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Recent progress of fat reduction strategies for emulsion type meat products

Haozhen Zhang#, Weiyi Zhang#, Xianming Zeng, Xue Zhao*, and Xinglian Xu*

Key Laboratory of Meat Processing and Quality Control, Ministry of Education; Jiangsu Collaborative Innovation Center of Meat Production and Processing, Quality and Safety Control, Nanjing Agricultural University, Nanjing 210095, PR China

# These authors contributed equally: Haozhen Zhang, Weiyi Zhang

* Corresponding author, E-mail: zhaoxue@njau.edu.cn; xlxus@njau.edu.cn

Abstract

With the continuous improvement of living standards, people's demand for meat products is increasing. However, the high fat content in traditional meat products will result in additional chronic diseases, causing harm to human health. Hence, there exists an urgent need for research on fat reduction technology of meat products. Recently, physical modification technologies and protein/carbohydrate/lipid/complex-based fat substitutes have gained great interest in reducing animal fat, which can simultaneously improve the technological and sensory properties of meat products. In this thriving field, many newly presented works lack comprehensive summary and critical comparison. Therefore, this paper reviews the latest research progress on the application of physical technologies and fat substitutes in fat-reduced meat products, highlighting their advantageous and disadvantageous in reducing total fat, improving the fatty acid profile and modifying technological and sensory properties of products. Finally, future trends are proposed with the aim to provide new insight into the development of quality fat-substituted meat products.

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Introduction

Emulsion type meat products play an important role in the food market, they are attractive to consumers because of high sensory quality and convenience. Animal fat addition decides the quality and palatability of emulsified meat products, especially endowing meat products with improved texture, smooth mouthfeel and unique flavor[1]. To maintain improved sensory quality, the fat content in emulsion type meat products like frankfurter and bologna sausage should be 20%–30%[2,3]. However, the animal fat often contains a high level of saturated fatty acid (SFA). For instance, pork frankfurters prepared with pork backfat were reported to include 8.7% SFA[2]. Compared with unsaturated fatty acid (UFA), SFA tends to increase total cholesterol and low density lipoprotein (LDL) in the human body[4]. As a result, extensive research has reported that the incidence of obesity, cardiovascular diseases, diabetes, cancers and other harmful chronic diseases are highly associated with the consumption of SFAs[1,5,6]. According to the reports of the Chinese National Health Commission in 2020, more than half of China's adult residents and nearly 30% of adolescents under the age of 18 are overweight or obese[7,8]. Therefore, it is urgent to develop feasible strategies to lower the intake of SFA to below 10% to ensure a healthier diet[1].

Predictably, the consumption of highly-processed emulsified meat products would keep a constant increasing trend for decades to come. Nowadays, with the spread of knowledge, health-conscious consumers not only care about the sensory and flavor properties of meat products, but also emphasize the nutritional and healthy qualities[9,10]. The development of meat products tends to be functional and healthy[11]. Therefore, low-fat products are more welcomed by the market[12]. It is predicted that the annual sales of low-fat meat products would increase at a rate of 25.5% worldwide. Hence presently, the fat-reduction technology of meat products is becoming the center of attention. However, it is challenging to improve or even maintain the quality of low-fat meat products due to the above-mentioned role that fat plays[13].

Considering the difficulty as well as importance in achieving a balance between fat replacement and meat quality maintenance, there are mainly two strategies to reduce the content of animal fat in meat products or improve the quality of lower-fat meat products: (1) treating low-fat meat batters with physical modification methods to inhibit the deterioration induced by fat reduction; and (2) substituting animal fat with UFA-enriched lipid, which not only optimizes the fatty acid profile by limiting the unhealthy SFA intake, improving the content of beneficial monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA), but also improves textural, nutritional and sensory properties of meat products. Extensive advanced progress of fat reduction technology of meat products are emerging constantly owing to: (1) the scientific rationale that a high intake of SFA will lead to chronic and physiological disorders; and (2) the critical difficulty to achieve a balance between fat substitution and sensory attributes, considering the significant role that fat plays in the mouthfeel (i.e. juiciness, tenderness etc.), flavor of meat products. Keeton[14] previously summarized the technological problems concomitant with fat substitution in meat and introduced potential methods to relieve these problems which paved the way for the further burgeoning of fat-reduced meat markets. However, these proposed methods were far from comprehensive and efficient due to the limited development of scientific cognition at that early time. Some systematic reviews later summarized novel technologies used in animal fat replacement like oleogels[1], hydrogels[15], microencapsulation[16] and others. Badar et al.[17] recently discussed the application of different emulsion types in fat-reduced meat products, paying more attention on the comparison of vegetable oil types but lacking that of protein and carbohydrate types. In this work, the emphasis is placed on the detailed review of fat-substitution technologies (physical technology, oleogel, hydrogel, emulsion gel, microencapsulation), materials (protein, carbohydrate, vegetable oil) and processing parameter optimization to provide feasible suggestions for practical production. The advantages and disadvantages of these processes are discussed critically afterwards. Finally, future potential developments to further decrease fat content without sacrificing the sensory quality of meat products are proposed.

