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Review Article

Beeswax-structured oleogels and bigels in functional meat products: nutritional, technological, and sensory implications

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Abstract: Beeswax-structured oleogels and bigels represent an innovative strategy to improve the lipid profile of meat products by replacing animal fat with oils rich in polyunsaturated fatty acids. This review integrates the most recent findings and describes how the composition and functionality of beeswax-structured systems determine their ability to substitute animal fat and their impact on the nutritional, technological, and sensory quality of meat products. From a nutritional standpoint, these systems reduce saturated fatty acids and cholesterol while increasing *n*-3 fatty acids such as *α*-linolenic acid, eicosapentaenoic acid, and docosahexaenoic acid. From a technological perspective, they enhance water-holding capacity and influence color and texture parameters. Fat replacement levels of up to 50% (*m*/*m*) maintain acceptability comparable to control products; however, higher levels may negatively affect aroma and flavor. Despite these improvements, oxidative stability remains the main limitation. The incorporation of natural antioxidants and functional compounds, as well as the exploration of alternative waxes derived from native bees—whose bioactive potential remains unexplored—could improve the performance of these systems. Future research should focus on optimizing sensory acceptance and gaining a deeper understanding of the structural and molecular mechanisms determining texture and lipid and protein oxidation during storage. Overall, beeswax-structured lipid systems offer a sustainable and healthy solution for the development of functional meat products.

Keywords: beeswax; oleogels; bigels; functional meat products; nutritional quality; fat mimetics; oxidative stability

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1 Introduction

Global meat consumption was estimated to reach 361 million tons in 2025, with red and processed meats being major dietary sources of saturated fat and cholesterol[1–2]. These products contain variable fat levels (5%–50%), and their high intake has been associated with an increased risk of cardiovascular diseases (CVD), obesity, type 2 diabetes, colorectal cancer, and mortality[1]. In response to this concern, international nutritional guidelines advocate for the reduction of saturated fatty acids (SFA) and cholesterol intake, promoting their replacement with healthier lipid sources such as monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA)[2–3].

Within this framework, the reformulation of meat products through the substitution of animal fat with vegetable oils has emerged as a promising strategy for developing functional products that support human health[4]. However, the direct incorporation of vegetable oils into meat matrices may compromise texture, sensory acceptability, and oxidative stability due to their liquid physical state and susceptibility to lipid degradation[5–7].

To overcome these technological limitations, lipid structuring systems such as oleogels have been developed over the last decade, enabling the transformation of liquid oils into semi-solid or solid matrices without altering their fatty acid profiles[8–9]. Among the most recent innovations, bigels have been proposed as hybrid gels that combine a structured oil phase (oleogel) with a structured aqueous phase (hydrogel), conferring enhanced physicochemical stability as well as tunable functional and viscoelastic properties[10–12]. These systems can effectively mimic the behavior of animal fat in foods, particularly in key attributes such as juiciness, tenderness, and heat transfer during thermal processing[8,13].

The functionality of oleogels depends directly on their composition. They are typically formulated using gelling agents such as ethylcellulose, methylcellulose, hydroxypropyl methylcellulose, mono- and diglycerides, fatty acids and alcohols, phytosterols, lecithin, and various plant and insect derived waxes[14–17]. These compounds form a three-dimensional network capable of physically entrapping oil and providing structural stability. Among these agents, beeswax—extracted from *Apis mellifera* honeycombs and approved as a food additive in the European Union (E901)—stands out due to its economic viability, high gelling capacity, thermoreversibility, and biodegradability[18].

Additionally, it has a low gelling threshold and forms strong crystalline networks that efficiently retain the oil phase[5]. These characteristics confer greater hardness, elasticity, and physical and oxidative stability to oleogels compared to those formulated with monoglycerides or glycerol monolaurate, whose gels tend to be weaker and susceptible to oil leakage, compromising their technological and sensory performance in meat applications[15,19]. In comparison with ethylcellulose, beeswax offers notable technological advantages. Ethylcellulose requires high temperatures for dissolution (130–170 °C), which increases process complexity and promotes lipid oxidation in oleogels and reformulated products[19]. In contrast, beeswax can effectively structure oils, even at higher volumes, at moderate temperatures (~65 °C)[20].

Furthermore, ethylcellulose oleogels have been associated with lower sensory acceptability, regarding color, flavor, and overall acceptance, in matrices such as burgers and pâtés, especially when high levels of fat replacement are applied[6,20–21]. In contrast, beeswax-based oleogels maintain favorable sensory acceptability and suitable technological properties across a variety of meat matrices[21].

Beyond these technological and sensory advantages, such systems also contribute to improved nutritional profiles by reducing saturated fat and cholesterol levels, increasing MUFA and PUFA contents, and enhancing the *n*-3 PUFA/*n*-6 PUFA ratio[22]. Additionally, they offer functional benefits, as they imitate the properties of animal fat in terms of texture, flavor, mouthfeel, water and oil retention, and emulsion stability[5,11]. They also optimize technological parameters, such as shrinkage and thermal stability[12], as well as sensory attributes including acceptability, aroma, and taste, which can be modulated depending on the level of fat substitution (Figure 1).

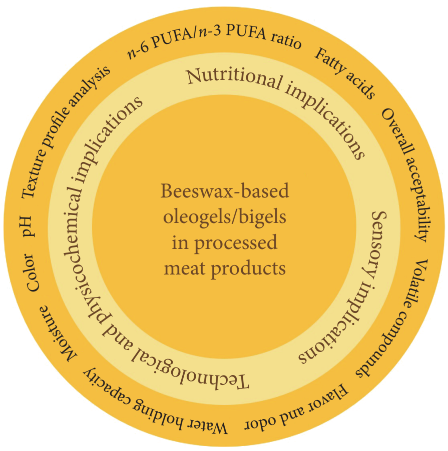

Figure 1 Key implications of beeswax-based oleogels/bigels in functional meat products.

Beeswax-based oleogels and bigels represent promising alternatives for replacing animal fat in meat products. These structured lipid systems—formulated from vegetable and marine oils such as olive, flaxseed, canola, camellia, and fish oils, as well as their blends—have shown significant potential to mimic the technological functions of animal fat. They also contribute to improving the lipid profile of products such as pâtés, surimi, sausages, and burgers, all while preserving favorable sensory acceptability[6,12,19,21,23–25]. Nonetheless, challenges persist regarding oxidative stability, structural resilience, and standardization of formulation methodologies[5,20,26]. Moreover, there is a limited number of studies focused on behavior during storage, thermal stability, and consumer perception[27–28].

Despite these advances and remaining limitations, an integrative review that analyzes how the composition and functionality of beeswax-based oleogels and bigels—emerging alternatives to conventional fats—determine their ability to replace animal fat and their impact on the final quality of functional meat products is still lacking. In this context, the present review provides an overview of the role of beeswax as a structuring agent, describes formulation variables in oleogels and bigels, and offers a detailed analysis of their application in meat matrices, with emphasis on their nutritional, technological, and sensory implications.

2 Beeswax

Beeswax is produced worldwide, and following honey harvesting, it is obtained as a by-product through processes such as crushing or pressing of honeycombs, yielding 10%–15% wax per kilogram of harvested honey[29]. Although beeswax is initially white, it acquires yellowish tones due to the incorporation of natural pigments originating from pollen and propolis.

The quality and chemical composition of beeswax depend on the bee species and its diet[30], botanical origin and pollen sources[31], and wax age[32]. Other factors include hive location, season, climatic conditions, and non-climatic factors[33]. Likewise, the extraction and purification method significantly influence the yield, composition, and physical properties of the wax[30]. This compositional variability not only defines its functional properties but also determines its safety profile. Beeswax is an essential component of the hive, remaining in direct contact with brood and food; however, it may contain natural toxins, chemical or microbial contaminants, microplastics, or allergens, compromising its safety[34].

In sensitive individuals, allergic reactions may occur, potentially associated with pollen proteins with allergenic potential—such as profilin, expansin, catalase, and lipase—as well as pollen from the Asteraceae family (ragweed, mugwort) or propolis-derived compounds (caffeic acid, benzyl salicylate, benzyl cinnamate)[35]. Although the incidence is low, regulatory frameworks vary among countries and, in some cases, remain insufficient. According to Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT)[36], official beeswax production prices in 2023 ranged from 4 325 to 6 424 USD/t, with an average of about 5 108 USD/t. Nevertheless, the cost of certain structuring agents—including beeswax and other plant waxes—is expected to decrease with the industrial-scale production of structured oils[37]. These aspects—composition, variability, safety and availability—determine its performance as a structuring agent.

