric point (pI) of the protein, lipid oxidation is inhibited due to electrostatic repulsion between transition metals (cations) and the positively charged droplet surfaces (Donnelly, Decker, and McClements 2006). This is an important property that can be exploited when using GE as fat replacers in reformulated meat products, because these products are rich in iron, a potential pro-oxidant transition metal. It is also important because vegetable oils, which have a high amount of polyunsaturated fatty acids, are used to formulate the GE and consequently lipid oxidation may occur more easily in meat products using GE rather than saturated fat.

As previously mentioned, polysaccharides, such as modified starches and celluloses, gum Arabic, pectin, and galactomannans, show some surface/interfacial activity (Dickinson 2003). These molecules are less efficient at stabilizing emulsions compared to proteins and small-molecule surfactants but they can still form a thick interfacial film around dispersed oil droplets (Guo, Ye et al. 2017). An advantage of using polysaccharides over proteins is that even though protein emulsifiers have better emulsifying properties when used in low concentration and generate finer oil droplets, polysaccharides can generate emulsions that are stable to a variations in environmental conditions such pH, ionic strength, temperature, and freezing. This enhanced stability occurs because polysaccharide-coated lipid droplets are primarily stabilized by steric repulsion (McClements and Gumus 2016).

The following sections describe the potential application of some natural emulsifiers/thickeners used to form a GE and their advantage as functional ingredients.

Soy proteins. One of the most widely studied plant-based proteins is soy protein, which is commercially available as protein concentrate (minimum 65% protein content) or isolate (minimum 90% protein content) (Nishinari et al. 2014). Soy proteins have been used in food formulations due to their high nutritional value (Lo, Farnworth, and Li-Chan 2006) and desired functionality as an emulsifier and gelling agent (Molina, Defaye, and Ledward 2002). The isoelectric point of soy proteins is around 4.5 (Molina Ortiz, Puppo, and Wagner 2004). In particular, soy protein isolates (SPI) are composed by glycinin (11S) and β-conglycinin (7S) accounting for 34% and 27% of total protein content of SPI, respectively (Iwabuchi and Yamauchi 1987). Smaller amount of 2S and 15S are also present in SPI. Moreover, each of these fractions (11S, 7S, 2S, and 15S) contain various subunits with specific molecular and functional characteristics (McClements 2016). For example, soy glycinin is needed to form gel-like networks in emulsions stabilized by heated soy proteins (Luo, Liu, and Tang 2013).

Advantages of soybean protein include a good balance in amino acid composition since these proteins contain all essential amino acids (96.6 phenylalanine + tyrosine, 49.1 valine, 38.4 threonine, 11.4 tryptophan, 68.1 methionine + cysteine, 85.1 leucine, 47.1 isoleucine, 63.4 lysine, and 25.4 histidine mg/g protein) (Friedman 1996; Mojica, Dia, and Mejıa 2015). Soy proteins have also shown to decrease blood cholesterol reducing the risk of hyperlipidemia and cardiovascular diseases, and has excellent processing functionality such as emulsifying ability, gelling, and water and oil- holding capacity (Nishinari et al. 2014).

Several studies have used soy protein as an ingredient in GE formulation (Freire et al. 2018; Herrero et al. 2018; Hou et al. 2016; Wang et al. 2017; Yang, Liu, and Tang 2013). In particular, SPI has been used as an emulsifier in GE to replace animal proteins (Silva et al. 2019). SPI plays an important role in GE formulations since it contributes to the gel network strength and water holding capacity (Paglarini, Furtado et al. 2018). In addition, the size and the content of SPI aggregates formed during processing impact GE rheology properties where bigger aggregates increase the elastic modulus and viscous component of the gels (Wang et al. 2017).

Carrageenan. Carrageenan is a linear water-soluble polysaccharide obtained from red algae (Rhodophyceae). Carrageenan is a negatively charged sulfated polysaccharide normally commercialized as Na^+, K^+, and Ca^{+2} salts with molecular weights between 200 and 400 kDa. Its structure consists of alternating β (1–3)- and α (1–4)-linked galactose residues (McClements 2016). The main classification of carrageenan types are kappa- κ (I and II), iota-ι, and lambda-λ, depending of the number and position of the sulfate groups and the number of 3,6-anhydrogalactose rings per disaccharide. The carrageenan types vary in their solubility and in the characteristics of the gels that they form (gel strength and stability, and gel formation temperature) (Valsta, Tapanainen, and Männistö 2005). While λ-carrageenan is used as a thickening agent, (McClements 2016) κ- and ι-carrageenans are commonly employed as cold-setting reversible gelling agents and both undergo a coil (disordered state) to helix (ordered) transition during cooling, depending on the temperature and on their ionic environment. The junction zones formed by the helices between carrageenan chains lead to the formation of a three-dimensional network and therefore to gelation (Banerjee and Bhattacharya 2012; Schorsch, Jones, and Norton 2000).