Progress of physical technology in low-fat meat products

Physical technologies, such as high-pressure processing (HPP) and ultrasonic technology, were reported to be able to effectively improve the qualities (i.e. pH, color and texture) of low-fat meat products. Such improvements might be correlated with the stronger protein-protein (mainly myofibrillar protein in meat) crosslinking, and thus a more compact 3D gel network, which is enhanced by applied pressure and ultrasound[18].

High-pressure processing (HPP)

HPP belongs to a kind of non-thermal processing[19]. Briefly, during HPP, the water molecules are pressed into the interior of muscle fibers to reduce cross-linking between non-polar groups of muscle proteins, resulting in partial denaturation and unfolding of protein molecules. Hence, the strength of intermolecular forces (i.e. hydrophobic interaction, hydrogen bond, van der Waals forces, etc.) between meat proteins and water molecules is promoted[20,21] which might improve the water holding capacity and homogeneity of 3D gel matrices. In addition, due to more active residues being exposed and thus the protein-protein interactions are facilitated in this process, the compactness of the 3D network of the gel structure formed during cooking is enhanced, leading to a better ability to retain liquid[22−24], improving the texture and yield of low-fat meat products[25]. As listed in Table 1, the optimized pressure in meat processing is roughly 200-300 MPa, and most of them were of great significance in improving the water holding capacity (WHC)[22,23,26,27]. The improvements of texture in low-fat meat products through HHP were closely related with adopted parameters, such as pressure value, time, and temperature. Specifically, the optimization was focused on tenderness, elasticity, juiciness and chewiness[23,26,28]. For instance, 1% NaCl + HPP at 200 MPa (2 min) improved hardness, springiness and chewiness of heated pork gel[22]. According to Yang et al.[26], pressurized (200 MPa, 3 min) low-fat and low-salt (LFLS) pork sausage possessed a better tenderness. Considering the positive effect of HPP on improving the interfacial properties of meat proteins in emulsified meat products[21], more studies should be focused on how HPP compensating the deficiency of low-fat meat products from the mesoscopic view around the oil-water interface. For example, HPP of 200 MPa could improve the emulsion properties of LFLS pork sausage through modifying the chemical interactions between adsorbed proteins and enhancing the rearrangement of interfacial protein films[29].

As a pre-processing stage for meat products, HPP has a good prospect in reducing fat in meat products[30]. Using HPP (600 MPa, 5 min) kept sensorial (appearance, texture and flavor) qualities and edible safety while reducing the 35% fat content in dry-cured fermented sausage[31]. However, in recent years advanced research related to developing low fat

Table 1. Effects of physical lipid-lowering technology on the quality of meat products.

Types of treatment object	Lipid lowering technology	Processing parameters	Implications		
			Physicochemical property	Nutritional ingredients	Reference
RFRS pork sausage	High pressure process	200 MPa, 3 min	↑Tenderness, WHC ↓ Hardness	↑Moisture ↓Fat, salt	[26]
Pork sausage	High pressure process	200 MPa, 2 min, 10 °C	↑Hardness, springiness, chewiness, L* color parameter, pH, WHC ↓a* and b*color parameters, CL	↑Moisture ↓Fat	[22]
RFRS pork sausage	High pressure process	300 MPa; 10 min	↑WHC ↓Gel strength, the water relaxation time of the gel	↓Fat, salt	[23]
Dry-cured fermented sausage	High pressure process	600 MPa; 5 min	↑L* and b* color parameters, texture ↔a* color parameter, edible safety	↑Moisture, protein ↔Lipid oxidation, microbial growth ↓Fat, caloric	[31]
Low-fat pork emulsion sausage	Sonication	Sonication frequency: 20 kHz; time: 30 min; powder: 200 W	↑WHC, hardness, cohesiveness, chewiness, emulsion stability ↓CL	↓Expressible fat	[32]
Frankfurter	Sonication	Sonication frequency: 20 kHz; time: 30 min; amplitude: 60 μm; powder: 30-40 W	↑L* and b* color parameters ↓CL, hardness	↑Protein content, UFA, dietary fiber ↓Fat, SFA	[8]

meat products with HPP have not been widely reported[19]. Accordingly, besides improving physicochemical qualities, further studies should more deeply focus on the prospect of employing HPP-treated meat as a fat-replacer due to its ability to mimic the fat particles and to ensure a stable incorporation of other fat substitutes like vegetable oil[31].