One of the key advantages of beeswax is its ability to structure vegetable oils, with a critical gelation concentration ranging between 6%–10% (*m*/*m*) in oleogels[5,29]. Furthermore, bigels have been developed using ≥ 10% (*m*/*m*) beeswax in combination with hydrogels based on alginate, *κ*-carrageenan, and starch[12,38–40]. The gelation capacity of beeswax is strongly determined by its chemical composition, which is characterized by a high content of wax esters (50%–71%), hydrocarbons (15%–28%), free fatty acids (8%–18%), and free fatty alcohols (1%–12%)[14,29]. Its moderate melting point (61–65 °C) facilitates the solubilization of medium- and long-chain SFA with low melting points, such as myristic ($C_{14:0}$), palmitic ($C_{16:0}$), and stearic acids ($C_{18:0}$)[14,41].

This thermal condition not only aids dissolution but is also critical during the cooling stage, in which crystallization initiates. During this process, beeswax promotes the formation of lamellar structures that evolve into a robust and well-organized crystalline network, which is essential for maintaining gel firmness[8]. Texture, firmness, and oil-holding capacity are key attributes of these gelled systems for their use as fat mimetic in meat products. Considering these structural and functional characteristics, beeswax-based oleogels are typically prepared through the direct method, which involves heating the oil above the wax melting point, followed by continuous mixing and controlled cooling (Table 1, Figure 2). This procedure promotes the development of a stable three-dimensional network capable of immobilizing lipids.

Table 1 Incorporation of beeswax-structured oleogels in meat products: technological, sensory, and nutritional implications.

No.	Meat product	Oleogel system			Substitution level (%)	Implications			Reference
		Gelling agent	Oil	Heating/cooling/ mixing conditions		Technological	Sensory	Nutritional	
1	Beef burger	Beeswax (*A. mellifera*) (10%)	Sesame oil	OG: 70 °C, stir until beeswax dissolved; cool at 4 °C (fast) or 25 °C (slow) overnight	25, 50	↑ Moisture ((36.67 ± 1.18)%–(37.03 ± 0.74)%); ↓ Fat ((22.50 ± 0.50)%); → Protein ((14.52 ± 0.22)%–(14.26 ± 0.04)%), ash ((1.99 ± 0.09)%–(1.92 ± 0.05)%); ↓ Hardness ((11.65 ± 0.36)–(9.43 ± 0.39) N) in raw samples, cohesiveness (0.15 ± 0.01), gumminess ((13.43 ± 0.70)–(12.96 ± 1.57)), chewiness ((39.52 ± 3.20)–(35.35 ± 2.70)) in cooked samples; → Springiness ((2.94 ± 0.24)–(2.73 ± 0.12)); ↓ L^* ((49.34 ± 0.53)–(41.47 ± 0.28)); → a^* ((9.13 ± 1.68)–(8.85 ± 0.40)), b^* ((15.11 ± 1.10)–(17.48 ± 1.35)); ↓ Cooking loss (~19%–23.75%), fat absorption (~7%); ↑ Shrinkage (25%); ↑ Oxidation	Type of sensory panel: trained panel; Number of panelists: 36; Scale/method: 7-point hedonic scale; → Color (1.33–1.52), texture (1.25–1.58); ↑ Flavor preference (1.55–1.69), overall acceptability (1.39–1.86)	↓ Calories from absorbed fat	[5]
2	Pork pâté	Beeswax (11%)	Olive oil (44.39%), flaxseed oil (37.87%), and fish oil (17.74%) blend	65 °C, thermomix speed 3 until melted; stand room temperature for 30 min; store at 3 °C overnight	60, 100	↑ pH ((6.55 ± 0.02)–(6.58 ± 0.01)); ↓ Moisture ((65.3 ± 0.2)%–(65.2 ± 0.1)%); → Protein ((13.4 ± 0.4)%–(13.1 ± 0.1)%), fat ((15.4 ± 1.2)%–(16.2 ± 0.1)%), ash ((3.3 ± 0.0)%), total fluid loss ((4.78 ± 0.30)%–(2.56 ± 0.81)%), water loss ((4.26 ± 0.27)%–(2.28 ± 0.73)%), lipid loss ((0.52 ± 0.04)%–(0.29 ± 0.08)%), L^* ((61.7 ± 0.7)–(61.6 ± 0.9)), hue ((71.1 ± 2.1)–(73.9 ± 3.4)), C^* ((15.0 ± 0.5)–(15.4 ± 0.4)), penetration force ((0.99 ± 0.05)–(0.91 ± 0.20) N), gel strength ((7.32 ± 0.99)–(6.14 ± 0.69) N·mm)	Type of sensory panel: untrained panel; Number of panelists: 40; Scale/method: 10-point hedonic scale; → Color ((7.15 ± 1.60)–(7.20 ± 1.80)), taste ((6.4 ± 1.8)–(6.0 ± 2.2)), texture ((6.4 ± 2.3)–(6.8 ± 1.9)), overall acceptability ((6.4 ± 2.0)–(6.3 ± 2.2)); All reformulated products were rated as "neutral", with no clear negative attributes	↓ SFA, *n*-6 PUFA/*n*-3 PUFA ratio ↑ PUFA, *n*-3 PUFA (EPA and DHA), ΣPUFA/ΣSFA ratio	[6]
3	Model meat product (T1) and hamburger-type meat product (T2) (beef)	Beeswax (*A. mellifera*) (10%) + κ-carrageenan (2%) + potato starch (10%)	Canola oil	OG: 60 °C, 700 r/min; HG: 80 °C, 700 r/min; mix OG:HG (25:75/50:50/75:25): 1 200 r/min, 3 min; cooling: 0 °C, 30 min (~8–10 °C/min), storage: 4 °C, 24 h; gelation criteria: tube inversion test (2 cm × 3 cm) confirms 3D gel network formation	0, 25, 50, 75, 100	↑ Moisture ((51.55 ± 0.24)%–(56.37 ± 0.29)%) and a_w ((0.78 ± 0.01)–(0.85 ± 0.00)); ↑ Higher thermal stability in T2; ↓ Shrinkage rate ((9.39 ± 0.53)%–(4.39 ± 0.27)%); ↓ Hardness ((92.27 ± 3.13)–(15.95 ± 2.64) N); ↓ Mastication ((40.59 ± 0.88)–(3.81 ± 0.83) N), and gumminess ((40.72 ± 0.99)–(3.81 ± 0.83) N); → ΔE;		Improved lipid profile: ↓ SFA; ↑ PUFA	[12]
4	Pork sausages	Beeswax (10%)	Camellia oil	90 °C, 500 r/min, 120 min; cooling: 4 °C, 24 h	50	↓ Hardness ((10.23 ± 0.24) N) and chewiness ((5.74 ± 0.44) N); → WHC (92%), resilience (0.33 ± 0.01), springiness (0.80 ± 0.05), cohesiveness (0.70 ± 0.01), pH (5.66 ± 0.08), L^* (62.91 ± 1.97), a^* (−1.01 ± 0.09), b^* (15.10 ± 2.61)	Type of sensory panel: consumer panel; Number of panelists: 15; Scale/method: 20-point scale; Acceptable appearance: → Color (18); → Texture and flavor (19), although slightly different from the control	↓ SFA	[19]

Table 1 (*Continued*)

