



INNOVATIVE FAT MODIFICATION TECHNOLOGIES IN MEAT PRODUCTS FOR IMPROVED NUTRITIONAL QUALITY AND SENSORY PERFORMANCE

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Abstract

A strategic research focus on fat modification in meat products aims to improve nutritional quality and lower health hazards related to consumption of cholesterol and saturated fat. The high percentage of animal fat found in conventional meat products is linked to a higher risk of metabolic disorders such as obesity, atherosclerosis, and cardiometabolic syndrome. Thus, it is now crucial for the modern food business to create fat reformulation techniques that preserve sensory and functional qualities while enhancing the lipid profile. This study intends to assess different fat modification technologies in meat products, such as using oleogels and structured lipids, using fiber- and protein-based fat mimetics, and replacing animal fat with vegetable oils. This review also looks at how reformulation affects texture, emulsion stability, lipid oxidation, nutritional composition, and consumer sensory acceptability. Using keywords associated with fat modification and meat reformulation technology, a literature search was carried out in the PubMed, Scopus, and Web of Science databases. Publications from 2000 to 2026 were analyzed. The synthesis results show that fat modification, especially utilizing oleogelation techniques and stable emulsion systems, has the ability to boost unsaturated fatty acids and decrease saturated fat content without sacrificing sensory quality. Nonetheless, many formulations continue to encounter difficulties, such as altered texture and heightened oxidation susceptibility. All things considered, the development of lipid innovations in meat products presents the industry with substantial opportunity to create healthier goods without sacrificing quality, as well as to promote sustainable food reformulation and public health initiatives.

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Introduction

One of the most crucial structural and functional elements of meat products is thought to be fat [1,2]. In emulsified and comminuted meat systems, the impact of animal fat on a number of quality aspects, including texture, flavor, juiciness, emulsion stability, and perceived overall product quality, has been extensively studied [3]. From a physiological perspective, fat also serves as a concentrated energy source, a solvent for lipophilic vitamins, and a precursor to bioactive substances, such as those linked to the lipid-mediated health effects of meat eating [4]. However, researchers and the food business have placed a lot of emphasis on the lipid profile of meat, which is naturally dominated by cholesterol and saturated fatty acids, as well as growing consumer awareness of food safety and health [5,6]. In this instance, fat is an essential component of meat products that have been reformed utilizing a modern nutritional approach, including fat replacement and reduction techniques like oleogelation and emulsion fat substitutes [7,8].

In nutritional epidemiology, health problems associated with consumption of saturated fat and cholesterol, especially its role in obesity, metabolic syndrome, and cardiovascular disease, have grown to be significant worldwide concerns [9]. Global health groups, such as the World Health Organization (WHO) and the American Heart Association (AHA), advise consuming less saturated fat and more unsaturated fatty acids to lower the risk of atherosclerosis and metabolic issues [10]. The idea that traditional meat products are one of the main sources of saturated fat in people's diets drives the need for innovation that can balance the functional and nutritional aspects of products [11].

Consumer preferences are changing, which further emphasizes this imperative [12]. Food items that promote long-term health and environmental sustainability in addition to being delicious are becoming more and more popular worldwide [13]. One of the main forces behind the meat industry's development is the move toward functional meals, clear labels, low-fat goods, and substitutes for animal fats [14]. As health-conscious diets like the Mediterranean and plant-forward diets gain popularity, consumers are becoming more interested in reformulated meat products that include unsaturated fatty acids, dietary fiber, and bioactive substances that offer extra physiological benefits [13].

To maintain competitiveness and comply with dietary rules, the industrial setting requires innovation in fat modification [15]. Fat reformulation in meat products includes a variety of techniques, from using fibers and natural emulsifiers as fat mimetics to replacing animal fats entirely or partially with PUFA-rich vegetable oils, structured lipids, and oleogels [16]. The tactics aim to reduce the saturated fat content of a product and improve its health value while maintaining its functional and sensory attributes [17]. However, as variations in lipid content can impact the texture, durability, and flavor profile of the final product, using this technique requires a deep comprehension of the

physicochemical interactions between lipids, proteins, and water in the meat matrix [18].

Studies on fat alteration in meat products are therefore extremely urgent from a scientific and industrial standpoint. To enumerate technological advancements, evaluate the efficacy of different strategies, and pinpoint obstacles and prospects for further development, a thorough analysis in this area is required. The purpose of this review is to give a thorough overview of fat modification techniques in meat products, their effects on physicochemical and nutritional quality, and their usefulness on an industrial level. Furthermore, this article presents ideas on the future course of research in the creation of meat products that are healthier, more functional, and sustainable, as well as the most recent scientific and commercial trends.

Objects and methods

To find pertinent research on fat modification techniques in beef products and their impacts on nutritional quality, physicochemical characteristics, and consumer acceptance, a thorough literature search was carried out. Major scholarly databases, such as PubMed, Scopus, Web of Science, and Google Scholar, were searched in order to increase the coverage of references. The terms “meat products,” “fat modification,” “fat replacer,” “oleogel,” “structured lipids,” “reduced-fat meat,” and “sensory evaluation” were used in conjunction with Boolean operators to thoroughly capture research on fat reformulation.

Peer-reviewed experimental research, review articles, and technical reports discussing fat modification in meat products in connection with nutritional qualities, emulsion stability, texture, lipid oxidation, and sensory attributes made up the inclusion criteria. Studies that just examined the lipid content of animals without taking processing into account, as well as non-scientific and non-peer-reviewed publications, were not included. In order to reflect advancements in contemporary lipid technology, the literature reviewed encompassed the years 2000 to 2026; key works were also included as supporting references.