Ultrasound

Ultrasound is extensively applied in emulsification, refrigeration, thawing and other non-thermal processes in meat products, leading to various impacts on the functional properties of low-fat meat products (i.e. pH, color, tenderness, WHC, and oxidation stability). Regarding the mechanism, ultrasound could modify the meat proteins through cavitation phenomenon, which is characteristic of the propagation of sinusoidal compression and rarefaction waves[18]. The cavitation could impose physical forces including shearing, shocking and turbulence on myofibril, thus modifying intermolecular interactions and inducing the protein unfold as well as crosslinking to form a compact gel network[18]. Currently, the utilization of ultrasound technology in low-fat meat products has given more attention to improving the meat qualities (i.e. color parameters, WHC and texture) of low-fat meat products. Synergistically, basic amino acids (L-lysine and L-arginine) cooperated with ultrasound (20 kHz 30 min 200 W) remarkably enhanced WHC, textures (hardness, cohesiveness, chewiness) of low-fat pork emulsion sausage exhibited with lower cooking loss (CL) and expressible fat[32]. Similarly, low-fat frankfurter subjected to ultrasound (frequency: 20 kHz, amplitude: 60 μm, powder: 30−40 W) had a reduced CL, texture and color parameters[33]. Nevertheless, current studies focussing on low-fat meat products with sonication treatment are still rare, indicating that more verified tests and optimized parameters (i.e. sonication power, frequency and time interval) need to be further explored.

As noted above, non-thermal process technology prominently improved physicochemical characteristics (WHC, CL etc.) of low-fat meat products. However, sensory evaluation and fat reduction efficiency are still unknown in most cases for physical lipid-lowering technologies. Therefore, this gap should be further filled to meet the consumers' healthy diet demand.

Recent applications of fat substitute to meat products

It is has become more mainstream that fat substitutes have become the central topic for fat reduction technology. Fat substitutes, also called 'fat replacer' or 'fat analogue', could not only reduce the fat content in meat products, but also enhance meat quality with regards to improving the fatty acid profile (i.e. the ratios of PUFA/SFA and ω-6/ω-3 UFA), physicochemical characteristics (i.e. pH, color parameter, WHC and CL) and sensory properties (i.e. flavor, consumer acceptability). Basically, fat substitutes can be categorized into two types: (1) single fat substitute that only contain one kind of macromolecule (protein, carbohydrate or lipid); (2) complex matrix fat substitutes that are composed of two or more kinds of macromolecules. Recent studies on developing of fat-substituted meat products and the optimized parameters are summarized in Table 2.

Protein-based fat substitutes

Protein-based fat substitutes mainly consist of plant protein (i.e. soy protein) and animal protein (i.e. whey proteins, collagen, casein)[34]. These proteins can be used to facilitate gel[35] or emulsion[15] formation to replace fat via different processes (i.e. high speed or pressure homogenization, enzymatic, heat or cold treatment)[34].

The replacement ratio of animal fat in meat products (i.e. pork or beef sausages) ranged between 50%−75%. In these cases, proteins were used to replace fat after proper pretreatments, such as SDS supplement[35], microparticulated process[36] and hydrolysis[37]. Moreover, the fat replacement resulted in a significant improvement in WHC[37], and in turn a decrease of CL[35] for sausages, while the changes in texture (i.e. hardness, chewiness etc.) were varying. Specifically, whey protein isolate[35] or collagen[37] as fat substitutes led to higher hardness and/or chewiness of pork sausages, while microparticulated whey protein (MWP) applied in beef sausage gave the opposite result[38], which might be related to the variation in meat types and reformulations. Additionally, as for nutritional and sensory properties, the content of protein and other nutrients in most cases increased with higher consumer acceptability. It is important to note that although the utilization of protein-based fat replacer has been widely investigated in food such as ice cream or mayonnaise[39], their application in meat products still needs to be further studied.

Carbohydrate-based fat substitutes

Carbohydrate-based fat substitutes mainly refer to plant polysaccharides (i.e. starch, cellulose, gum arabic and pectin), which are commonly directly incorporated into meat products to replace animal fat.