No.	Meat product	Oleogel system			Substitution level (%)	Implications			Reference
		Gelling agent	Oil	Heating/cooling/mixing conditions		Technological	Sensory	Nutritional	
5	Pork burgers	Beeswax (11%)	Olive oil (44.39%), flaxseed oil (37.87%), and fish oil (17.74%) blend	65 °C, thermomix speed 3 until melted; stand room temperature for 30 min; store at 3 °C overnight	100	→ Moisture ((71.92 ± 0.19)%), ash ((1.88 ± 0.06)%), protein ((17.87 ± 0.08)%); ↑ Fat ((7.72 ± 0.15)%); ↓ Kramer shear force ((2.23 ± 0.23) N); → L^* (52.12 ± 2.07), hue (76.9 ± 1.9); ↑ a^* (2.55 ± 0.40), b^* (11.00 ± 0.95); Good oxidative stability	Type of sensory panel: untrained panel; Number of panelists: 40; Scale/method: 10-point hedonic scale; ↓ Overall acceptability (~5.8), flavor (~5.8); → Color (~7), texture (~7)	↓ SFA, Σ*n*-6 PUFA/Σ*n*-3 PUFA ratio by approximately 23-fold; ↑ MUFA and PUFA, especially ALA, EPA, and DHA, ΣPUFA/SFA ratio	[20]
6	Pork burger	Beeswax (11%; W); beeswax (11%) + curcumin (0.2 g/100 g oleogel; W + Cu)	Olive oil (44.39%), flaxseed oil (37.87%), and fish oil (17.74%) blend	Mix oils + organogelator + curcumin; 65 °C, thermomix speed 3 until melted; stand 30 min at room temperature; sonication: 2 × 1 min, 30 s interval, 100 Hz; store at 3 °C overnight	100	→ Moisture ((65.48 ± 0.15)%), ash ((2.37 ± 0.38)%–(2.23 ± 0.08)%), protein ((22.71 ± 0.16)%–(22.62 ± 0.25)%), fat ((9.44 ± 0.53)%–(9.67 ± 0.67)%); ↓ Kramer shear force ((2.232 ± 0.229)–(2.482 ± 0.186) N); → Cooking loss ((18.86 ± 0.82)%–(20.03 ± 0.22)%); ↑ Lipid oxidation in W samples; ↓ Lipid oxidation in W + Cu samples	Type of sensory panel: untrained consumers; Number of panelists: 40; Scale/method: 10-point scale; ↓ Color (5.22 ± 2.26) in W-Cu samples; → Flavor ((5.73 ± 2.42)–(5.63 ± 2.03)), texture ((6.79 ± 1.60)–(6.35 ± 1.49)), overall acceptability ((5.74 ± 2.33)–(5.50 ± 1.93))	↓ SFA; ↑ MUFA and PUFA, *n*-3 PUFA (ALA, EPA, DHA); ↑ ΣPUFA/ΣSFA ≈ 3.6 times; ↓ *n*-6 PUFA/*n*-3 PUFA ratio ≈ 23 times	[21]
7	Processed meat	Beeswax (1.2%)	Canola oil	70 °C, 20 min, continuous stirring; cool at room temperature overnight; store refrigerated	50	→ WHC (32%); ↑ Cooking loss (39%); ↓ Hardness (10 N), chewiness (≈ 2 N); ↑ Springiness (≈ 2.5 mm) and cohesiveness (≈ 1.5 N); → L^* (51.90 ± 6.80), a^* (17.40 ± 3.30), and b^* (19.10 ± 2.50) → pH (≈ 7); → Moisture ((65.78 ± 0.12)%), protein ((11.56 ± 0.19)%), total cholesterol ((47.96 ± 0.98) mg/100 g); ↓ Fat ((8.40 ± 0.09)%), ash ((0.58 ± 3.61)%), calories ((1 913.00 ± 65.05) cal/g)	Type of sensory panel: untrained consumers; Number of panelists: 30; Scale/method: 9-point hedonic scale; → Color (≈ 7); ↓ Score in aroma (≈ 6.7), flavor (≈ 6.3); ↑ Score in oiliness (≈ 5.8), juiciness (≈ 5.5), firmness (≈ 5.9); ↑ Product acceptance	↑ MUFA, PUFA, *n*-3 (ALA, EPA, DHA); ↓ Total fat and caloric value of the product; ↓ SFA	[23]
8	Alaska pollock surimi	Beeswax (10%)	Canola oil and fish oil in ratios 0:10, 3:7, and 5:5	90 °C, 30 min, magnetic stirring; cooling: 4 °C, 24 h; storage: 25 °C	100	↑ WHC ((72.44 ± 0.01)%–(76.00 ± 0.01)%), b^* ((13.16 ± 0.01)–(13.26 ± 0.04)), a^* ((−0.73 ± 0.01)–(−0.96 ± 0.01)); ↓ L^* ((89.38 ± 0.01)–(90.64 ± 0.01)), WI ((86.71 ± 0.02)–(86.84 ± 0.01)); ↑ Hardness ((55.47 ± 1.62)–(69.80 ± 1.08)), cohesiveness (0.39 ± 0.04), springiness (7.94 ± 0.24); → Adhesiveness ((−0.42 ± 0.20)–(0.56 ± 0.07)); ↑ Thermal stability at 0:10		Potential for products low in saturated and trans fats	[24]
9	Pork pâté	Beeswax (8%)	Flaxseed oil	80 °C, stir 30 min until beeswax melted; cool at room temperature; gelation criteria: stable 3D network formed after 48 h at room temperature	30 (P-30), 60 (P-60)	↓ pH (6.29 ± 0.01), protein ((10.75 ± 0.36)%–(11.12 ± 0.71)%), fat ((20.55 ± 1.86)%), ash ((2.70 ± 0.12)%–(2.77 ± 0.05)%); ↑ Moisture ((52.83 ± 1.53)%); → L^* ((63.33 ± 5.25)–(59.77 ± 2.75)); ↑ b^* ((23.82 ± 1.09)–(28.29 ± 2.79)); ↓ Hardness, adhesiveness, gumminess	Type of sensory panel: semi-trained/expert; Number of panelists: 13; Scale/method: 7-point scale; Global acceptance: ↑ 4.08 (P-30); ↓ 5.85 (P-60)	↓ SFA; ↑ PUFA, especially *n*-3 PUFA ($C_{18:3\ n\text{-}3}$); ↓ *n*-6 PUFA/*n*-3 PUFA ratio, associated with anti-inflammatory effects and metabolic benefits	[25]

Table 1 (*Continued*)

No.	Meat product	Oleogel system			Substitution level (%)	Implications			Reference
		Gelling agent	Oil	Heating/cooling/ mixing conditions		Technological	Sensory	Nutritional	
10	Beef heart burger	Beeswax (10%)	Canola oil	90 °C, 200 r/min, 45 min; store at 4 °C or 25 °C for 24 h; gelation criteria: confirmed by phase diagram (liquid→gel transition) and tube inversion test; stable 3D network formed at ≥ 7.5% beeswax	100	→ Protein ((16.75 ± 0.11)%–(17.07 ± 0.28)%); ↑ Moisture ((64.83 ± 0.16)%–(69.48 ± 0.71)%); ↓ Fat ((13.57 ± 0.02)%–(14.54 ± 0.02)%); ↓ Hardness ((153.43 ± 8.24)–(63.03 ± 6.89) N), gumminess ((39.20 ± 5.92)–(17.02 ± 2.27) N); ↑ L^* ((51.91 ± 0.16)–(58.23 ± 0.33)) and b^* (21.38 ± 0.08) (during refrigerated storage); ↑ Lipid oxidation		↓ 13% in total fat; ↓ SFA (54.08–8.34 g/100 g); ↑ PUFA (8.88–34.37 g/100 g); ↑ Linoleic acid, ALA, and oleic acid; → PUFA/SFA ratio within dietary recommendations; ↓ PUFA and MUFA during storage due to lipid oxidation	[26]
11	Shrimp meat batter	Beeswax (6%, 10%, 14%)	Fish oil (tuna and anchovy)	60–80 °C, cool to 25 °C, storage: 4 °C, 24 h	100	↑ Hardness, gumminess, chewiness, adhesiveness; ↑ WHC-OHC in the protein network; ↓ Water and fat loss		May offer a potential source of health-promoting PUFAs (EPA and DHA)	[27]
12	Fish balls	Beeswax (10%) + fish scale hydrogel (1:5)	High-oleic sunflower oil	OG: 90 °C, 350 r/min, 45 min; HG: 10 000 r/min, 100 s; mix OG:HG: 80 s; gold gel: 0 °C, 6–12 min/ 18 °C, 2–8 min; homogenize: 10 000 r/min, 80 s; storage: 4 °C; gelation criteria: formation and stability of bigels evaluated via structure	0, 25, 50, 75, 100	↑ Moisture (> 60%, ≈ 80%) and whiteness; ↓ Hardness when substitution > 50% (600–1 000 g); ↑ WHC, freeze-thaw stability; ↑ Lipid oxidation (50% substitution)	Type of sensory panel: trained panel; Number of panelists: 10; Scale/method: 10-point scale; ↑ Acceptance (50% substitution) with flavor richness (8.7); ↑ Freshness, juiciness; ↑ Volatile compounds (alkanes, sulfides, alcohols) (50%–75% substitution)		[28]
13	Beef patties	Beeswax	Sunflower oil	90–95 °C, 150 r/min, 60 min; cooling and storage: 4 °C, 24 h; gelation criteria: structure stabilized after cooling	10	↑ Moisture ((57.62 ± 0.86)%), carbohydrates ((2.56 ± 0.09)%); ↓ Protein ((19.47 ± 0.28)%), pH (6.02 ± 0.17), and fat ((18.37 ± 0.26)%); ↑ WHC (2.53% higher than the control sample); → Microstructure	Type of sensory panel: trained panel; Number of panelists: 20; Scale/method: 5-point hedonic scale; ↑ Appearance (4.80 ± 0.08), aroma (4.90 ± 0.06), and consistency (5.00 ± 0.09); → Color, flavor, and texture	↑ PUFA (12.45%–18.94%); ↑ Linoleic acid (11.80%–18.85%); ↓ Stearic acid, myristic acid, margaric acid	[42]
14	Semi-smoked sausage	Monoglycerides and beeswax (2:1)	Sunflower oil	90–95 °C, 150 r/min, 60 min; cooling and storage: 4 °C, 24 h; gelation criteria: structure stabilized after cooling	7 (OG7), 10 (OG10)	↑ Moisture ((57.23 ± 0.92)%–(56.80 ± 1.14)%); ↓ Fat ((17.90 ± 0.33)%–(17.83 ± 0.17)%); → pH ((6.08 ± 0.10)–(6.13 ± 0.08)), protein ((19.52 ± 0.23)%–(19.49 ± 0.31)%), carbohydrates ((3.26 ± 0.11)%–(3.30 ± 0.15)%), and ash ((2.39 ± 0.03)%–(2.47 ± 0.04)%)	Type of sensory panel: trained panel; Number of panelists: 20; Scale/method: 5-point hedonic scale; → Taste, flavor and aroma, color; ↓ Appearance ((4.90 ± 0.05)–(4.69 ± 0.07)), consistency ((4.83 ± 0.07)–(4.70 ± 0.05)), view on the cut ((4.87 ± 0.05)–(4.68 ± 0.08)), juiciness ((4.86 ± 0.05)–(4.72 ± 0.05))	↓ SFA (40.89% to 25.27%–26.37%); ↓ Stearic acid (14.42% to 6.31%–6.69%); ↓ Palmitic acid (24.28% to 16.89%–18.10%); ↑ PUFA; ↑ Linoleic acid (12.37% to 45.29%–47.88%)	[43]
15	Pork sausages	Beeswax (4.5%, 9.0%)	Soybean oil	OG: 80 °C, 15 min. Pickering emulsions: 80 °C, 10 000 r/min, 2 min + ultrasonic at 60% amplitude, 2 min; cool ice bath for 15 min, storage: 4 °C	100, 50	↓ Cooking loss ((1.53 ± 0.24)%–(2.01 ± 0.10)%); ↑ L^* ((62.76 ± 0.24)–(67.14 ± 0.14)), b^* ((10.92 ± 0.05)–(11.32 ± 0.13)); ↓ a^* ((7.58 ± 0.15)–(8.60 ± 0.04)); ↑ WHC ((85.19 ± 0.49)%–(86.91 ± 1.03)%); ↓ Hardness ((52.26 ± 0.41)–(55.20 ± 1.84) N), cohesiveness ((0.61 ± 0.01)–(0.63 ± 0.03)), chewiness ((216.53 ± 7.62)–(233.52 ± 6.40)); → pH ((5.69 ± 0.09)–(5.78 ± 0.02));		↓ SFA	[44]