Duplicate removal, title and abstract screening, and full-text review were all steps in the screening process to make sure it was in line with the goals of the study. The steps in the selection process were identification, screening, eligibility evaluation, and final inclusion. In order to find other pertinent studies, a snowballing technique was also used, looking through the reference lists of chosen papers.

Role of fat in meat products

One essential ingredient in meat products is fat, which has a significant impact on functional, sensory, and nutritional aspects [19,20]. Fat functions as an emulsifying agent, matrix filler, and component that affects the water-binding capacity during processing, all of which have a physicochemical impact on the structure and stability of meat products [21]. Fat improves the capacity of animal

protein systems to create cohesive, stable gels, which is essential for sausages, meatballs, and nuggets [22,23]. Additionally, fat acts as a mechanical lubricant throughout the mincing and mixing procedures, helping to create the ideal texture and minimizing friction-induced protein degradation [24,25].

Fat significantly influences the organoleptic quality of meat products from a sensory standpoint [26,27]. Because fat has thermal qualities that cause it to melt when heated and generate a juicy taste when consumed, it contributes to texture by making it more soft and juicy [28,29]. Tenderness and customer satisfaction are closely linked to the distribution of intramuscular fat, or marbling; an ideal proportion of marbling produces a smooth mouthfeel and a more nuanced savory flavor [30,31]. Additionally, fat plays a crucial part in the Maillard reaction and lipid oxidation that give meat its distinctive aroma during cooking by acting as a solvent and carrier of flavor chemicals [32,33].

Meat fat contains a variety of fatty acids, including polyunsaturated fatty acids (PUFA), monounsaturated fatty acids (MUFA), and saturated fatty acids (SFA) [34,35]. Meat from monogastric animals exhibits more flexible lipid composition variations based on the animal's diet, but meat from ruminants is often richer in SFA and contains special fatty acids such as conjugated linoleic acid (CLA), which is created by the biohydrogenation process in the rumen [36,37]. The presence of MUFAs and PUFAs in meat nonetheless offers beneficial physiological contributions, such as support for cell membrane function and energy metabolism, even though particular meat fat fractions are thought to have implications for cardiometabolic health concerns [38,39].

Strategies for fat modification in meat products

Numerous innovative fat modification techniques have been developed as a result of consumer demand for healthier meat products and advancements in food science [7,40]. These techniques aim to maintain the functional and sensory attributes of conventional meat products while reducing the levels of cholesterol and saturated

fat [41]. As concerns about cardiometabolic health and food sustainability have grown, alternative fat formulations through animal fat reduction, lipid substitution, emulsion technology, encapsulation, structured lipid, and oleogel formation have taken center stage in the reformulation of meat-based products [2]. These various strategies offer promising technical solutions that optimize nutritional profiles without compromising organoleptic quality and product stability, opening doors for the meat industry to transform into more competitive and practical goods [42]. Figure 1 illustrates the conceptual framework of fat modification strategies in meat products, including fat reduction, substitution with healthier lipid sources, lipid structuring techniques such as oleogels and emulsions, and stabilization approaches aimed at maintaining product quality, functionality, and sensory properties.

Reduction of animal fat

One of the primary strategies for reformulating meat products with a healthier nutritional profile is lowering animal fat, particularly when it comes to lowering the amount of cholesterol and saturated fat [43]. This tactic involves changing the composition of the formulation by lowering the amount of animal fat without sacrificing the functional and sensory qualities of products [44]. Lean meat or high-protein fillers are frequently used to replace some of the adipose tissue in order to achieve direct fat reduction [45]. Additionally, physicochemical methods are used to preserve emulsion stability in spite of decreased fat content, such as the application of mincing procedures with regulated temperature and pH [46].

Since fat aids in water binding, protein gel flexibility, and mechanical lubrication, reformulating low-fat goods necessitates the insertion of alternative components to imitate the techno-functional role of fat [47]. Soluble and insoluble dietary fiber, plant and animal proteins, modified starches, and hydrocolloids (such as carrageenan and xanthan gum) that can raise matrix viscosity, preserve emulsion structure, and enhance the final texture of products are frequently utilized alternative ingredients [48]. To retain a compact and stable texture, some formulas also

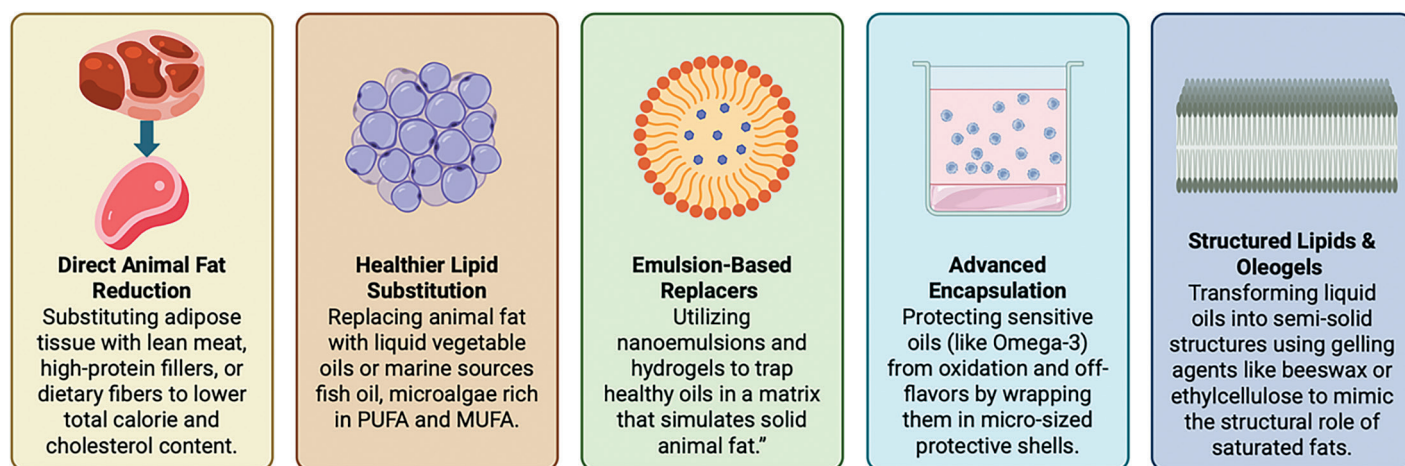


Figure 1. Conceptual framework of fat modification strategies in meat products, including reduction, substitution, structuring, and stabilization approaches

employ emulsifying agents and water additions to make up for the loss of fat volume [49].