Previous studies have shown that carrageenan interacts with oil during GE structure formation affecting their hardness and syneresis. At high concentrations of oil and carrageenan hardness decreased and syneresis increased in GE and the opposite occurred at lower carrageenan concentration (Poyato et al. 2014). Many previous studies have successfully used carrageenan as a gelling agent in the GE formulation (Alejandre, Ansorena et al. 2019; Freire et al.

Table 1. Literature reports of gelation methods to form gelled emulsions.

Protein/polysaccharide	Oil	Gelation method	Gel characteristics	References
Gelatin	Sunflower	Cold	• Viscosity of the system and its elastic characteristics increased as the molecular weight of the gelatin increased • The high shear stresses induced denaturation of the gelatin and gelation of the whole system.	(Lorenzo et al. 2011)
WPI	Sunflower	Cold (GDL)	• High magnitude of pre-thermal treatment resulted in gels with high storage modulus	(Mao et al. 2018)
Oat bran, SPI, and chia flower	Chia	Cold (Na alginate, $CaSO_4$, and SP)	• The plant-based ingredient had influence on the GE texture, color, pH, and lipid structure and interaction	(Herrero et al. 2018)
SPI	Corn	Enzymatic (MTG)	• Microstructure, mechanical properties and breakdown patterns of GE were greatly affected by the interfacial composition and size of oil droplets	(Hou et al. 2016)
Oat bran	Olive	Cold (alginate, $CaSO_4$, SP and gelatin)	• Gel strength and penetration force presented a positive correlation with gelling agent concentration	(Pintado et al. 2016a)
Chia flour and seeds	Olive	Cold and enzymatic (MTG, alginate, $CaSO_4$, SP and gelatin)	• Samples containing MTG as a gelling agent exhibited lower gel strength and penetration force than those containing alginate or gelatin	(Pintado et al. 2015)
Soy 11S globulin	Soybean	Enzymatic (MTG)	• Coarse, medium and fine GE presented the same amount of ε-(γ -glutaminyl) lysine isopeptide bonding	(Matsumura, Kang et al. 1993)
SPI	Soybean	Enzymatic (MTG)	• The gel strength progressively increased with increasing the volume oil fraction	(Yang, Liu, and Tang 2013)
WPI	Corn	Heat (90 °C, 15 min)	• The gel strength increased as the droplet size decreased	(McClements, Monahan, and Kinsella 1993)
WPI, and κ-carrageenan	Soybean	Heat (55 °C)	• Oil droplets aggregated and formed a network structure In the presence of κ-carrageenan	(Singh et al. 2003)
Inulin	Canola	Heat (70 °C)	• Inulin addition cause an increasing in apparent viscosity	(Glibowski, Kordowska-Wiater, and Glibowska 2011)
WPI	Soybean	Heat (90 °C, 30 min)	• The hardness of the gels was increased with NaCl concentration	(Guo et al. 2013, 2014b)
WPI	Canola	Heat (90 °C, 30 min)	• Gels added of NaCl and $CaCl_2$ showed the highest fracture force	(Guo, Bellissimo, and Rousseau 2017b)
WPI, tween 20	Triolein	Heat (85 °C, 35 min)	• Rheological properties were influenced by oil volume fraction and the type of emulsifier (active or inactive fillers)	(Dickinson and Chen 1999)

GE, gelled emulsion; SC, sodium caseinate; SPI, isolated soy protein; MTG, microbial transglutaminase; WPI, whey protein isolate; GDL, glucono-δ-lactone; SP: sodium pyrophosphate.

2018; Gayoso et al. 2017; Paglarini, Furtado et al. 2018; Poyato et al. 2015).