Table 1 (*Continued*)

No.	Meat product	Oleogel system			Substitution level (%)	Implications			Reference
		Gelling agent	Oil	Heating/cooling/ mixing conditions		Technological	Sensory	Nutritional	
16	Beef sucuk (traditional sausage)	Beeswax (*A. mellifera*) (10%)	Cold-pressed flaxseed oil	80 °C, mix until wax melted; cool to (23 ± 2) °C overnight; store refrigerated; gelation criteria: structure stabilized after cooling	100	→ Crude protein ((17.95 ± 0.87)%), pH (5.27 ± 0.01); ↓ Moisture ((41.84 ± 1.79)%); ↑ Total fat ((34.44 ± 1.09)%), ash ((3.77 ± 0.02)%); ↓ Surface L^* (39.23 ± 0.08), cross-section L^* (40.33 ± 0.07), surface a^* (11.06 ± 0.05), cross-section a^* (15.90 ± 0.29), surface b^* (10.07 ± 0.09), cross-section b^* (14.59 ± 0.18); ↓ Weight loss ((9.29 ± 0.51)%) and cooking losses ((10.50 ± 1.33)%); ↓ Hardness ((45.83 ± 4.20) N), cohesiveness (0.15 ± 0.02), gumminess ((7.15 ± 5.60) N), chewiness ((4.96 ± 3.50) N); → Springiness (0.68 ± 0.02); ↑ Adhesiveness ((−0.65 ± 0.20) N·s), resilience (0.20 ± 0.02)	Type of sensory panel: trained panel with quantitative descriptive analysis (QDA); Number of panelists: 12; Scale/method: 10-cm line scale; ↓ Appearance (5.83 ± 1.59), hardness (4.25 ± 1.05), aroma (6.17 ± 1.75), flavor (5.92 ± 1.44); ↑ Chewiness (7.17 ± 1.34), fattiness (5.08 ± 1.73), juiciness (5.08 ± 1.62); ↑ Perceived fat content; ↑ Volatile compounds	↑ MUFA, PUFA; ↑ Linoleic and linolenic acids	[45]
17	Pork fuet (dry fermented sausage)	Beeswax (10%)	Olive oil (80%) + chia oil (20%)	65 °C, 500 r/min, thermomix until melted; stand room temperature for 60 min; store at 3 °C	80	→ Moisture ((37.45 ± 0.70)%), ash ((4.90 ± 0.01)%), protein ((31.92 ± 0.96)%); ↓ Fat ((22.30 ± 2.13)%); ↑ a_w (0.91 ± 0.01); ↑ pH ((5.27 ± 0.01)–(6.64 ± 0.03)) (during refrigerated storage); → L^* ((41.69 ± 2.47)–(40.76 ± 2.39)); ↑ b^* ((7.91 ± 0.98)–(10.43 ± 1.10)); ↓ Hardness ((3.75 ± 0.49)–(5.36 ± 0.52) N); ↑ Lipid oxidation	Type of sensory panel: trained panel; Number of panelists: 30; Scale/method: 10-point scale; ↓ Flavor (~5.8) and acceptability due to aldehydes (day 0); ↑ Flavor (~6.0) and acceptability (day 30)	↓ SFA; ↑ PUFA, ALA; ↓ *n*-6 PUFA/*n*-3 PUFA ratio; → Improvement in the PUFA/SFA ratio; ↓ Energy value by 14%–16%	[46]
18	Dry-cured "Salchichón" sausage	Beeswax (8%)	Linseed oil	OG: 80 °C, stir 30 min until solubilized	20, 40	↓ pH ((5.08 ± 0.08)–(4.85 ± 0.05)); ↑ L^* ((46.64 ± 2.64)–(54.68 ± 1.82)), a^* ((14.96 ± 0.63)–(15.01 ± 0.95)), b^* ((11.76 ± 0.62)–(15.58 ± 0.89)), chroma ((19.07 ± 0.74)–(21.64 ± 1.15)), moisture (~45%); → Fat, protein, ash, carbohydrates; ↓ Hardness ((16.48 ± 1.71)–(5.85 ± 0.39) N), gumminess ((5.97 ± 0.58)–(2.47 ± 0.05) N), chewiness ((3.09 ± 0.43)–(1.35 ± 0.08) N·mm); ↑ Springiness ((0.53 ± 0.02)–(0.55 ± 0.01))	Type of sensory panel: trained panel; Number of panelists: 28; Scale/method: 7-point scale; ↑ Overall acceptability ((3.21 ± 0.22)–(4.57 ± 0.29)); → Color, flavor, odor	↓ SFA (31.85–28.78 g/100 g); ↑ PUFA, ALA, *n*-3; ↑ PUFA/SFA ratio (0.89–1.48); ↓ *n*-6 PUFA/*n*-3 PUFA ratio (1.75–0.90); ↓ AI, TI	[47]
19	Frankfurter-type sausage	Beeswax (8%)	Linseed oil	80 °C, stir 30 min until beeswax melted; cool at room temperature until gel formation; gelation criteria: structure stabilized after cooling	25 (SP-25), 50 (SP-50)	↓ Moisture ((55.98 ± 0.49)%–(56.74 ± 0.67)%), protein ((10.63 ± 0.39)%–(10.62 ± 0.22)%), ash ((4.05 ± 0.09)%–(4.04 ± 0.10)%), cholesterol ((20.12 ± 0.77)–(17.23 ± 0.38) mg/100 g); ↑ Carbohydrate ((9.30 ± 0.66)%–(9.63 ± 0.60)%); ↑ L^*, b^*; ↓ a^*; → Hardness; ↑ Cohesiveness, gumminess, chewiness (SF-50)	Type of sensory panel: semi-trained/expert; Number of panelists: 32; Scale/method: 7-point hedonic scale; ↑ Yellow color, which may be related to lipid oxidation; ↓ Acceptance with the increase in oleogel percentage, flavor perception, juiciness (SF-50), overall acceptability ((2.06 ± 0.17)–(2.69 ± 0.19))	↓ SFA (palmitic and stearic acids), cholesterol, *n*-6 PUFA/*n*-3 PUFA ratio, AI, TI; ↑ PUFA, oleic acid, h/H	[48]

Note: ↓ Represents lower than control; ↑ represents higher than control; → represents not changed or similar to control. OG, oleogel; HG, hydrogel; WHC, water-holding capacity; OHC, oil holding capacity; a_w, water activity; ΔE, color difference; L^*, lightness value; a^*, redness value; b^*, yellowness value; C^*, chromaticity; WI, whiteness index; AI, atherogenic index; TI, thrombogenic index; h/H, hypocholesterolemic/hypercholesterolemic acid ratio. ≈ Represents approximate values obtained from the figures of the original article.