Reducing animal fat presents serious problems for the stability and sensory qualities of a product [50]. Reducing fat content might result in syneresis because of decreased water retention capacity, increase textural hardness, and decrease juiciness [51]. The strength of the unique flavor of meat is also diminished by the loss of fat fractions since fewer aroma-carrying lipid components remain [52]. Furthermore, increased water and protein phase proportions make a product more vulnerable to microbial growth and metabolic interactions, which could jeopardize oxidative stability [53]. In order to assure successful reformulation without sacrificing product quality, fat reduction techniques necessitate well-planned formulations that include the selection of suitable alternatives, processing technology optimization, and thorough sensory evaluation [54].

Fat replacement and substitution

An increasingly popular tactic to enhance nutritional profiles while preserving sensory and functional qualities is substituting fat in meat products with other lipid sources [55]. In order to lower the amount of saturated fat and cholesterol and increase the consumption of monounsaturated, polyunsaturated, and vital omega-3 fatty acids, this method substitutes healthy fats for conventional animal fats [56]. Given the intricate role that fat plays in delivering flavor and mouthfeel, careful formulation is necessary for fat substitution in order to maintain emulsion stability, texture, and consumer approval [57].

Olive, canola, sunflower, soybean, and flaxseed oils are common substitutes that are high in MUFAs and PUFAs [58]. If employed in the right amounts, these alternatives may improve nutritional value and reduce cholesterol without appreciably diminishing sensory qualities [59]. The liquid state of vegetable oils, however, can cause emulsion stability issues, raise the possibility of syneresis, and result in a softer texture [60]. Thus, to enhance the incorporation of vegetable oils into the meat protein matrix, emulsification, gelation (oleogel), and encapsulation are employed [61].

The goal of adding fish oil and omega-3 sources to meat products is to enhance them with EPA and DHA, which have anti-inflammatory and cardiovascular health benefits [62]. The vulnerability of fish oil to lipid oxidation and the development of fishy smells and aromas that may diminish consumer liking are the primary barriers to its use [63]. Product stability during storage has been improved by the use of encapsulation technology, natural antioxidants, such as tocopherols and plant polyphenols, and modified environment packaging [64].

Microalgae are a source of functional lipids high in polyunsaturated fatty acids (PUFAs), particularly DHA. Their bioactive pigment and antioxidant content enhance the oxidative stability of products [65]. In emulsified meat products, some species including *Schizochytrium* spp. and

Nannochloropsis spp. have been utilized as omega-3 fortifiers or fat alternatives [66]. Additionally, the fiber and protein content of microalgae biomass enhances its functional value [67]. The potential for color changes, the smell of seaweed, and the expensive cost of manufacture are the main obstacles to its utilization [68]. Thus, the development of microalgal lipid-based meat products depends heavily on the optimization of addition concentration, cell processing, and encapsulation techniques [69].

Emulsion-based fat replacers

An inventive method for reformulating meat products to obtain a better lipid profile without sacrificing texture quality and sensory qualities is the use of emulsion systems in place of fat [47]. Emulsions allow vegetable oils high in MUFAs and PUFAs to substitute animal fats in a stable matrix that mimics the physical properties of solid fats [70]. Oil-in-water (O/W) or water-in-oil (W/O) emulsions are used in this system, which is typically enhanced with emulsifiers or structurizers to preserve mechanical and thermal stability when processing meat [71].

Vegetable oils are trapped in a structured protein matrix by protein-oil emulsions, which take advantage of the capacity of proteins to function as stabilizers and emulsifiers [72]. The oil phase is bound by vegetable proteins (such as soy, pea, and wheat protein isolates) and animal proteins (such as whey and blood plasma) to provide a texture akin to animal fats [45]. During heating, this method creates a durable gel structure, preserves the viscosity of a meat mixture, and enhances water retention [73]. Protein concentration, pH, and ionic strength all affect the mechanical and thermal durability of emulsions, therefore formulation conditions must be optimized to produce sensory qualities similar to those of conventional fats [74].

Emulsion systems with extremely small droplet sizes (often less than 200 nm) that offer excellent optical transparency and physical stability are known as nanoemulsions [75]. Their use in meat products makes it possible for healthy oils to disperse at the nanoscale, which produces consistent lipid distribution and lowers the possibility of phase separation during processing and storage [76]. The contact surface area is increased by the small droplet size, which may enhance the absorption of important fatty acids and promote flavor penetration [77]. However, the use of nanoemulsions necessitates the use of safe and efficient food surfactants as well as methods like high-pressure homogenization or ultrasonication [78]. The primary obstacles of these systems are the high cost of technology, the requirement for extra stabilizers, and the possibility of rapid lipid oxidation because of the large surface area of droplets, which makes the addition of antioxidants a crucial part of the formulation [79].