Different from protein-based fat substitutes, the percentage of animal fat replaced by plant polysaccharides ranged between 25%−34% and the reformulated products were mostly sausages and burgers. Regarding physicochemical properties, the use of carbohydrate-based fat replacer resulted in the increase of L^*, a^* and/or b^* in most cases[40−42], which might affect the consumer choices to different extents. Only the study of Santos et al.[43] suggested that the partial replacement (25%) of animal fat by 2% of dietary fiber (microcrystalline cellulose, resistant starch or oat fiber) did not significantly affect color parameters mainly owing to the lower replacement ratio. Except for the study on beef burgers whose fat was replaced with hydrate wheat fiber, which exhibited deteriorated hardness, elasticity and chewiness[41], the textural performance of other carbohydrate-based fat-replacement products showed an increased tendency[40,43]. Besides, the lipid and/or protein oxidation in some cases decreased[40,42−44], leading to a longer shelf-life and a lower LDL level.

With respect to nutritional compositions, application of polysaccharide replacer led to lower total fat, protein, salt, calorie, energy values and higher moisture, fiber and lactic acid bacteria content in the final meat product[40−43], further resulting in a healthier diet. From a sensorial point of view, the use of polysaccharides-based fat substitutes did not impair and even enhanced consumer acceptability[40]. It was interesting to note that hydrated wheat fiber (3.75 g fiber/80

Table 2. Effects of protein matrix, carbohydrate matrix, lipid matrix and complex matrix fat substitutes on the quality of meat products.

Types of fat substitutes	Types of meat products	Main replacement ingredients	Replacement ratio of animal fat (%)	Substitution form	Implications			Reference
					Physicochemical property	Nutritional	Sensorial	
Protein matrix fat substitute	Pork sausage	WPI 10%, SDS 0.06%	75	Gel	↑Viscosity, hardness ↓CL	↑Moisture	–	[35]
Protein matrix fat substitute	Beef sausage	Beef fat 10%, MWP 5%	50	Emulsion	↑Emulsion stability, processing yield, a* and b* color parameters ↓Hardness, chewiness, adhesiveness, lipid oxidation	↑Protein ↓Fat, energy	↔Consumer acceptability	[38]
Protein matrix fat substitute	Frankfurter	Hydrolyzed collagen 50%	50	Direct incorporation	↑WHC, hardness, chewiness	↑Protein, minerals ↓Fat	↑Consumer acceptability	[37]
Carbohydrate matrix fat substitutes	Pork sausage	Regenerated cellulose fiber 0.8%	33	Direct incorporation	↑Emulsion stability, L* color parameter, viscosity (raw meat batter), hardness, gumminess, chewiness ↓Lipid oxidation	↓Fat	↑Consumer acceptability	[40]
Carbohydrate matrix fat substitutes	Beef burger	Hydrated wheat fiber 4.7%	34	Direct incorporation	↑L* and b* color parameters ↓CL, hardness, elasticity, chewiness	↑Moisture ↓Calorie values, protein, fat	↔Consumer acceptability	[41]
Carbohydrate matrix fat substitutes	Salami	MCC/RS/OF 2%	25	Direct incorporation	↑Antioxidant characteristic, hardness, chewiness (MCC and OF) ↔Appearance, color, weight loss, pH ↓A_w	↑Lactic acid bacteria count (MCC) ↓Fat, salt	↔Consumer acceptability	[43]
Lipid matrix fat substitute	Pork sausage	Sunflower oil 5%–20% Gelator: Glyceryl monoglyceride 5%	50	Oleogel	↑Hardness, L* color parameter ↓pH	↑PUFA, MUFA ↓Fat, SFA	↑Consumer acceptability	[46]
Lipid matrix fat substitute	Pork sausage	Sunflower oil 25%, pork skin 37.5%	50	Oleogel	↑Emulsion stability, hardness, chewiness ↓CL	↑MUFA ↓Linoleic acid, cholesterol, energy, fat, SFA	↔Consumer acceptability	[47]
Lipid matrix fat substitute	Pork sausage	Linseed oil, γ-oryzanol: β-sitosterol = 3:22 Gelator: Beeswax 8%	40	Oleogel	↑L* and a* color parameters ↓Hardness	↑Moisture, MUFA, PUFA ↓Fat, SFA	↔Consumer acceptability	[48]
Lipid matrix fat substitute	Frankfurter	Linseed oil Gelator: Beeswax 8%	25 or 50	Oleogel	↑L* and b* color parameters, cohesiveness, gumminess, and chewiness ↓a* color parameter	↑PUFA ↓Fat, SFA, cholesterol, AI, TI, ω-6/ω-3 ratio	↓Consumer acceptability	[2]
lipid matrix fat substitute	Pork burger	Curcumin (0.2 g/100 g oleogel), oleogel (olive oil, linseed oil etc.) 6.0 g/100 g	100	Oleogel	↑Hardness ↓Lipid oxidation	↑PUFA, MUFA	↑Consumer acceptability	[49]
Lipid matrix fat substitute	Beef burger	Soybean oil 0–6% Gelator: Ethyl cellulose 2%, adipic acid 4%	50	Oleogel	↑Hardness, OBC ↓L* and a* color parameters	↓Fat	↑Consumer acceptability	[50]
Lipid matrix fat substitute	Beef burger	Sesame oil 15 g Gelator: Beeswax 10%	25–50	Oleogel	↑Cooking shrinkage, L* and b* color parameters ↓Hardness, gumminess, chewiness, lipid oxidation, CL	↑UFA ↓Fat, acid value	↑Consumer acceptability	[51]