Inulin. Inulin is a soluble dietary fiber and it has been used as a functional ingredient and fat replacer in food products, especially meat products (Doolaege et al. 2012; Felisberto et al. 2015; Huang, Tsai, and Chen 2011; Menegas et al. 2013; Naveena et al. 2014; Serdaroğlu, Nacak, and Karabıyıkoğlu 2017; Shan et al. 2009; Yu and Ahmedna 2013). The addition of inulin results in similar juiciness and softness to conventional products (Huang, Tsai, and Chen 2011; Luisa et al. 2006; Naveena et al. 2008; Serdaroğlu et al. 2016). Technological properties of inulin are associated to the degree of polymerization of its chains, making it an interesting ingredient for use as a low-calorie sweetener, fat replacer, or texturizing agent (Herrero et al. 2014; Tungland and Meyer 2002). In addition, health benefits such as prebiotic properties have been associated with inulin consumption (Kim, Faqih, and Wang 2001; Öztürk and Serdaroglu 2016; Tungland and Meyer 2002). Inulin gel formation is different from that obtained with other hydrocolloids. While inulin forms particle gels, gels formed by hydrocolloids are due to an increase in viscosity achieved by bonds formed between chains (Glibowski 2009). In a previous study inulin

Table 2. Literature data of using gelled emulsions to carry healthier ingredients.

Gelled emulsion				
Oil0	Emulsifier	Gelling agent	Healthy bioactive compounds	References
Chia	Oat bran, SPI, and chia flour	Sodium alginate and $CaSO_4$	α-linolenic acid, insoluble fiber, and soluble dietary fiber (β-glucan), antioxidants, valuable proteins	(Herrero et al. 2018)
Soybean	SPI	$CaSO_4$	Essential amino acids, unsaturated fatty acid	(Wang et al. 2017)
Olive	Chia flour	MTG, $CaSO_4$, sodium alginate, gelatin	α-linolenic acid, insoluble fiber, antioxidants, valuable proteins	(Pintado et al. 2015)
Sunflower	WPI	–	Essential amino acids, unsaturated fatty acids	(Mao, Roos, and Miao 2014)
Perilla	SC	Bovine gelatin and MTG	α-linolenic acid, hydroxytyrosol	(Freire, Bou et al. 2017)
Sunflower	WPI, goma guar	GDL	Medium-chain triglyceride, maltodextrin, dietary fiber	(Mao et al. 2018)
Soybean	Sodium caseinate and Bovine β-lactoglobulin, lecithin	MTG	Phospholipids, essential amino acids, unsaturated fatty acids	(Dickinson and Yamamoto 1996)
Sunflower, and algae	polysorbate 80	κ-carrageenan	Antioxidant (spike lavender extract)	(Gayoso et al. 2017)
Oliveoil, linseed oil, and fish oil	SC, WPI, or SPI	κ-carrageenan, bovine gelatin and MTG	Condensed tannins and n-3 fatty acids	(Freire et al. 2018)
Olive oil	Oat bran, chia flour	Sodium alginate, $CaSO_4$, sodium pyrophosphate	α-linolenic acid, insoluble fiber, and soluble dietary fiber (β-glucan), antioxidants	(Pintado et al. 2018)
Tristearin and babacu oil	WPI, tween 60 and span 80	xanthan gum	Curcumin	(Geremias-Andrade et al. 2017)
Docosahexaenoic acid	Lactoferrin, WPI	–	Lutein, Docosahexaenoic acid	(Li et al. 2017)
Medium chain triglyceride	WPC	$CaCl_2$	Nobiletin	(Hu et al. 2019)

SPI, soy protein isolate; $CaSO_4$, calcium sulfate; MTG, microbial transglutaminase; WPI, whey protein isolate; WPC, whey protein concentrate, GDL, glucono-δ-lactone; SC, sodium caseinate.

gel was affected by concentration, heating temperature and time, shear, solvent used, and pH (Kim, Faqih, and Wang 2001).

Inulin is added in GE formulations as health promoting ingredient to obtain meat products with high fiber content (Glisic et al. 2019; Paglarini, Martini, and Pollonio 2019). This ingredient also has an impact on GE rheological properties acting in synergy with SPI and increasing elastic moduli (Paglarini, Furtado et al. 2018). Replacing animal fat by inulin-based GE seems to impact the texture (softer products) and color (higher b*) of meat products. However, when the animal fat was only partially replaced (50%) by GE, products with similar properties to those observed in the control samples were obtained (Glisic et al. 2019; Serdaroğlu, Nacak, and Karabıyıkoğlu 2017).