Hydrogel fat substitutes are three-dimensional hydrophilic substances that mimic the physical properties of solid fat by holding onto water and oil in the gel matrix [80]. Polysaccharides (such as kappa-carrageenan, alginate, pectin,

and xanthan gum) or polysaccharide-protein combinations can be used to create hydrogels [81]. Low-fat meat products benefit from the elastic texture, increased juiciness, and improved mouthfeel of this system. It also permits control over taste and water release during heating to reduce syneresis [82]. Vegetable oil is included into the hydrogel to create a hybrid organogel-hydrogel structure that mimics the natural marbling phase of fat [2]. Optimizing the water-polysaccharide-oil ratio and its effects on elasticity, compactness, and stability during heating is the primary difficulty in its utilization since structural instability will alter the texture and juiciness of the final product [83].

Encapsulation technology

In meat product reformulation, encapsulation technology has emerged as a tactical method for incorporating healthy lipids without sacrificing functional stability or sensory quality [43]. Oil molecules or bioactive components are encapsulated in a protective matrix to allow for regulated release while shielding them from external factors that cause deterioration [84]. For oils enriched in unsaturated fatty acids, including fish oil, flaxseed oil, and microalgae lipids, which are extremely vulnerable to lipid oxidation and the development of off-flavors, this strategy is especially crucial [85].

Microencapsulation utilizes several methods, such as spray drying, coacervation, extrusion, or freeze drying, to turn oil into tiny particles [86]. To provide a stable matrix, coating solutions are typically either polysaccharide-based (maltodextrin, gum arabic, alginate) or protein-based (casein, whey protein, soy isolate) [87]. Healthy oils can be uniformly distributed in the meat matrix through microencapsulation without affecting the texture or structural bonds of protein. Additionally, the lipid release profile can be controlled during heating to prevent premature degradation during cooking, sterilization, or cold storage [88].

It has been demonstrated that using this technology improves the retention of omega-3 fatty acids, strengthens the functional value of products, and creates opportunities for the creation of high-value meat products like functional sausages, functional nuggets, and meat substitutes with improved lipid profiles [89]. The vulnerability of unsaturated oils to lipid oxidation, which results in a reduction in quality through the formation of volatile compounds that cause rancid odors, color changes, and a decrease in nutritional value, continues to be one of the primary obstacles to reformulating fats in meat products [90]. In this situation, encapsulation prevents oxidative processes by acting as a physical barrier that restricts the movement of oxygen, light, and moisture [84].

The encapsulation system is crucial for taste stabilization in addition to safeguarding the lipid structure [91]. Because encapsulated oils are typically more resilient to thermal deterioration and volatility during processing, the integrity of lipid aroma compounds is preserved, and unwanted flavors and scents are kept from emerging [92]. This protection

has a significant impact on consumer approval, particularly when using fish or microalgae oils, which have unique flavor profiles and may produce aftertaste if improperly prepared [93]. Natural antioxidants, such as tocopherols, green tea extract, rosemary, and different plant polyphenols, are frequently used in encapsulation methods to provide protection against oxidation [94]. Encapsulation and antioxidants together give reformed meat products double protection against lipid degradation, extend their shelf life, and preserve their organoleptic qualities [95].

Structured lipids and oleogelation

Modern methods of fat reformulation in meat products, such as oleogelation and structured lipids, seek to substitute vegetable oil-based lipid systems with comparable structural properties for solid animal fats [96]. This technique focuses on using physical or chemical procedures to turn liquid oils into semi-solid structures that resemble solid fats but have better fatty acid profiles, especially those that are high in MUFAs and PUFAs [97]. Therefore, this method enables a decrease in cholesterol and saturated fat without sacrificing the texture, thermal characteristics, and sensory attributes that have long been significant aspects of animal fats [8].

Oleogel is a lipid gel system that was created by stabilizing liquid vegetable oils with an oleogelator, a gelling agent, to create a semi-solid structure [98]. Because of their high MUFA and PUFA composition, olive oil, canola oil, sunflower seed oil, soybean oil, and flaxseed oil are frequently utilized [58]. Through non-covalent physical interactions, such as hydrogen bonds and van der Waals forces, the oleogelation process creates a three-dimensional network that traps oil molecules [99]. The resultant oleogel is useful for application in sausages, burgers, nuggets, and other meat emulsion products because of its flexibility and thermal stability, which can mimic animal fat [8]. Its primary benefit is its capacity to preserve mouthfeel, juiciness, and lubricating qualities, all of which have a significant impact on customer acceptance [100].

The structure of triglycerides in oil is altered by the development of oleogels and interesterification technologies to produce a fat profile like that of solid fats [101]. Enzymatic interesterification is the preferred method for food applications due to its selectivity, environmental friendliness, and lack of trans fatty acid production compared to partial hydrogenation. This process entails the exchange of fatty acid positions in the glycerol backbone through chemical or enzymatic catalysis [102,103]. Vegetable oils can be altered through interesterification to raise their melting point, oxidative stability, and flexibility, allowing them to replace animal fats without sacrificing functional quality [104,105]. Additionally, this method can enhance the manufacturing of processed meat by improving whipability, gel density, and emulsion stability [106].

The use of natural gelling agents in the oleogelation process is growing in popularity as a way to guarantee food safety and regulatory compliance [107]. Waxes (such as

beeswax, candelilla wax, and carnauba wax), phytosterols, fatty acids, monoglycerides, and polysaccharides, such as ethylcellulose, are often utilized gelling agents [108]. While phytosterols and fatty acids act by causing molecules to crystallize on a micro scale to create a semi-solid structure, waxes and monoglycerides serve as structuring agents that create robust lipid crystal networks [109]. Because ethylcellulose is a polymer that can produce thermoreversible gels, it can be used in meat processing applications because it offers a stable structure under high processing temperatures [110].