(to be continued)

Table 2. (continued)

Types of fat substitutes	Types of meat products	Main replacement ingredients	Replacement ratio of animal fat (%)	Substitution form	Implications			
					Physicochemical property	Nutritional	Sensorial	Reference
Lipid matrix fat substitute	Beef patty	Canola oil (2%, 4%, 6%) Gelator: Hydroxypropyl methylcellulose 1%	50	Oleogel	↑Firmness, work of shear, CL ↓Lipid oxidation	↑UFA ↓SFA	↑Consumer acceptability	[54]
Lipid matrix fat substitute	Beef heart patties	Rapeseed oil Gelator: Beeswax 10%	100	Oleogel	↑L* color parameter, melting points, melting enthalpies, lipid and protein oxidation ↓Hardness, gumminess, lipid and protein oxidation	↑PUFA, moisture ↓Fat, SFA	–	[61]
Compound matrix fat substitute	Frankfurter	Rye bran addition (5 g/100 g) with collagen (1 g/100 g)	74	Direct incorporation	↑Hardness, firmness	↓Fat	↑Consumer acceptability, spiciness	[63]
Compound matrix fat substitute	Beef batter	Pea protein isolate 24%, agar-agar 1.5%, NaCl 2%	100	Gel	↑L* and b* color parameters ↓a* color parameter, CL, chewiness, hardness, lipid oxidation	↑Moisture, protein, dietary fiber ↓Fat, energy	–	[65]
Compound matrix fat substitute	Chicken sausage	Chicken skin 1.5%, water 2.5%, wheat fiber 1%	25	Direct incorporation	↑Hardness, L* color parameter ↓Tenderness, cooking yield, b* color parameter	↑Moisture ↓Fat	–	[64]
Compound matrix fat substitute	Chicken sausage	Perilla-canola oil 50%, PGPR 3.2%, soy protein isolate 4.48%, inulin 14%	100	Emulsion	↑Emulsion stability, L* color parameter, whiteness, hardness ↓CL	↑Moisture, protein, carbohydrate, PUFA ↓Fat, energy, ω-6/ω-3 ratio	–	[68]
Compound matrix fat substitute	Pork sausage	Sunflower oil 50%, xanthan gum 1%, succinylated chicken liver protein 2%	40	Direct incorporation/Emulsion	↑Gel strength, whiteness, emulsion stability, WHC, heating stability ↓Lipid oxidation, CL	↑PUFA ↓FA	–	[66]
Compound matrix fat substitute	Chicken batter	Inner water phase (W_1): MKB extract and NaCl 0.6% (w/w) Oil phase (O): soybean oil 35%, PGPR 6% Outer water phase (W_2): whey protein concentrate 6% and NaCl 0.6% (W_1:O:W_2 = 7:7:6)	100	Double emulsion	↑Emulsion stability, cooking yield, hardness, chewiness, L* color parameter ↓Shrinkage, a* color parameter, pH, lipid oxidation	↑Moisture ↓Fat	–	[70]
Compound matrix fat substitute	Frankfurter	Olive oil 6.5%, chia flour 10%	100	Direct incorporation/Emulsion/Emulsion gel	↑Hardness, chewiness, emulsion stability ↓Cohesiveness, springiness, processing loss	↑MUFA, linolenic acid, protein	↔Consumer acceptability	[53]
Compound matrix fat substitute	Frankfurter	Olive oil 16.8%, chia flour 25.84%	100	Direct incorporation/Emulsion/Emulsion gel	↑pH, water and fat binding properties, hardness ↓Processing loss, lipid oxidation, cohesiveness, springiness	↑Dietary fibre, minerals, linolenic acid ↓Fat, energy	↔Consumer acceptability	[67]

(to be continued)

Table 2. (continued)