Gelation methods

Hydrocolloids, such as polysaccharides and proteins, are high molecular weight hydrophilic biopolymers that can be added to the aqueous continuous phase of O/W emulsions to increase their stability by gelling or by increasing the viscosity of the continuous phase (McClements 2016). The properties of the GE generated using these molecules are driven by interactions between the emulsifier adsorbed onto the surface of the droplets and the biopolymer molecules in the continuous phase (Dickinson 2012). A firm gel is formed if this interaction is strong. If no interaction exists, the droplets may disrupt the network of the continuous phase and weaken the gel strength (McClements 2016).

Hydrocolloids-based oil-in-water emulsions containing low or moderate oil content ($< 30\%$) can be structured from the liquid state to a soft solid-like state by gelling the continuous phase using various processing steps such as heating, acidification, and enzyme action (Dickinson 2012; Lee, Choi, and Moon 2006). At high oil concentration ($> 30\%$) most proteins are adsorbed on the surface of the emulsion droplets and the content of free protein in the continuous aqueous phase is very small and insufficient to induce gelation. In this case, the emulsion gel can be formed by aggregation of the emulsion droplets and not by gelation of the continuous phase (Farjami and Madadlou 2019; Sarkar, Ye, and Singh 2017). Figure 1 and Table 1 summarize the properties of the gelled emulsion obtained by various gelation methods and the influence that different protein/polysaccharide molecules and oils have on the characteristics of the gels.

The choice of the method used to produce a GE depends on the aim of the application. For example, cold-set GE can be used in food matrices as a controlled-release carrier, especially for labile lipid-soluble bioactive compounds, as well as for thermally unstable bioactive compounds (antioxidants, vitamins, etc).

Heat treatment

Globular proteins are the more sensitive to changes in the physicochemical environment and temperature compared to fibrillar proteins. This means that globular proteins, such as soybean proteins, can easily form a gel when heated (Banerjee and Bhattacharya 2012; Schorsch, Jones, and Norton 2000). Some fibrillar proteins, such as myosin (major functional component of muscle protein) may form a gel when heated, and the mechanism that explains their gelation is the head to head bonding and posterior self-assembly through cross-linking of tail portions (Samejima, Ishioroshi, and Yasui 1981). Although fibrillar proteins are naturally present in meat being responsible for the most important functional properties such as water holding capacity, gelation, and emulsion formation, in some reformulated meat products, is necessary adding others food components aiming to preserve the physicochemical, microbial and sensory properties. In this way, the unique functional properties of globular proteins to heat makes them the most commonly used in GE.

The preparation of heat-set gels made of globular food proteins (soybean and whey protein, for instance) usually comprises three different steps that occur consecutively during the heat treatment: denaturation, aggregation, and gelation (Alting et al. 2003; Pires Vilela, Cavallieri, and Lopes da Cunha 2011). In the denaturation step, the heating temperature must be higher than the protein denaturation temperature, the pH should be kept away (higher or lower) from the isoelectric point of the proteins to avoid immediate aggregation upon heating (and formation of disordered and weak structures), and the salt concentration must be low enough to prevent excessive aggregation of protein molecules (Bryant and McClements 1998). However, a more complex process occurs during the formation of a GE since proteins are adsorbed on the oil droplet surface to stabilize the emulsion and therefore different gel structures will be formed compared to the ones formed in a non-emulsified system (Guo et al. 2014b).

Rheological and structural characteristics of heat-set GE depend on the interactions that occur between the surfactant adsorbed on the droplets' surface and the protein network formed in the continuous aqueous phase (Anton et al. 2001). Heat treatment in emulsions based on globular protein induces droplets flocculation due to an increase in surface hydrophobicity (McClements 2015). During heat treatment after emulsification globular proteins adsorbed on the oil droplet unfold and denature exposing hydrophobic segments. These events induce the gelling process in the emulsion which also depends on the ionic strength and on the content of non-adsorbed protein (Dickinson 2010).

Recent studies have investigated the role of biopolymers in increasing the stability of heat-set GE or acting as a delivery matrices for functional ingredients in food products (Geremias-Andrade et al. 2017; Jiang et al. 2019; Lam and Nickerson 2014; Paglarini, Martini, and Pollonio 2018). For example, the addition of heat-gelling-indigestive polysaccharide in the gelled emulsion is a good strategy to develop low-calorie food (Jiang et al. 2019).