Optimizing process conditions and choosing the appropriate gelling agent are critical to the overall success of oleogelation applications and structured lipids [95]. The oxidative stability, texture, flexibility of oleogels, and their integration into the meat product system will depend on the choice of gelator type and concentration, process temperature settings, and chemical compatibility with the meat protein matrix [111]. Thus, creating reformulated meat products with a healthier lipid profile while preserving sensory qualities similar to traditional fat-based products requires formulation modification [112].

Nutritional impacts of fat modification

A key tactic in food reformulation to enhance nutritional quality and promote public health is the alteration of fat in meat products [113]. This method involves substituting some or all of the animal fat with healthier substitute lipid sources, such as fish oils, vegetable oils high in unsaturated fatty acids, and novel lipid structures like oleogels and multilayer emulsions [43]. The goal of lipid composition engineering is to reduce the percentage of saturated fatty acids (SFA) and cholesterol that typically predominate in conventional meat products while increas-

ing the proportions of polyunsaturated fatty acids (PUFAs) and monounsaturated fatty acids (MUFAs) [2]. In line with this, Table 1 summarizes the major nutritional and physiological effects of fat modification strategies in meat products, highlighting improvements in fatty acid composition, lipid metabolism, and cardiovascular health outcomes.

There are major physiological advantages of increasing the amount of PUFAs and MUFAs in products through fat modification [114]. PUFAs, particularly omega-3 (EPA, DHA) and omega-6, are crucial for preserving the fluidity of cell membranes, promoting the production of lipid mediators that reduce inflammation, and controlling immunological responses [115]. Meanwhile, by controlling the metabolism of fats and carbohydrates, MUFAs, such as oleic acid, are known to help enhance insulin sensitivity and balance blood lipid profiles [116]. Therefore, enhancing the content of fatty acids not only offers a substitute for saturated fats but also fortifies biological processes that directly affect the avoidance of metabolic disorders and persistent inflammation [115]. Figure 2 illustrates the functional health benefits of fat modification in meat products, including improved fatty acid composition through increased PUFA and MUFA levels, reduced saturated fat and cholesterol content, improved blood lipid profile, lower atherogenic risk, and enhanced metabolic and cardiovascular regulation.

Reductions in cholesterol and SFA content, which have long been linked to elevated LDL levels and the risk of atherosclerosis, are also facilitated by improvements in the composition of fat reformulation in meat products [68]. Fat modification lowers the risk of cardiovascular diseases and improves blood lipid profiles by lowering atherogenic fat components [117]. This technique

Table 1. Nutritional impacts of fat modification strategies in meat products

Nutritional aspect	Fat modification strategy	Changes in lipid composition	Physiological and metabolic effects	Health implications	References
Fatty acid profile	Partial or total replacement of animal fat with vegetable oils rich in MUFA/PUFA, fish oils, oleogels, and multilayer emulsions	↑ PUFA (omega-3 and omega-6), ↑ MUFA, ↓ SFA, ↓ cholesterol	Maintains cell membrane fluidity, improves insulin sensitivity, regulates lipid and glucose metabolism	Prevention of metabolic disorders and chronic inflammatory diseases	[2,43,113,114]
Omega-3 enrichment (EPA, DHA)	Incorporation of fish oil and microencapsulated marine lipids	↑ EPA and DHA content in meat matrix	Promotes synthesis of anti-inflammatory lipid mediators, modulates immune response, improves blood lipid metabolism	Protection against atherosclerosis and systemic inflammation	[115]
Cholesterol and saturated fat reduction	Reduction of animal fat and substitution with vegetable oils and structured lipids	↓ Total cholesterol, ↓ SFA	Reduces atherogenic LDL formation and lipid accumulation in blood vessels	Reduced risk of cardiovascular disease and atherosclerosis	[68,117]
Blood lipid profile	Reformulation with MUFA/PUFA-rich oils, oleogelation, and emulsion systems	↓ LDL, ↓ triglycerides, ↑ HDL	Improves lipid transport, endothelial function, and cardiovascular regulation	Protection against metabolic syndrome and type 2 diabetes	[114,120,121]
Clinical metabolic parameters	Functional lipid reformulation and health-oriented meat product design	↓ Systemic inflammation, ↓ blood pressure, improved glucose stability	Enhances metabolic homeostasis and vascular health	Prevention of coronary heart disease and metabolic complications	[114,119,121]

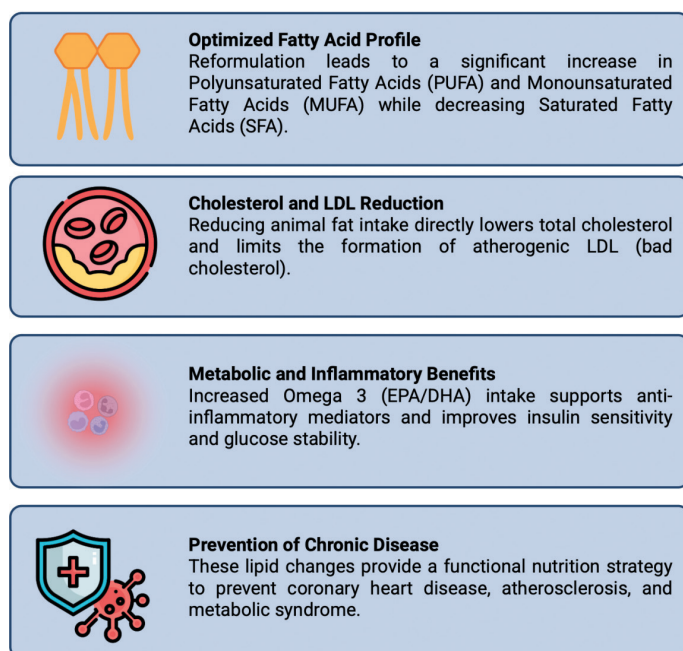


Figure 2. Functional health benefits of fat modification in meat products: improved lipid profile, reduced atherogenic risk, and enhanced metabolic regulation

is consistent with international nutritional guidelines, which suggest consuming more unsaturated fats and less saturated fats as part of a dietary strategy to prevent degenerative illnesses [118].