Types of fat substitutes	Types of meat products	Main replacement ingredients	Replacement ratio of animal fat (%)	Substitution form	Implications			
					Physicochemical property	Nutritional	Sensorial	Reference
Compound matrix fat substitute	Frankfurter	SPI 33%, carrageenan 0.5%, inulin 16.5%, soybean oil 50%	100	Emulsion gel	↑L* and b* color parameters ↓CL, hardness	↑Protein, PUFA, dietary fiber ↓Fat, SFA, ω-6/ω-3 ratio, AI, TI	↓Consumer acceptability	[33]
Compound matrix fat substitute	Bologna sausage	Soybean oil 50%, soy protein 4%, inulin 16.5%	50 or 100	Emulsion gel	↑L* color parameter, elasticity, cohesiveness, resilience, lipid oxidation ↓a* color parameter	↑PUFA, fiber ↓Fat, sodium	↔Consumer acceptability	[71]
Compound matrix fat substitute	Model meat emulsion	Soybean oil 50%, remainder (soy protein isolate, sodium caseinate etc.) 50%	100	Emulsion gel	↑WHC, a* and b* color parameters ↓L* color parameter	↑PUFA, fiber ↓SFA	–	[52]
Compound matrix fat substitute	Pork sausage	Olive oil 40%, water 53%, MC 5%, remainder (sodium alginate 0.75%, calcium sulfate 0.75%, sodium acid pyrophosphate 0.5%) 2%	100	Direct incorporation/ Emulsion gel	–	↑Dietary fiber ↓Energy, fat, protein digestibility	↔Consumer acceptability	[45]
Compound matrix fat substitute	Beef batter	Canola oil 40%, polysorbate 80 0.05%, BHT 0.01%, kappa carrageenan 1.5%	100	Emulsion gel	↑L* color parameter, hardness ↓Lipid oxidation	↑PUFA ↓SFA, ω-6/ω-3 ratio	–	[55]
Compound matrix fat substitute	Pork burger	Pork back fat 10%, microparticles of chia oil 10%, sodium alginate 2%, rosemary leaves 1.25%	50	Microencapsulation	↓Protein oxidation	↓Ketone content	↑Consumer acceptability	[56]
Compound matrix fat substitute	Deer pâté	Tigernut/Chia/Linseed oil 6.25%, sodium caseinate 6.25%, lactose 6.25%	50	Microencapsulation	↑a* and b* color parameters, lipid oxidation ↓pH	↑PUFA, MUFA ↓Fat, SFA, ω-6/ω-3 ratio, cholesterol	↓Consumer acceptability	[57]
Compound matrix fat substitute	Frankfurter	Fish oil 6.7%, maltodextrin 13%, caseinate 6%, gum arabic 1%	50	Microencapsulation	↑L* and b* color parameters, lipid oxidation	↑Protein, carbohydrate ↓Fat, SFA, MUFA, ω-6/ω-3 ratio, energy	–	[72]
Compound matrix fat substitute	Beef burger	Chia oil/linseed oil 25%, sodium alginate solution 2.0%	50	Microencapsulation	↑Fat retention, heating stability, cohesiveness, chewiness, lipid oxidation ↓CL	↑PUFA/SFA ratio ↓ω-6/ω-3 ratio, AI, TI	–	[73]
Compound matrix fat substitute	Beef burger	Chia oil 100 g, rosemary leaves 12.5 g, sodium alginate solution 2.0%	50	Microencapsulation	↓Lipid oxidation	↑Moisture ↓Fat	↑Consumer acceptability	[62]

RFRS: reduced-fat and reduced-salt; WHC: water-holding capacity; PDI: polydispersity index; CI: cream index; WI: white index; UFA: unsaturated fatty acids; WPI: whey protein isolate; SDS: sodium dodecyl sulfate; CL: cooking loss; MWP: microparticulated whey protein; A_w: water activity; MCC: microcrystalline cellulose; RS: resistant starch; OF: oat fiber; FA: fatty acids; SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; AI: atherogenic index; TI: thrombogenic index; EC-Cu: sample formulated with total pork backfat replacement by oleogel elaborated with ethyl cellulose and with curcumin; OBC: oil binding capacity; SPI: soybean protein isolate; MC: mucilage chia; BHT: butylated hydroxytoluene; MKB: *Murraya koenigii*; PGPR: polyglycerol polyricinoleate g burger portion) was highly prone to maintaining the satiety mainly due to the low processing level of the fibers (whole grain treatment), the high viscosity of the digestible content and the viscous matrix effect[41,45]. Hence, it would be an excellent alternative for consumers who want to reduce fat and caloric intake without staying hungry.

With all results of protein and carbohydrate based fat substitutes in mind, there are a great deal of improvements in physicochemical, nutritional and sensorial properties of meat products, while the fatty acid profile optimization is limited. Under such circumstance, lipid-based fat substitutes have attracted growing interest in reformulated meat products.