Cold treatment (acidification, addition of salts, or hydrocolloids)

Cold hydrogelled emulsions are formed by change in the pH (such as the use of glucono-δ-lactone) and/or modification of ionic strength (addition of salts). Another possibility is with of the addition of proteins such as gelatin or polysaccharides as alginate (Herrero et al. 2018; Mao et al. 2018; Sato, Moraes, and Cunha 2014). By changing the pH the emulsions can flocculate by lowering the pH toward pI. Divalent ions (especially Ca^{2+}) can interact with the protein adsorbed at the interface forming a protein network, but the increase of the ionic strength by adding electrolytes (e.g., NaCl or $CaCl_2$) to the aqueous phase also reduce the inter-droplet repulsion by electrostatic screening (Dickinson 2010), inducing droplets flocculation.

The addition of alginate to GE as a potential cold gelling agent has been studied (Pintado et al. 2015; Sato, Moraes, and Cunha 2014). During cold gelation alginate forms an "egg-box model" gel characterized by a 3-dimensional network formed by the cross-linking of polymeric molecule. This network contains a large amount of water entrapped in the structure, exhibiting a more rigid texture (Roopa and Bhattacharya 2010). The cold gelation induced by gelatin addition typically generate elastic polymeric gels of flexible, random-coil protein chains formed at cooling temperature (Sala et al. 2009).

To induce cold gelation in GE by changing the pH, a stable emulsion must be first formed followed by acidification by slowly decreasing the pH with the addition of a chemical acidulant such as glucono-δ-lactone (Chen and Dickinson 2000; Mao et al. 2018). The slow decrease in pH is important to induce a more ordered gelation and avoid emulsion destabilization. When cold gelation is performed by adding polysaccharides to the GE, these gelling agents are added to the aqueous phase before the emulsion is formed. After emulsion formation a gel network is induced by decreasing the temperature to 2–10 °C (Pintado et al. 2016a; Pintado et al. 2015; Sato, Moraes, and Cunha 2014).

Enzymatic treatment

Enzymes are commonly used to modify foods, i.e., proteases to breakdown proteins in polypeptide fragments such as papain, bromelain, trypsin, chymosin, etc. Few proteins can catalyze the formation of covalent bonds among protein molecules and modify textural properties in food systems. Among them, transglutaminase (TG), a crosslinking enzyme type, is available commercially. One of the advantages of enzymatic cross-linking is that contrary to chemical modification, it doesn't generate off-flavors and preserves essential nutrients (Dickinson 1997). Other advantages of TG are related to their ability to cross-link most of the proteins and that reaction conditions are mild. Heating, change in pH, and/or ionic strength are not required (Matsumura, Kang et al. 1993).

The enzyme transferase microbial transglutaminase (m-TGase) (EC 2.3.2.13) catalyzes the transfer of acyl groups among glutamine residues in proteins, peptides, and primary amines. If the reaction occurs with a ε-amino group of a lysine residue an ε-(γ -glutaminyl) lysine cross-link is formed. In this case, mTGase can form intra- and intermolecular covalent bonds between glutaminyl and lysine residues of proteins (Dickinson 1997; Lee, Choi, and Moon 2006).

The conversion of a liquid-like emulsion into a protein-stabilized GE with TG will occur due to the aggregation of droplets mediated by crosslinking among protein molecules adsorbed onto oil droplet surfaces (Dickinson and Yamamoto 1996). The conventional process to obtain m-TGase-induced GE consists of adding the enzyme after the emulsion has been formed and incubating it at 37 °C for a period of time between 2 and 6 h (Lee, Choi, and Moon 2006; Yang, Liu, and Tang 2013). A novel process to form a m-TGase-induced GE was proposed by Tang et al. (2013) by adding m-TGase prior to the emulsification. Their findings show that gelled emulsion with much higher stiffness was formed when the enzyme was added before the emulsification. Successive heat treatment of the m-TGase-induced GE can also produce an increase in elasticity (Dickinson and Yamamoto 1996) or may keep the mechanical properties constant, suggesting that the m-TGase can improve the thermal stability of GE (Lee, Choi, and Moon 2006). Few studies have been performed using enzymatic treatment to form a gelled emulsion (Matsumura, kang et al. 1993; Pintado et al. 2015; Yang, Liu, and Tang 2013) and further studies in this area presents a great potential to elaborate fat mimetic for healthier foods.