Clinically, using this approach improves metabolic and cardiovascular health [119]. Meat products with altered fat composition can enhance blood lipid markers, such as lowering LDL and triglycerides and raising HDL levels, according to several intervention studies [120]. Consuming unsaturated fatty acids is also linked to better endothelial function, decreased systemic inflammation, and control of blood pressure and glucose balance [114]. This emphasizes that altering the fat content of meat products is not just a novel approach to food formulation but also a practical nutrition strategy that helps avoid metabolic syndrome, type 2 diabetes, and coronary heart disease [121].

Effects on processing and technological properties

Changing the amount of fat in meat products has an impact on their nutritional value as well as their functional qualities and features of processing technology [50]. Animal fat naturally aids in the creation of emulsion systems, thermal stability, water-holding capacity, and product texture and viscosity [55]. Therefore, rigorous formulation techniques are needed to preserve the physical and sensory quality of the final product when substituting vegetable oil, structured fat, or oleogel systems for animal fat [8]. This is summarized in Table 2, which shows the major effects of fat reformulation on processing performance and technological quality attributes of meat products, together with the main challenges and technological solutions applied to maintain product stability.

Specifically, thermal stability is a crucial component in the reformulation of lipids in meat products as it significantly affects how well fats function during heat processing [43]. Vegetable oils and PUFAs are far more vulnerable to oxidation and heat damage, whereas animal fats heavy in saturated fatty acids have a higher melting point and superior resistance to thermal deterioration [122]. When liquid oils are used in place of solid fats, the melting dynamics and fat distribution during heating may change, perhaps leading to the release of surplus fat and decreasing system stability [105]. Numerous technical techniques, including oleogelation, microencapsulation, and the inclusion of antioxidants, are employed to improve thermal resistance and reduce lipid oxidation during the heating process in order to solve these issues [123].

In terms of water-holding capacity (WHC), fat functions as a matrix filler by physically interacting with protein tissue to assist retain moisture [124]. WHC frequently decreases when animal fat is lowered because the tissue structure becomes thicker and has less capacity to retain fluids [125]. In order to make up for this, water-retaining substances like hydrogels, plant protein, and dietary fiber are utilized to boost water retention capacity and preserve

Table 2. Effects of fat modification on processing and technological properties of meat products

Technological aspect	Functional role of animal fat	Effect of fat modification	Main challenges	Technological approaches / Solutions	References
Thermal stability	Provides high melting point and resistance to thermal degradation during heating	↓ Thermal stability, ↑ susceptibility to lipid oxidation, altered fat melting behavior	Lipid oxidation, heat-induced degradation, fat release during cooking	Oleogelation, microencapsulation, incorporation of natural antioxidants	[43,122,123]
Water-holding capacity (WHC)	Acts as a matrix filler and helps retain moisture and cooking yield	↓ WHC, denser structure, reduced juiciness	Cooking loss, reduced yield, texture hardening	Addition of dietary fiber, plant proteins, and hydrogels	[124,125]
Emulsification properties	Stabilizes protein–fat emulsion systems and maintains product uniformity	↓ Emulsion stability, ↑ fat separation and syneresis	Emulsion destabilization during thermal processing	Pre-emulsification, natural emulsifiers, oleogel-based fat analogs	[48,126,127]
Texture and viscosity	Provides lubrication, softness, mouthfeel, and viscoelasticity	Firmer and drier texture, ↓ juiciness and mouthfeel	Loss of viscoelastic properties and sensory acceptability	Structural fibers, gel-forming proteins, oleogel systems	[25,97,128]
Microstructural matrix	Maintains uniform fat distribution and structural integrity of meat matrix	Altered matrix structure and uneven fat distribution	Increased porosity, structural heterogeneity	Lipid structure engineering and fat globule size optimization	[7,105]

the juiciness of products. This method is crucial to avoid fluid loss while cooking, which can lower yield and degrade texture quality [124].

Additionally, lipid reformulation has a major impact on the emulsification capabilities [126]. The distinctive protein-fat emulsion system in meat products is formed and stabilized in part by animal fat, but the introduction of liquid oil might decrease emulsion stability and raise the possibility of fat separation and syneresis during heating [48]. Pre-emulsification methods, natural emulsifiers, and the creation of oleogels as solid fat analogs were used to preserve system integrity. These methods were successful in enhancing emulsion stability and preserving product uniformity during heat processing [127].

Because fat adds to the lubricating effect, softness, and rheological character of meat products, it also directly affects texture and viscosity [25]. Without the proper technological assistance, substituting liquid oils for solid fats can lead to a drier, harsher texture with less juiciness and mouthfeel [97]. This is addressed by creating a network that replicates the presence of solid fat and aids in restoring the viscoelastic qualities of products using structural fibers, gel-forming proteins, or oleogel systems [128].

Quality, safety, and sensory evaluation

Modifying fat in meat products has a substantial impact on physical quality, safety considerations, and sensory acceptability in addition to nutritional value and technological features [129]. The viability of reformulating low-fat or alternative-fat-based meat products on an industrial scale is determined by factors like texture, juiciness, flavor, color, and oxidative stability [50]. Table 3 summarizes the effects of fat reformulation on the quality attributes, oxida-

tive safety, and sensory acceptance of meat products, along with the major technological strategies used to maintain consumer acceptability.