Lipid-based fat substitutes

Regarding lipid-based fat substitutes, vegetable oils (i.e., sunflower oil[46,47], linseed oil[2,48,49], soybean oil[50], sesame oil[33,51,52], olive oil[45,49,53], canola oil[54,55] and chia oil[56,57]), in general, are used to replace animal fat in meat products by means of direct addition, organogelation, interesterification and structured emulsions[58], among which organogelation is the most commonly employed strategy.

Organogelation is featured on semi-solid vegetable oils with a liquid hydrophobic phase, which is generally cemented by a 3D organogel network[59,60]. This feature, which can provide suitable technological and organoleptic properties, together with the thermo-reversibility of organogelators promote the application of organogel in meat products[1]. The percentage of animal fat replaced with lipid-based fat replacer ranged between 25%−100%, with 50% being the major substitution ratio. These reformulated meat products (i.e. sausages and burgers) possessed a lower CL[47], OBC (oil binding capacity)[50] and lipid/protein oxidation[49,51,54,61], while color parameters[2,48,50] and texture[2,51] were various.

In comparison with the two fat-substitute strategies mentioned above, lipid-based fat substitution with oleogel resulted in a significant increase of MUFA or/and PUFA as well as a reduction of SFA[2,46−49,51] in meat products. Under this condition, oleogel facilitated the optimization of fatty acid profile, such as PUFA/SFA, n-6/n-3 ratio, AI (atherogenic index) or TI (thrombogenic index), making it a healthier alternative.

Maintained or even enhanced sensory properties were generally observed with a moderate high fat-replacement ratio[46,49−51,54]. However, certain organoleptic properties such as color and texture were inevitably impaired when adding vegetable oils as the fat substitutes[51,62]. Concerning color parameters, Franco et al.[2] indicated that the fat-replaced frankfurter (25% or 50% linseed oleogel) obtained a low acceptability score with a higher b^* (representing yellow color), which is usually recognized as the characteristic of moldy foods owing to lipid oxidation in meat products[2,57]. Hence, it is necessary to take these problems into account in future research.

Complex matrix fat substitutes

In complex matrix fat substitution, two or more ingredients mentioned above are employed to replace animal fat, which can, to some extent, synergistically compensate the defect of single matrix fat substitution. Hjelm et al. found that the direct incorporation of the complex of collagen/rye bran fiber reduced 74% of the animal fat of frankfurter sausages, whose textural (firmness, hardness) and sensory attributes were simultaneously improved compared with the products which had fat replaced with only rye bran fiber[63]. This might be because the collagen interacted or cross-linked with the myofibrillar protein (MP) matrix during the comminution and heating process, which formed a stronger gel network to enhance the texture and water/oil-binding capacity of emulsified meat products. A similar result was also obtained when chicken skin (containing collagen) was used to replace 25% pork back fat cooperatively with wheat fiber[64]. Furthermore, composite gels formed by the complex of protein and polysaccharide have recently become a novel formulation for fat substitution. For example, the incorporation of pea protein-agar agar gel complex into a model meat emulsion system could fully replace animal fat, as well increase the texture and stability of meat emulsions[65]. However, the comparison between the effect of these two substitution forms (direct incorporation and pre-formed gels) still needs to be further studied. Meanwhile, the incorporation of the complex of protein/polysaccharide barely improved the fatty acid profile of reformulated meat, in which situation the incorporation of vegetable oils along with the above two ingredients has achieved great attention.

Vegetable oils are commonly incorporated as fat-replacers in the form of pre-emulsions along with protein and/or polysaccharide. These components synergistically improve the fatty acid profile (low levels of SFAs, high levels of MUFAs and n-3 PUFAs) and reduce fat content[66−69]. During emulsification, emulsifiers (protein or polysaccharide) adsorb on the oil/water interface to form a viscoelastic interfacial film which shields oil droplets from collision and oxidation, thus rendering the end-products with an improved stability[66,68−70]. What's more, the oil droplets aggregate and a 3D-gel network forms through macromolecular interactions between the interfacial layer and the MP matrix during processing, which contributes to favorable textural (i.e. hardness, chewiness, springiness etc.)[66,67,70], processing (i.e. WHC, heat stability or gel strength etc.)[66−68,70] and organoleptic attributes[67,38]. However, Ozturk-Kerimoglu et al. indicated that the textural properties of emulsified sausages were impaired when pre-emulsions prepared using a complex of soy protein/sodium caseinate/MWP were incorporated, possibly owing to the lower total fat content and variations in emulsifier types[38]. Additionally, the pre-emulsions are further gelled through thermal or enzymatic treatment[15], and the replacement of animal fat by emulsion gels also plays an important role in reducing fat content and improving the fatty acid profile ascribed to the more lipid interactions in the reformulated products[33,45,52,55,67,71]. Regarding physicochemical properties, higher WHC/OBC[52,67] and enhanced texture (i.e. hardness, cohesiveness)[55,67,71] were also observed with the incorporation of emulsion gels. When comparing these two incorporation strategies (pre-emulsions and emulsion gels), Herrero et al. found that the incorporation of emulsion gels resulted in a significant lower CL than the incorporation of pre-emulsions[53], which might be due to the less porous microstructure of the meat matrix ensured by the pre-formed gel network. However, Pintado et al. suggested no significant differences between the fatty acid profile and physicochemical properties of these two incorporation strategies[67].