Gelled emulsions as carriers of healthy ingredients

Emulsions can be used in the food industry to deliver functional ingredients (McClements 2010). Recent trends of using environmentally friendly and natural ingredients in food formulations to claim a "clean label" have triggered a tendency of substituting synthetic emulsifiers or stabilizers by natural ones. Table 2 shows recent studies that used healthier ingredients in gelled emulsion. We can observe that vegetable ingredients such as soy, oats, and their byproducts (isolate, flour, oil, etc.) could be promising options for this application since these ingredients contain various healthy bioactive compounds (Herrero et al. 2018). Healthier oils (olive, algae, chia), antioxidants (phenolic compounds, and carotenoids), vitamins, minerals, fibers, and others bioactive compounds can also be added to gelled emulsion systems.

In addition, nutritional claims can be reached by reformulating meat products with gelled emulsion. Products labeled as reduced-fat, high omega-3 fatty acids, high content of unsaturated lipid, fiber source, source of minerals (zinc, manganese) can be obtained depending on the ingredients used to elaborate the emulsion (Pintado et al. 2018).

In vitro bioavailability of gelled emulsion

Dietary fats and oils are important components of a healthy diet. They are significant contributors to total energy intake and to the ingestion of lipophilic nutrients and bioactive compounds (n-3 fatty acids, conjugated linoleic acid, butyrate, phytosterols, carotenoids, antioxidants, coenzyme Q, and vitamins A and D) (Guo, Ye et al. 2017; McClements and Li 2010). The bioaccessibility of these lipids is determined by the digestion process which in turn affects their bioavailability (Lin and Wright 2018).

Understanding the mechanisms of lipid digestion and absorption is important to ensure that lipids provide appropriate nutritional properties. In recent years, studies have shown that the rate of lipid digestion and therefore the bioavailability of fatty acids depend on the delivery matrix (Singh, Ye, and Horne 2009). That is, the structure of the food can affect how lipids are digested and absorbed. Therefore, knowledge of the disintegration of food structures during eating and digestion is useful for the design of foods with appropriate bioaccessibility (Singh, Ye, and Ferrua 2015).

Structured emulsions such as gelled emulsions allow for nutrient delivery (i.e., DHA) in a controlled manner, and high bioaccessibility of the bioactive compounds can be achieved. This enhanced bioaccessibility is attributed to an enhanced transfer of lipids from the oil to the aqueous phase due to the emulsification process (Gayoso, Ansorena, and Astiasarán 2018). In some cases the gelation of simple or double emulsions can also delay lipid digestion (Cofrades et al. 2017; Wang et al. 2013) and reducing fat consumption by decreasing fatty acid uptake (Mao and Miao 2015). Several factors may influence release and digestion of the nutrients, especially lipids, in gelled emulsion. Previous studies have shown that ionic strength (Guo et al. 2013, 2014b), firmness (Guo, Bellissimo, and Rousseau 2017b), droplet size (Guo et al. 2014a), structure (Guo, Bellissimo, and Rousseau 2017b), physical state of the emulsified fats (Guo, Bellissimo, and Rousseau 2017a), type and concentration of dietary fibers (Qin et al. 2016), emulsifier type (Chang and McClements 2016; Zhang et al. 2015), and oil content (Sala et al. 2007) play a key role in the emulsions gastric digestion and in the release of compounds during intestinal digestion. The formation of a more resistant interfacial film using plant proteins as emulsifier may protect the oil droplet against lipolysis during digestion compared to animal proteins (Guo, Ye et al. 2017).

Bioavailability can be evaluated by in vitro studies that attempt reproduce physicochemical changes and nutrient digestion that occur in a real digestive tract. However, these are only an approximation and not a true representation of the events that occur in the human body. In vivo food digestion is more complex to perform and is a better representation of real digestion processes. These tests are affected by diet habit, health state, volume of digestive juice, gastrointestinal tract microflora, etc. More complex in vitro digestive models need to be designed to evaluate the bioaccessibility of gelled emulsion and to improve formulation of healthy diets (Mao and Miao 2015). When fat reduction and/or fat substitution in meat products are desired the knowledge of the digestion of dietary triacylglycerols in the gastrointestinal tract is important to design products with improved or decreased bioavailability of fatty acids.

Table 3. Use of gelled emulsions to improve/replace animal fat content in meat products.