In terms of texture, fat helps give beef products their perceived tenderness and juiciness by acting as a lubricant inside the protein matrix [130]. Because protein predominates, decreasing fat content typically results in increased tissue density, a harder, drier texture, and a decrease in juiciness due to decreased water-binding capacity and the loss of the ability of fat to retain moisture during cooking [131]. Fat mimetics, such as soluble dietary fiber, gel-forming polysaccharides, and plant oil-based oleogels, are used in fat substitution technologies to preserve these qualities by mimicking the lubricating and moisture-retaining properties of animal fat [132].

Fat is essential to the development of the distinctive aroma of meat products because it serves as the main medium for dissolving and releasing volatile chemicals during heating [111]. While employing vegetable oils with a high percentage of PUFAs increases susceptibility to oxidation, which can cause off-flavors and diminish palatability, fat reformulation can change the flavor profile by altering lipid composition and its interaction with proteins and Maillard processes [133]. In order to combat this, methods including utilizing encapsulating technology, enhancing taste ingredients, and adding natural antioxidants are used to shield lipid components from oxidative deterioration [134].

Changes in the fat fraction also affect the color and appearance of products, since solid fat gives processed beef products their characteristic opacity and pale tint [135]. The distribution of lipids within the matrix can be changed by substituting liquid oil or microencapsulated fat, which can modify surface reflectance and provide a less appealing

Table 3. Effects of fat modification on quality, safety, and sensory evaluation of meat products

Evaluation aspect	Functional role of animal fat	Effect of fat modification	Emerging challenges	Technological strategies / Improvements	References
Texture	Acts as a lubricant within the protein matrix, contributing to softness, tenderness, and elasticity	Firmer and drier texture, ↑ tissue density, ↓ tenderness	Reduced softness, mouthfeel, and sensory acceptability	Fat mimetics (soluble dietary fiber, polysaccharide gels), oleogels, gel-forming proteins	[130,132]
Juiciness	Helps retain moisture during heating and cooking	↓ Juiciness due to reduced water-holding capacity and moisture retention	Dry mouthfeel, reduced cooking yield	Addition of water-retaining fibers, hydrogels, and pre-emulsified lipid systems	[131,132]
Flavor and aroma	Serves as a solvent and release medium for volatile flavor compounds	Risk of off-flavor formation due to PUFA oxidation, altered meat aroma profile	Reduced palatability and loss of characteristic meat flavor	Natural antioxidants, flavor enhancers, lipid microencapsulation	[111,133,134]
Color and appearance	Provides opacity, pale tone, and uniform visual appearance	Changes in surface reflectance and less attractive color	Reduced visual appeal and pigment instability	Oxidation control, lipid distribution optimization, microencapsulation	[135,136]
Oxidative stability and safety	More resistant to oxidative deterioration than PUFA-rich oils	↑ Lipid peroxidation and free radical formation	Quality deterioration, shorter shelf life, potential toxicological risks	Natural antioxidants (rosemary extract, tocopherols, polyphenols), process control	[21,137]
Sensory acceptance	Strongly influences consumer preference and overall acceptability	Acceptance varies depending on formulation and fat substitute type	Risk of imbalance between nutritional improvement and sensory quality	Trained sensory panel evaluation, consumer acceptance testing, formulation optimization	[74,138]

color. Additionally, interactions with oxidative chemicals might impair the durability of meat pigments. Thus, preventing oxidation becomes crucial to preserving the aesthetic appeal of reformulated products [136].

Since the high PUFA concentration in vegetable oils speeds up lipid peroxidation, generating free radicals, lowering organoleptic quality, and perhaps posing toxicological hazards due to oxidative degradation products, lipid reformulation and oxidative stability are strongly related [137]. To increase oxidative stability and prolong the shelf life of reformulated meat products, natural antioxidants including rosemary extract, tocopherol, and polyphenols from fruits and seeds are frequently included [21].

In order for fat reformulation to be successful, sensory evaluation is an essential stage. Trained panels and consumer preference tests are used to evaluate factors like scent, flavor, tenderness, juiciness, and overall acceptability using established procedures [74]. A crucial tactic in the creation of commercially competitive low-fat or alternative-fat-based meat products is the integration of nutritional, technological, and sensory approaches. Reformulations that disregard sensory factors are typically poorly received by the market despite offering significant nutritional benefits [138].

Industrial and economic considerations

A thorough assessment of raw material availability, production costs, technical viability, and adherence to laws and labeling norms is necessary before implementing fat modification techniques in the meat processing sector [139]. Although substituting better lipid sources for meat products can increase their nutritional value and competitiveness in the market, supply chain preparedness, production process efficiency, and customer and regulatory authority approval are critical to their success [137].

Utilizing vegetable oils high in unsaturated fatty acids, oleogels, structured fats, or fiber-based fat substitutes frequently poses logistical and budgetary difficulties from a raw material and cost standpoint [140]. Olive oil, flaxseed oil, and algal oil are examples of high-quality alternative fat sources that are typically more costly than traditional animal fats, which could raise overall production costs [141]. On the other hand, in producing nations, using local resources like palm oil or palm-derived oleogels can be a more cost-effective option. Therefore, supply chain optimization and effective process development are essential to preserving industrial competitiveness [142].

The success of the reformulation is also determined by scalability and technology deployment [143]. At the laboratory level, technologies such as oleogelation, microencapsulation, and pre-emulsification frequently yield promising results; however, their industrial adoption is hampered by issues with equipment suitability, production consistency, stability during storage, and compatibility with high-pressure thermal processes [144]. Therefore, in order to maintain consistent product quality without incurring

undue costs, technology adaptation must take into account the capabilities of current production lines, the availability of skilled manpower, and operational efficiency [145].