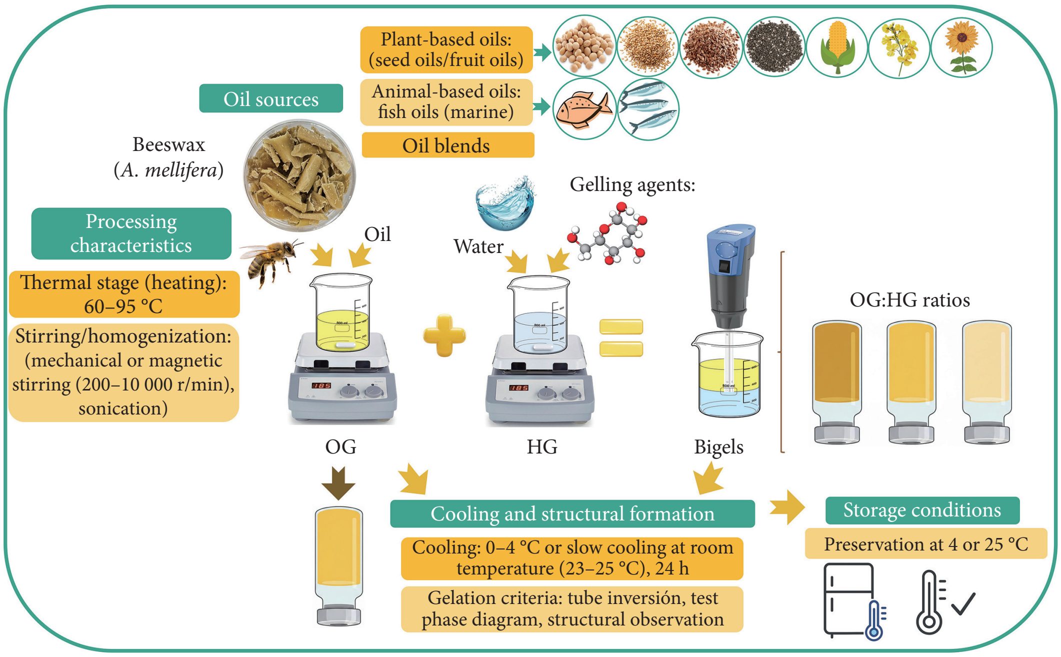

Figure 2 Common processing and gelation conditions of beeswax-based oleogels and bigels.

The use of structured lipid systems with beeswax falls within the broader development of innovative fat-replacement technologies. Within this same context, polysaccharide-based hydrocolloids are widely used as fat substitutes in meat products due to their functional and nutritional benefits, including the provision of soluble dietary fiber, glycemic control, and potential prebiotic effects[49]. In particular, gums mimic the textural attributes of fat with minimal caloric contribution, improve moisture retention, reduce drip and cooking losses, exert cryoprotective effects, and enhance viscosity and gel formation[50]. However, high levels of substitution may lead to undesirable technological effects, such as structural alterations, increased water release, system instability, or reduced gel firmness[51–52].

Protein-based fat replacers, in turn, function primarily as stabilizers and emulsifiers, improving system stability and enabling fat reduction without compromising technological quality, although in some cases they may alter lipid digestion or the color of the final product[53–55]. Compared with these conventional technologies, beeswax-structured lipids—whether employed as oleogels or as the oil phase in bigels—offer additional advantages. They can function as effective encapsulation agents for antioxidants, thereby contributing to improved oxidative stability during storage[21].

Likewise, they enhance oiliness and juiciness[23], impart cryoprotective effects, improve structural stability[28], and do not induce color changes, which helps maintain key technological parameters in the final products[12]. Furthermore, combining waxes and vegetable oils with hydrocolloids or proteins in bigel systems can overcome the limitations of individual fat substitutes by integrating textural and emulsifying properties with a healthier lipid profile[12,28,56].

3 Nutritional implications

From a public health perspective, and in accordance with the World Health Organization (WHO), CVD are the leading cause of mortality worldwide. In 2022, the Centers for Disease Control and Prevention reported that nearly 80% of individuals who experienced strokes had a history of hypertension. Additionally, more than 60% of diabetes cases were associated with hypertension and elevated low-density lipoprotein cholesterol levels[57]. Consequently, an adequate diet is considered a key factor in the prevention of CVD. Clinical trials have demonstrated that replacing SFA with PUFAs can reduce the risk of CVD by up to 30%[58–59].

The American Heart Association recommends that individuals with hypercholesterolemia limit their intake of SFA to 5%–6% of total daily calories, while the general population is advised not to exceed 10%. The FAO and the WHO recommend that fats contribute 15%–30% of total caloric intake, with saturated fats limited to less than 10% and trans fats avoided entirely[60]. In this context, the incorporation of oleogels and bigels as structured lipid systems in processed meat products represents an effective strategy to align these foods with international nutritional guidelines.

These innovative technologies enable the development of healthier meat matrices and contribute to reducing the risk of CVD associated with excessive SFA consumption. Reformulating meat products using oleogels and bigels offers a promising approach to improving their nutritional quality, particularly regarding the lipid profile. The nutritional composition of meat products reformulated with these systems depends on the type of oil used, the extent of animal fat replacement, and the potential addition of functional compounds. Furthermore, their nutritional impact is influenced by the lipid profile of the fat being replaced.

Scientific studies show a growing trend toward the use of vegetable oils rich in unsaturated fatty acids (UFA), such as canola, sunflower, soybean, flaxseed, and fish oils, as well as their blends. Once structured as oleogels or bigels, these oils help reduce the content of SFA and cholesterol, while increasing the proportion of UFA, especially PUFAs, including *n*-3 PUFA. Table 2 presents the nutritional composition and fatty acid profiles of the main oils used in the formulation of structured lipid systems with beeswax as a gelling agent.

Vegetable oils structured as oleogels have shown significant improvements in the lipid profile of reformulated meat products, regardless of the oil source. Canola and sunflower oils, both rich in

Table 2 Fatty acid composition (g/100 g of fat) of oils commonly used for the formulation of oleogels and bigels with beeswax.