Meat system	Oil	Protein/Polysaccharide/as a functional ingredient and gelling agents	Storage conditions	References
Fresh sausage (*longaniza*)	Olive	Chia flour or oat bran	18 days at 2 °C	(Pintado et al. 2018)
Meat emulsion	Soybean	Soy protein isolate, sodium caseinate, carrageenan, inulin, pectin, sodium tripolyphosphate, and soy lecithin.	–	(Paglarini, Furtado et al. 2018)
Frankfurter	Olive	Chia, transglutaminase, alginate, or gelatin	85 days at 2 °C	(Pintado, Herrero, Ruiz-Capillas et al. 2016)
Burger patties	Sunflower	Carrageenan, Polysorbate 80	Raw and cooked burger patties	(Poyato et al. 2015)
Burger patties	Algae	Carrageenan, Polysorbate 80	4 °C/vacuum, 4 °C/no vacuum, 25 °C/vacum and 25 °C/no vacuum for 31 days	(Alejandre et al. 2017)
Pork patties	Perilla	Gelatin and transglutaminase	Raw patties (2 °C for 14 days) and cooked patties	(Freire, Cofrades et al. 2017)
Dry fermented sausage	Linseed	Carrageenan, Polysorbate 80	–	(Alejandre et al. 2016)
Bologna-type sausage	Linseed	Carrageenan, Polysorbate 80	–	(Poyato et al. 2014)
Frankfurter	Olive	Chia flour, alginate, sodium alginate, $CaSO_4$ and pyrophosphate	–	(Pintado et al. 2016b)
Turkey breast emulsion, chicken patties and meat emulsion	Olive	polyglycerol polyricinoleate, gelatin and inulin	–	(Serdaroğlu, Nacak, and Karabıyıkoğlu 2017; Serdaroğlu et al. 2016; Serdaroğlu and Öztürk 2017)
Burger patties	Linseed and chia	Carrageenan, Polysorbate 80	–	(Heck et al. 2019)
Meat emulsion	Canola	Carrageenan	–	(Alejandre, Astiasarán et al. 2019)
Burger patties	Microalgae	Blackthorn branch extract, carrageenan	–	(Alejandre, Ansorena et al. 2019)
Fermented sausage	Linseed oil	Inulin, pork gelatin	30 days at 4 °C	(Glisic et al. 2019)

Gelled emulsion as a fat replacer in meat products

Animal fat is a semi-solid material that provides many desired properties in meat products such as mouthfeel, juiciness, texture, bite, and heat transfer. Consequently, the replacement of animal fats with liquid fats in meat products is a challenge since many of the desired product quality mentioned above are lost (Jiménez-Colmenero et al. 2015; Jiménez-Colmenero 2007).

Several techniques have been developed in recent years to structuring liquid oils to be used in reformulated products and meet the desired characteristics of the original product (Jiménez-Colmenero 2007). Gelled emulsions, in particular, were used in meat products without affecting their hardness and water holding capacity (Alejandre et al. 2017; Alejandre et al. 2016; Freire, Cofrades et al. 2017; Herrero et al. 2017; Paglarini, Furtado et al. 2019; Paglarini, Martini, and Pollonio 2019; Pintado et al. 2018). A summary of the use of GE in meat products is presented in Table 3. Consumers demand for healthier foods provides a commercial interest from the food industry to develop novel meat gelled emulsions that contain healthy fats (Dickinson 2012). Furthermore, the using GE as fat replacers improved fat bioaccessibility and also protects lipids from environmental factors such as light, oxygen, and enzymes, and they usually have improved chemical stability (Mao and Miao 2015) (Poyato et al. 2015).

Nutritional composition, technological, microstructural, microbiological, and sensorial properties in meat products must be considered when pork back fat is replaced by gelled emulsions. Table 4, summarizes the main effects on these properties based on the results published in previous studies (Alejandre et al. 2017; Alejandre et al. 2016; Freire, Bou et al. 2017; Herrero et al. 2017; Paglarini, Martini, and Pollonio 2018; Pintado et al. 2018; Pintado et al. 2016b; Pintado et al. 2015; Poyato et al. 2014; Poyato et al. 2015; Serdaroğlu, Nacak, and Karabıyıkoğlu 2017; Serdaroğlu et al., 2016; Serdaroğlu and Öztürk 2017).

GE properties depend mainly of the type or amount of hydrocolloids and oil added to GE. Regarding texture, products similar to the control formulation (conventional product) have been found when carrageenan, soy protein isolate, or oat bran were added as gelling, emulsifying, or stabilizing agents (Paglarini, Martini, and Pollonio 2019; Pintado et al. 2018; Poyato et al. 2014). The replacement of animal fat by inulin-based GE has shown a decrease in hardness of meat products (Glisic et al. 2019; Serdaroğlu, Nacak, and Karabıyıkoğlu 2017).