Regulations and nutritional labeling are essential elements in the lipid reformulation of meat products, in addition to technical and financial considerations [139]. The FDA (U. S. Food and Drug Administration), EFSA (The European Food Safety Authority), BPOM (Indonesian Food and Drug Supervisory Agency), and other national and international authorities have established food safety standards, health claim regulations, and nutrition labeling requirements that manufacturers must adhere to [113]. It is only acceptable to use statements like “low in saturated fat,” “contains omega-3 fatty acids,” or “healthier” if they are backed by reliable scientific data and nutritional research [107]. Additional safety status review, such as GRAS determination or new food ingredient certification, may be necessary for the use of novel materials or cutting-edge technologies, such as polysaccharide-based oleogels or microencapsulated lipids [60]. Therefore, adhering to regulations not only guarantees product safety but also increases consumer confidence in the health benefits that producers promote [59].

Challenges and future prospects

Even though meat product fat modification technologies have significantly improved nutritional and functional quality, there are still a number of technological, financial, and consumer perception issues that must be resolved before this approach can be stably applied in the food sector [113]. The success of fat reformulation is largely determined by the intricacy of the meat matrix, interactions between components, and consumer needs for consistent sensory quality [50]. Figure 3 illustrates the major challenges and future prospects of fat modification strategies in meat products, highlighting issues such as texture deterioration, oxidative instability, emulsion breakdown, high production costs, and consumer sensory acceptance, as well as emerging technological opportunities including nanotechnology, biotechnology, and artificial intelligence to enhance product quality, stability, and sustainability.

There are still issues with the fat modification technologies that are now in use, especially with regard to the oxidative and physical stability of fat substitutes [49]. The texture, juiciness, and emulsion stability of low-fat or vegetable oil-based goods are frequently inferior to those of animal fat-based products [55]. However, commercial-scale improvement of production capacity, process efficiency, and adaption to high-pressure or extreme-temperature meat processing systems are still necessary for technologies like oleogelation, microencapsulation, and structured lipids [97]. Production prices and the scarcity of some alternative materials in particular areas present additional difficulties that could eventually impact the industry's profitability and accessibility [146].

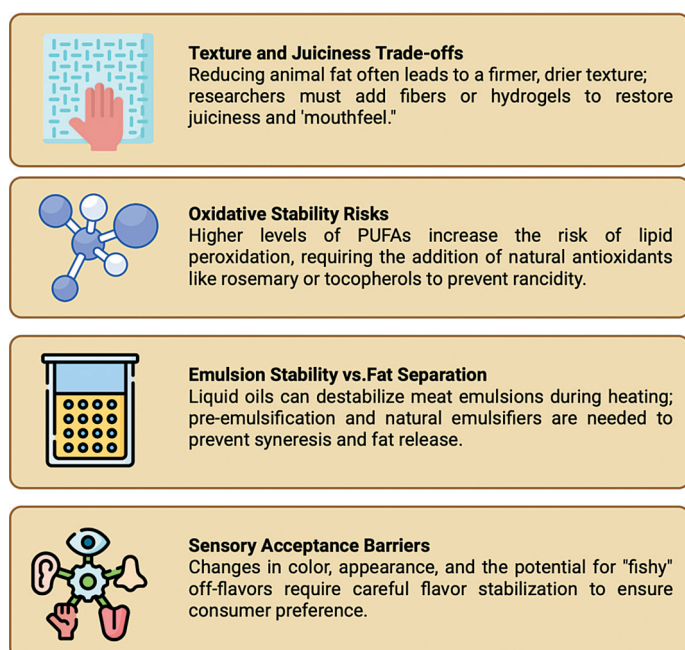


Figure 3. Overview of major challenges in fat modification strategies, including texture deterioration, oxidative instability, emulsion breakdown, and sensory acceptance issues

The development of multidisciplinary technology has a significant impact on the prospects for fat reformulation in the future [68]. The development of lipid nanoemulsions, which can enhance the bioavailability of important fatty acids, oxidative stability, and homogeneity of fat distribution in meat matrices, presents a significant opportunity for nanotechnology [76]. Simultaneously, food biotechnology has the ability to create structured fats by microbial fermentation or alter livestock's fatty acid profile nutrigenomically, offering novel sources of useful lipids without compromising sensory quality [147]. Furthermore, by optimizing fat composition, predicting sensory attributes, and simulating product stability, the application of artificial intelligence and machine learning in formulation design speeds up the creation of novel products that are in line with consumer preferences [76].

One of the main forces behind fat modification innovation is the movement in global consumption patterns toward healthier, more sustainable, and ecologically friendly food products [148]. Customers are becoming pickier when it comes to items that have little environmental impact, transparent ingredients, and health benefits [96]. In order to promote ecological sustainability, this situation is pushing the industry to maximize the use of regional vegetable fat sources, employ low-energy processing technologies, and use agro-industrial waste as a source of fiber and lipid structure [42]. However, lowering sensory bias and encouraging broader adoption of meat products with better fat profiles depend on educating consumers about the advantages and safety of reformulated fat products [103].

Conclusion

Modifying the fat content of meat products is a smart way to enhance their nutritional profile without compromising their functioning and sensory appeal. Numerous techniques, including oleogelation, structured lipids, and microencapsulation, have demonstrated promise in preserving the thermal stability, water-holding capacity, and textural qualities of traditional animal fats. Nevertheless, there are still issues with production costs, oxidative stability, and consumer acceptability that prevent these technologies from being widely used in industry.

All things considered, successful fat modification techniques require an integrated strategy that incorporates process improvement, technology innovation, and a deep comprehension of consumer behavior. More investigation is required to create formulation techniques that are more effective, enhance lipid stability, and guarantee the sustainability of substitute material sources. Adoption of this technology, from an industry standpoint, creates chances to manufacture meat products that are healthier and more competitive while also being in line with global trends toward sustainable and functional food.

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