	Fatty acid	Sesame oil[5]	Camellia oil[19]	Canola oil[61] (USDA FDC ID: 748278, 2019)	Sunflower oil[61] (USDA FDC ID: 1750349, 2019)	Soybean oil[61] (USDA FDC ID: 748366, 2019)	Olive oil[61] (USDA FDC ID: 748608, 2019)	Flaxseed oil[62]	Fish oil[63]	Tuna oil[64]	Anchovy oil[65]	Chia seed oil[66]
SFA	Butyric acid ($C_{4:0}$)	ND	ND	ND	0.004 ± 0.001	ND	ND	ND	ND	ND	ND	ND
	Caproic acid ($C_{6:0}$)	ND	ND	ND	0	ND	ND	ND	ND	ND	ND	ND
	Caprylic acid ($C_{8:0}$)	ND	ND	ND	0.001 ± 0.002	ND	ND	ND	ND	ND	ND	ND
	Capric acid ($C_{10:0}$)	ND	ND	ND	0.006 ± 0.005	ND	ND	ND	ND	ND	ND	ND
	Lauric acid ($C_{12:0}$)	ND	ND	ND	0.004 ± 0.001	ND	ND	ND	ND	ND	ND	ND
	Myristic acid ($C_{14:0}$)	ND	ND	0.047 ± 0.001	0.049 ± 0.012	0.075 ± 0.001	0.013 ± 0.002	0.03–0.05	14.73 ± 3.04	3.12 ± 0.01	0.67 ± 0.17	ND
	Pentadecanoic acid ($C_{15:0}$)	ND	ND	0.018 ± 0.001	0.018 ± 0.008	0.014 ± 0.000	0.006 ± 0.002	ND–0.01	ND	ND	5.36 ± 0.61	ND
	Palmitic acid ($C_{16:0}$)	9.70 ± 0.29	7.740 5	3.860 ± 0.047	4.478 ± 1.031	10.260 ± 0.089	12.144 ± 1.537	4.58–6.42	18.08 ± 0.77	19.26 ± 0.22	0.24 ± 0.10	6.7 ± 0.1
	Heptadecanoic acid ($C_{17:0}$)	ND	ND	0.041 ± 0.001	0.029 ± 0.003	0.086 ± 0.002	0.081 ± 0.029	ND–0.04	0.46 ± 0.02	ND	ND	ND
	Stearic acid ($C_{18:0}$)	5.80 ± 0.36	1.709 0	1.658 ± 0.018	2.986 ± 0.488	3.704 ± 0.088	2.592 ± 0.319	3.65–5.96	4.56 ± 0.16	6.62 ± 0.22	0.19 ± 0.04	3.2 ± 0.1
	Arachidic acid ($C_{20:0}$)	ND	0.354 0	0.537 ± 0.003	0.274 ± 0.039	0.292 ± 0.010	0.411 ± 0.023	0.01–0.20	0.29 ± 0.11	1.75 ± 0.01	ND	0.8 ± 0.0
	Heneicosanoic acid ($C_{21:0}$)	ND	ND	0.011 ± 0.001	0.013 ± 0.006	0.025 ± 0.001	0.014 ± 0.004	ND	0.55 ± 0.05	ND	1.60 ± 0.16	ND
	Behenic acid ($C_{22:0}$)	ND	ND	0.270 ± 0.004	0.821 ± 0.162	0.304 ± 0.013	0.118 ± 0.010	0.11–0.14	ND	1.62 ± 0.03	ND	ND
	Total SFA	15.50 ± 0.46	9.940 0	6.610 ± 0.048	8.991 ± 1.187	14.900 ± 0.100	15.492 ± 1.326	8.42–12.90	38.68 ± 1.98	32.37 ± 0.31	8.06 ± 1.08	10.8
MUFA	*cis*-10-Pentadecenoic acid ($C_{15:1}$)	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.49 ± 0.13	ND
	Palmitoleic acid ($C_{16:1}$)	ND	0.085 5	0.205 ± 0.004	0.122 ± 0.060	0.080 ± 0.002	1.033 ± 0.334	0.04–0.20	3.90 ± 0.37	4.36 ± 0.01	0.19 ± 0.04	ND
	Oleic acid ($C_{18:1}$)	42.24 ± 0.20	81.371 0	60.260 ± 0.391	62.950 ± 24.919	21.380 ± 0.327	67.781 ± 3.639	16.33–22.56	20.60 ± 1.47	14.67 ± 0.06	1.52 ± 0.11	6.0 ± 0.1
	Eicosenoic acid ($C_{20:1}$)	ND	0.388 5	1.892 ± 0.386	0.256 ± 0.071	0.597 ± 0.055	0.276 ± 0.030	ND–0.21	ND	4.41 ± 0.01	ND	0.8 ± 0.0
	Erucic acid ($C_{22:1}$)	ND	ND	ND	0.006	ND	ND	ND	ND	ND	0.51 ± 0.04	ND
	Total MUFA	42.24 ± 0.20	81.850 0	62.580 ± 0.719	63.375 ± 24.989	22.140 ± 0.321	69.229 ± 3.260	16.37–23.00	25.60 ± 1.87	23.44 ± 0.06	3.71 ± 0.18	6.9
PUFA	Linoleic acid ($C_{18:2}$)	40.54 ± 0.78	7.843 5	17.800	20.600	50.900	8.400	9.18–15.88	7.78 ± 0.88	1.53 ± 0.13	ND	16.6 ± 0.0
	ALA ($C_{18:3}$)	0.29 ± 0.01	0.226 5	7.450	0.163	6.620	0.651	42.97–61.06	2.45 ± 0.22	1.93 ± 0.02	ND	61.1 ± 0.9
	Stearidonic acid ($C_{18:4}$)	ND	ND	0	0	ND	ND	ND	0.93 ± 0.06	ND	ND	ND
	Arachidonic acid ($C_{20:4\ n\text{-}6}$)	ND	ND	ND	ND	ND	ND	ND	0.14 ± 0.12	ND	0.35 ± 0.05	ND
	EPA ($C_{20:5\ n\text{-}3}$)	ND	ND	ND	0.002	ND	ND	ND	4.34 ± 0.16	4.64 ± 0.02	65.13 ± 0.27	ND
	DHA ($C_{22:6\ n\text{-}3}$)	ND	ND	ND	ND	ND	ND	ND	18.48 ± 1.07	22.22 ± 0.01	22.75 ± 0.60	ND
	Total PUFA	40.83 ± 0.78	8.210 0	25.300 ± 0.696	20.715 ± 23.892	57.600 ± 0.361	9.070 ± 2.260	52.15–76.94	35.72 ± 0.21	30.32 ± 0.13	88.23 ± 0.66	78.3

Note: ND represents not detected.

oleic and linoleic acids[61], have been widely applied in meat matrices, where their structuring with beeswax led to reductions in total fat, caloric content, and SFA levels, together with increases in MUFA, PUFA, and *n*-3 PUFA such as *α*-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA)[12,23,26,28,42–43] (Table 1).

These formulations meet dietary recommendations for PUFA/SFA and *n*-6 PUFA/*n*-3 PUFA ratios, although some losses in UFAs may occur during storage due to oxidation. Flaxseed oil, characterized by its high PUFA content (particularly ALA)[62] (Table 2), has also been incorporated into oleogels for sausages and pâtés, achieving reductions in cholesterol and SFA while improving atherogenic and thrombogenic indices, as well as the hypo-/hyper-cholesterolemic ratio[25,45,47–48] (Table 1).

Blends combining fish, olive, and flaxseed oils have been used to optimize the SFA, MUFA, and PUFA balance in meat products. Such systems significantly improved lipid quality, increasing ALA, EPA, and DHA levels and enabling nutritional claims such as "high in *n*-3 PUFA" in accordance with European regulations[6,20–21,27] (Table 1). In marine-based meat products, oleogels have been developed using blends of fish and canola oils, as well as mixtures of tuna and anchovy oils rich in EPA and DHA[24,27,64–65]. However, their high PUFA content increased susceptibility to lipid oxidation[24,27].

Less common oils, including camellia and sesame oils, also exhibited promising fatty acid profiles—high in oleic acid and free of myristic acid—enhancing the nutritional potential of oleogel-based sausages and beef burgers[5,19] (Tables 1 and 2). Overall, the reduction in SFA, particularly palmitic and stearic acids, reinforces the suitability of these structured lipid systems as functional fat alternatives in the development of healthier meat products.

4 Oxidative stability

4.1 Oxidative stability in oleogels

Oxidative stability during the storage and transport of oleogels remains a major challenge, particularly when oils rich in PUFAs are used. Their high degree of unsaturation makes them prone to autoxidation and to the formation of secondary oxidation products that impair flavor, decrease nutritional value, and may pose potential health risks[67]. Structuring these oils with natural waxes—such as rice bran, sunflower, candelilla, or beeswax—enhances oxidative stability by forming a three-dimensional crystalline network that immobilizes the oil and reduces its exposure to oxygen, light, and other pro-oxidant agents[68]. However, the extent of this protection depends on the type and concentration of the oleogelator, the oil incorporated, processing conditions, and storage temperature[69].

The cooling rate (5.3–11.0 °C/min) and moderate wax concentrations (3%–5%, *m*/*m*) limit peroxide formation and the degradation of EPA and DHA; however, contents ≥ 9% (*m*/*m*) may induce pro-oxidant effects at elevated temperatures due to the presence of free fatty acids in the waxes[68]. The incorporation of synthetic antioxidants, such as butylated hydroxyanisole or tert-butylhydroquinone, complements the protection provided by oleogelation by reducing peroxide value (PV), *p*-anisidine value, total oxidation value, and thiobarbituric acid reactive substances (TBARS) value[70–71], as these compounds interrupt the free radical chain reactions[72]. Nonetheless, concerns regarding their safety have driven the search for natural alternatives.