Generally, the nutritive and technological properties of the end-products are related to the oil/emulsifier type and concentration[33,52], emulsification condition (i.e., temperature, pH, ionic strength, emulsification method) and incorporation strategy (emulsions or emulsion gels)[53,67]. Therefore, to achieve a better formulation of fat-substituted meat products, emphasis should be placed on systematically studying the above factors.

Microencapsulation has emerged as a new strategy for fat substitution when vegetable oils are involved. That is, the oil particles in pre-emulsions are encapsulated through the technique of spray-drying, freeze-drying, complex coacervation and external ionic gelation[16]. Vegetable oil (i.e., chia, linseed and tigernut oils) encapsulation not only modified the fatty acid profile (decreased the amount of SFAs and increased the amount of PUFAs or MUFAs)[57,72,73], but also increased the texture (i.e. cohesiveness, chewiness)[73]. With respect to color parameters, L^*, a^* and/or b^* increased after the utilization of oil microencapsulation due to the incorporation of varying ingredients[57,72]. However, the oil microencapsulation produced through spray-drying, freeze-drying and complex coacervation is not recommended in the reformulation of cooked meat products, as they tend to rupture at around the cooking point of meat products (72 °C)[16], leading to an excessive level of lipid oxidation[57,72]. Contrarily, Heck et al. proved that chia oil microencapsulation produced through external ionic gelation remained integral during the heating process of 50% fat-substituted burgers (72 °C) and its incorporation led to healthier PUFA/SFA and n−6/n−3 ratios[73]. Based on this study, the group found that the same oil microencapsulation with the addition of rosemary could increase the oxidative stability and sensory attributes when replacing 50% fat of beef burgers[56,62], suggesting a feasible application of oil microencapsulation through an external ionic gelation method in cooked meat products.

Conclusions and future trends

Nowadays, with the concept of healthy diet prevailing among consumers, the demand for low-fat meat products has become more prominent. Physical modification technology and protein/carbohydrate/lipid/complex matrix fat substitutes can be applied in meat to reduce total fat and improve the fatty acid profile, serving as a nutritional alternative to prevent chronic diseases. Furthermore, they can also provide the reformulated products with new technological and sensory properties. However, to achieve a balance between the fat replacement ratio and meat product quality, certain issues like physicochemical/sensory properties and nutritional value should be further elucidated before these fat-reduction strategies can be better applied in low-fat meat products:

(1) Non-thermal physical technologies including ultra-high pressure and ultrasound etc. should be widely employed in the future to firstly compensate the negative effect of fat reduction on the physicochemical and sensory properties of reformulated meat products, and secondly, to explore their potential in reducing total fat and modifying the fat profile, which meets the 'clean label' requirements.

(2) To achieve an improved quality of fat-substituted meat products, formulations (i.e., protein/carbohydrate/lipid type and concentration, emulsifier/gelator type and concentration, complex proportion, etc.) should be systematically studied. Based on these optimized parameters, the substitution effect of different substitution forms (i.e. direct incorporation, gel, emulsion, oleogel, etc.) should also be further compared.

(3) Lipid oxidation is unavoidable during fat substitution, with the reduction of SFA and increase of PUFA. Moderate lipid oxidation contributes to the release of aromatic compounds, ensuring the meat products attractive flavor, while excessive oxidation severely impairs the technological and sensory attributes. Therefore, novel embedding technology (i.e. double emulsions) that can remain intact during processing (i.e. thermal treatment, curing, mincing, etc.) should be developed to protect vegetable/fish oils, decelerating lipid oxidation.

(4) Finally, the production of low-fat meat products is so costly that they are difficult to put into large-scale production. Hence, more efforts should be focused on the standardization of formulations and the scaling of production to reduce cost for manufacturers, promoting the development of reformulated fat-reduced meat products.

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Conflict of interest

The authors declare that they have no conflict of interest.

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