In general, the color parameters (L*, a*, and b*) of meat products are affected by the addition of GE as a fat replacer and it is related to the diameter of emulsion oil globules, which reflect more light than the larger animal fat globules (Poyato et al. 2014). However, recent studies have found no effect on color parameters when a GE produced with microalgae oil and carrageenan were added as a replacement for animal fat in beef patties (Alejandre, Ansorena et al. 2019).

Nutritionally, the products formulated with GE presented an increase in MUFA and PUFA such as α-linolenic acid content and a decrease in SFA. Depending on the

Table 4. Quality parameters of meat products considering the replacement of animal fat by gelled emulsion (GE).

Quality parameters of meat products									
Cooking loss	Emulsion stability/WHC	Texture	Lipid oxidation	Fatty acid profile	Color	Microstructure	pH	Microbiology	Sensory
Effects to replacing animal fat by gelled emulsion									
Lower than control due to the capacity of the hydrocolloids from GE to hold water	Improved when compared to control with animal fat	Depending on polysaccharide/ protein and oil used to form the GE, and the type of raw material of meat product	It mainly depends on the oil source	Higher MUFA and PUFA contents And lower SFA content in samples with GE	Higher L* and b* values and lower a* values in samples with GE	More compact than control with animal fat	Generally is similar to control with animal fat	It mainly depends on the GE constituents	-Replacing 100% of animal fat by GE cause negative effects -When animal fat is partially replaced by GE similar or better results could be obtained

WHC – water holding capacity, MUFA – monounsaturated fatty acid, PUFA – polyunsaturated fatty acid, SFA – saturated fatty acid.

polysaccharide source used to form the GE, final products with health claims could be obtained. For example, GE added of oat bran has been developed and the final amino acid and mineral profile of the fresh sausage was improved (Pintado et al. 2018).

Lipid oxidation is an important quality parameter of meat products, as it affects their nutritional and sensory properties. The addition of GE had a different impact on lipid oxidation of meat products. Poyato et al. (2015) observed that 1.5% carrageenan-GE formulated with 40% sunflower oil increased the lipid oxidation rate in burger patties after the cooking process. In contrast, when a low oil ratio GE (1% algae oil and 3% of carrageenan) was used in beef burgers a considerable reduction in lipid oxidation was achieved, probably due to the amount of oil and the protective ability of algae oil (Alejandre et al. 2017). An interesting strategy is to add natural antioxidants to the emulsion gel formulation to delay oxidation in the final product. Alejandre, Ansorena et al. (2019) added blackthorn branch extract in a DHA rich oil GE used as fat replacer in beef patties and the result showed that peroxide content was reduced more than two-fold when compared to control patties.

The addition of GE as pork back fat replacer in meat products may affect or not (Alejandre et al. 2017; Poyato et al. 2015) sensory properties, but in general the final products are judged acceptable by the panelists. A relevant point in the findings of previous studies is the level of the fat substitution and the amount of ingredients with singular sensorial properties (i.e., chia flour) added in the GE formulation. A total animal fat substitution by GE showed a negative impact (Serdaroğlu, Nacak, and Karabıyıkoğlu 2017) and the reduction of chia flour level from 20% to 5% in GE did not affect general acceptability of sausages (Pintado et al. 2018; Pintado, Herrero, Ruiz-Capillas et al. 2016).

Conclusions and future directions

Gelled emulsions are systems with potential use as carriers of functional ingredients such as plant proteins, fibers, antioxidants, vitamins, and others. When used as a fat analog it is essential to understand their role as part of the food product. The oil of the dispersed phase, emulsifier type, gelation method, and the product to be added should be considered before making a gelled emulsion. The replacement of animal fat by structured oils such as gelled emulsion is an interesting strategy to make meat products with a better fatty acids profile. Characteristics such as texture, cooking loss, lipid oxidation, microstructure, microbiology, and sensory may be affected by replacing pork back fat by gelled emulsion and shelf life studies are necessary to evaluate these changes. Several studies have been published where gelled emulsion was used in meat products as a fat substitute, but future bioavailability studies are necessary to understand the release and digestion of the nutrients, especially lipids, from the intake of these reformulated meat products.

Acknowledgments

The authors thank CNPq, CAPES, and FAPESP (process numbers 140531/2015-7, 88881.135401/2016-01, and 2016/19967-7, respectively) for the financial support to this work and scholarships.

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