In beeswax-structured oleogels, natural antioxidants such as ascorbic acid, tea polyphenols, and β-carotene reduce PV and malondialdehyde (MDA) content during storage periods of 8–28 days at temperatures ranging from 25 to 60 °C. Their effectiveness depends on the strength of the structural network and on the compatibility between the antioxidant and the oil phase[73–75]. Likewise, the combination of hydrocarbon and monoester fractions (6%, *m*/*m*) derived from beeswax enhances the oxidative stability of oleogels formulated with sunflower oil stored at 35 °C for 20 days, yielding PV close to 20 meq/kg. In contrast, oleogels formulated with pure beeswax reach values of up to 50 meq/kg[76].

4.2 Oxidative behavior in reformulated meat products

The application of beeswax-based oleogels in meat products exhibits oxidative behavior influenced by heating, agitation, and the type of oil used[5–6,26]. Furthermore, susceptibility to oxidation varies according to the level of animal fat replacement, which can compromise the quality, safety, and nutritional properties of the products, especially during refrigerated or frozen storage[5,26,28].

Table 3 summarizes the lipid oxidation levels in meat products incorporating beeswax-based oleogels or bigels. Gómez-Estaca et al.[21] reported that turmeric was effective in reducing lipid oxidation; however, part of it is lost due to its own antioxidant activity and the melting of the oleogel. Nonetheless, the remaining fraction retained

Table 3 Lipid oxidation in meat products formulated with beeswax-based oleogels and bigels.

Oxidation technique	Marker	Storage conditions	Lipid system/processed meat product	Reference
POV; acid value; TBARS value	Hydroperoxides (g/100 g); MDA	Beef burger: frozen at −30 °C, packed under atmospheric conditions in polystyrene trays sealed with polyethylene film, and stored at −18 °C for 3 months	Oleogel: POV: (2.84 ± 0.23)–(3.13 ± 0.08) meq O_2/kg; Acid value: (0.78 ± 0.02)–(0.44 ± 0.00) mg KOH/g oil. Beef burger: ↑ TBARS value over time (0 → 3 months); 25% oleogel replacement: intermediate oxidation; 50% oleogel replacement: > 1 mg MDA/kg from day 0; ↑ Frozen storage (1–3 months): TBARS value > 1 mg MDA/kg in 25% and 50% oleogel; ↑ Oleogel concentration; ↑ Lipid oxidation	[5]
TBARS value	MDA	Pâtés: chilled storage at (3 ± 1) °C for 7, 30, and 60 days	Oleogel: ↑ Lipid oxidation during thermal processing (initial oil 0.177 ± 0.023 → W-OG (0.340 ± 0.042) mg MDA/kg); ↑ Oxidation due to air incorporation during stirring. Pâtés: Day 7: WPR: (0.129 ± 0.020) mg MDA/kg; WTR: (0.149 ± 0.003) mg MDA/kg; Day 30: WPR: (0.326 ± 0.063) mg MDA/kg; WTR: (0.304 ± 0.062) mg MDA/kg; Day 60: WPR: (0.215 ± 0.019) mg MDA/kg; WTR: (0.420 ± 0.034) mg MDA/kg	[6]
TBARS value	MDA	Oleogel: refrigerated storage: 28 days at (3 ± 1) °C; pork burgers: stored in trays under air atmosphere at (2 ± 2) °C until analysis	Oleogel: ↑ TBARS value progressively during 28-day storage but still < 1 mg MDA/kg. Pork burgers: → Intermediate oxidative status in pork burgers (W-B: (0.14 ± 0.00) mg MDA/kg)	[20]
TBARS value	MDA	Pork burger: stored in trays under aerobic conditions at (4 ± 2) °C for 6 days (samples taken on days 1, 3, and 6)	Pork burger: ↑ Oxidation products after cooking: 1.1 mg MDA/kg (below rancidity threshold); ↓ Oxidation in W-Cu: < 0.2 mg MDA/kg during 6-day storage; ↓ Curcumin content and antioxidant activity after cooking (greater loss in W-Cu); ↑ Beeswax melting: possible fat/curcumin leakage; Residual curcumin: maintains relevant *in vivo* antioxidant activity	[21]
POV (ISO 3960: 2017); TBARS value	Hydroperoxides (g/100 g); MDA	Beef heart burger: vacuum-packed, stored at 4 °C for 14 days (samples taken on days 0, 3, 5, 7, and 14)	Beef heart burger: ↑ Lipid oxidation (prolonged refrigeration); ↑ POV until day 7 > 1.5 g/100 g: then ↓ hydroperoxide degradation; MDA reached rancidity threshold (1 mg/kg) on day 3; Preheating of oleogels: promotes oxidation; ↑ Carbonyls during storage: protein oxidation induced by lipid radicals	[26]
TBARS value	MDA	Fish balls: three freezing cycles at −20 °C for 24 h and thawing at 4 °C for 6 h	Fish balls: Freeze-thaw groups: TBARS value > 1 mg MDA/kg; Ice/lipid crystals → gel microstructural damage; Lipid migration & polymerization: ↑ oxidation; 50% *vs*. 0%: minimal difference (difference in TBARS value ≈ 0.2 mg MDA/kg); Bigel: limited O_2 contact (suggesting a potential protective effect); Sunflower oil PUFA: ↑ oxidative susceptibility	[28]
AOCS method Cd 8–53; AOCS method Ti 1a–54; AOCS method Ca 5a–40	POV (meq O_2/kg oil); CD FFA (% linoleic acid)		Oleogel: ↑ POV in BWO (8.35 meq O_2/kg) → slight oxidation, still acceptable (< 10 meq O_2/kg); ↑ CD: (0.520 ± 0.008)%; ↑ FFA in BWO ((6.14 ± 0.08)%): beeswax contributes free fatty acids	[45]
TBARS value; Oxidation volatiles	MDA; Volatile aldehydes formed by lipid oxidation (area/sample weight)	Pork fuet: stored in plastic bags under aerobic conditions at (2 ± 2) °C for 30 days (samples taken on days 0, 15, and 30 after ripening) Ripening conditions: 2 days at 19 °C and 80%–85% relative humidity (RH) followed by 15 days at 13 °C and 75%–80% RH	Pork fuet (dry fermented sausage): ↓ Oxidation (day 0: (0.404 ± 0.028) mg MDA/kg → day 30: (0.384 ± 0.040) mg MDA/kg); → TBARS value during chilled storage: almost unchanged (structured systems may protect oils); ↓ Hexanal (day 0: (239.8 ± 26.2) area/sample weight → day 30: (153.1 ± 0.5) area/sample weight): better oxidation marker; Type of structured oil → influences volatile compound release (encapsulated < pre-emulsified < pure)	[46]

Note: AOCS, American Oil Chemists' Society; POV, peroxide value; CD, conjugated dienes; FFA, free fatty acidity; BWO, beeswax oleogel; W-Cu, beeswax oleogel with added curcumin; W-OG, beeswax oleogel; WPR, partial substitution; WTR, total substitution; W-B, olive oil/linseed oil/fish oil structured with beeswax.

protective capacity after cooking, limiting oxidation; the increase in MDA was not sufficient to detect rancidity over 6 days of storage. Other authors reported that pâtés[6] and pork burgers[20] remained below the threshold for perceivable rancidity in meat (1.0 mg MDA/kg).

Likewise, the formation of aldehydes—mainly hexanal—has been reported as the predominant volatile compounds derived from lipid oxidation in pork fuet[46]. Storage time and conditions also exert a significant influence on lipid oxidation. During refrigerated storage at 4 °C, beef burgers exceeded the rancidity threshold by the 3rd day, accompanied by an increase in carbonyl content, which suggests enhanced protein oxidation induced by the interaction between muscle proteins, free radicals, and peroxides generated during lipid oxidation[26]. These structural alterations lead to changes in texture, color, aroma, and WHC, in addition to affecting the biological and nutritional value of meat and meat products[77].

In contrast, Moghtadaei et al.[5] showed that both frozen storage time and the level of fat replacement exert a significant effect on MDA formation, concluding that these factors determine the degree of lipid oxidation in beef burgers. Finally, freeze-thaw cycles in fish-based balls have been reported to damage the gel microstructure and promote lipid oxidation. Nonetheless, formulations containing sunflower oil-based bigels exhibited oxidative stability comparable to the control, suggesting that these systems may limit oxygen diffusion by retaining the oleogel within the hydrogel phase[28].

5 Technological implications

5.1 Moisture content (MC), a_w, and WHC

The incorporation of bigels structured with 10% beeswax, combined with a hydrogel phase composed of 10% potato starch and 2% *κ*-carrageenan in a 75:25 (*m*/*m*) oleogel-to-hydrogel ratio, let to an increase in MC and a_w in reformulated meat products as the fat replacement level increased[12]. This effect was attributed to the higher MC of the bigel (23%) compared to pork fat (~9%), which enhanced WHC. Additionally, the functional groups in the hydrogel contributed to the retention of water released during cooking. In silver carp surimi, replacing 50% of pork fat with bigels (30% oleogel containing 10% beeswax and 70% fish-scale hydrogel) raised the MC from 69% to 75% and improved WHC, acting as an active filler that helped prevent ice crystal formation and reduce water loss[28].

In fermented products such as fuet, replacing 80% of pork backfat with an oleogel composed of 10% beeswax and a lipid blend (80% olive oil, 20% chia oil) significantly increased MC and a_w[46], probably due to the oleogel slowing down the loss of a_w during ripening. However, not all studies report increases in MC. Franco et al.[48] found no significant differences in Frankfurt sausages reformulated with linseed oil oleogels containing 8% beeswax. Similarly, Yılmaz et al.[45] observed a decrease in MC in sucuk when partially replacing beef fat (17.17%) with linseed oil oleogels containing 10% beeswax, which was attributed to differences in lipid composition and water loss during the seven-day fermentation process.

5.2 Instrumental colorimetric parameters

The incorporation of oleogels into meat products can modify their colorimetric properties, particularly the L^* and b^*. In colorimetric analysis, higher L^* indicate lighter samples, whereas higher positive b^* reflect a greater degree of yellowness.

Gao et al.[26] reported increased L^* and b^* in both raw and cooked beef heart burgers during storage after complete replacement of beef fat with a canola oil-based oleogel containing 10% beeswax. This was attributed to the yellowish hue of the oleogel compared to the opalescent tone of beef fat. Similarly, Pintado et al.[46] observed a significant increase in the b^* in dry-fermented fuet when animal fat was reduced or replaced with an oleogel composed of 80% olive oil, 20% chia oil, and 10% beeswax, which intensified the yellow hue; however, the characteristic red tone remained stable during refrigerated storage. In contrast, Moghtadaei et al.[5] reported a reduction in L^* upon substituting 50% of animal fat with a sesame oil-based oleogel containing 10% beeswax in beef burgers. This effect was attributed to increased structural heterogeneity within the meat matrix, which promoted light scattering despite the light tone of the oleogel.

Wei et al.[19] reported no significant color differences in sausages reformulated with 50% replacement using a camellia oil oleogel containing 10% beeswax. As an alternative, bigel systems—combinations of beeswax-based oleogels (10%) with polysaccharide or protein hydrogels—may help mitigate variations in L^* and b^*. Gao et al.[28] reported enhanced whiteness in fish balls with increasing bigel ratios, whereas Hernández-Nolasco et al.[12] found no significant effects on color or total ΔE in beef burgers across two different formulations. Adjusting the phase proportions in bigels can enhance product color by increasing L^* while keeping color differences below the visual perception threshold.

5.3 Textural properties

The use of oleogels as animal fat replacers in meat products has demonstrated significant effects on textural properties, with hardness reduction being one of the most consistent outcomes. Complete replacement of animal fat with oleogels structured with 10%–11% beeswax and healthy oils (olive, flaxseed, fish, or canola) in pork or beef burgers significantly reduced hardness and gumminess compared to controls, without compromising chewiness. This effect was attributed to the higher structural rigidity of animal fat compared to oleogels[20,26]. Similarly, in beef burgers, partial replacement (25%–50%) with sesame oil oleogels containing 10% beeswax reduced hardness in raw samples. This was linked to smaller fat globule size and the need for a larger interfacial protein film[5,78]. However, in cooked samples, hardness increased at 50% replacement, likely due to thermal destabilization of the oleogel network. Reductions in gumminess and chewiness were also observed at higher substitution levels[5].

In cooked pork sausages reformulated with oleogels containing 4.5%–10% beeswax and vegetable oils (camelina or soybean), significant reductions in hardness and chewiness were reported without affecting elasticity, cohesiveness, or adhesiveness compared to controls[19,44]. The presence of *n*-alkanes and esters in beeswax promoted the formation of microplates and crystalline networks with high gelling capacity[79], properties maintained even after freeze-thaw cycles.

In Pickering emulsions formulated with oleogels containing 9% beeswax and used to replace 50%–100% of pork fat, good textural stability was observed[44], attributed to the protein matrix formed during thermal processing and subsequent freeze-thaw treatment. In fermented sausages, replacing 80%–100% of animal fat with oleogels containing 10% beeswax and oils such as flaxseed, olive, or chia significantly decreased hardness, cohesiveness, and gumminess, due to limited ability to mimic the texture of animal fat[45–46].

In reduced-fat fuet, increased hardness was observed, likely due to greater water loss during ripening[46]. In seafood products, oleogels based on canola or fish oil with 6%–14% beeswax and 50%–100% fat replacement improved texture through different mechanisms[27]. Zhang et al.[24] proposed a physical effect involving cavity filling and increased structural cohesion, while Han et al.[27] highlighted molecular interactions between oleogels and muscle proteins, promoting denser networks with β-sheets and cross-links. Both studies reported improvements in hardness, cohesiveness, and chewiness. Collectively, these findings support the functional potential of oleogels to improve or modulate the texture of reformulated functional meat products, emphasizing their technological versatility.

6 Sensory implications

In general, food products enriched with beeswax-structured oleogels demonstrate favorable sensory acceptability or strong potential for consumer approval[15]. The acceptance of these reformulated meat products is closely related to sensory attributes such as color, flavor, aroma, texture, juiciness, and appearance[80–81]. The sensory evaluations summarized in Table 1 involved untrained consumers[6,19–21,23], semi-trained[25,48], and trained panels[5,28,42–43,46–47], including one study employing a QDA panel[45]. The number of participants ranged from 10 to 40. Typical evaluation criteria included color, aroma, flavor, texture, juiciness, consistency, and overall acceptability, assessed using hedonic scales ranging from 5 to 10 points.

6.1 Color

The incorporation of polyunsaturated oils, such as flaxseed oil, may intensify the yellow hue in frankfurter-type sausages, which is often associated with lipid oxidation or spoilage[48]. Similarly, the use of curcumin as an antioxidant in oleogels has been linked to significantly lower color scores in beef burgers with full animal fat replacement, due to its intense yellow color[21,82]. Although instrumental color differences were minimal, panelists' visual perception was affected, emphasizing the importance of subjective evaluation. In contrast, other studies have reported no perceptible color differences between control and reformulated products using oleogels[5,19–20,23,47]. These discrepancies highlight the influence of the oil type, beeswax concentration, replacement level, and the presence of functional ingredients.

6.2 Flavor and aroma

Flavor and aroma—key elements in consumer acceptance—are modulated by the lipid matrix and its interaction with volatile compounds. Gao et al.[28] reported greater aromatic complexity in fish ball-type meat products reformulated with bigels, especially at replacement levels of 50% and 75%. This complexity was associated with increased levels of volatile compounds such as sulfides, pyrazines, alcohols, alkanes, olefins, and hydrogen. However, increased acidity and bitterness were also observed, likely linked to lipid oxidation products, the formation of compounds like furfural, the presence of fresh collagen peptides, and the salt-enhancing effect.

In contrast, Yılmaz et al.[45] reported that sucuk reformulated with flaxseed oleogels lacked the characteristic volatile compounds of beef fat, which led to significantly lower aroma scores. The presence of 20 identified volatile compounds—including γ-terpinene, β-pinene, and 4-(1-methylethyl) benzaldehyde—did not contribute positively to the aroma profile, likely due to poor integration into the meat matrix or high sensory detection thresholds. Regarding flavor, to significantly lower scores may have resulted from the limited release of lipophilic compounds and the residual sensory notes associated with the oil and wax. Similarly, Pintado et al.[46] reported reductions in aroma and flavor scores in fermented dry fuets, attributed to aldehydes (hexanal, heptanal, octanal, and nonanal). However, after 30 days of storage, sensory acceptance improved, suggesting recovery of the sensory profile during maturation. Other formulations with low replacement levels (7%–10%) retained flavor, aroma, taste, and color profiles comparable to the control samples[43], with no significant differences observed among the three groups. In some cases, such as pâtés, the reformulated products were even described as having a "neutral" flavor[20], indicating a minimal impact on sensory perception.

6.3 Texture and juiciness

Replacing animal fat with oleogels significantly modifies textural attributes. A 50% replacement was associated with increased oiliness, juiciness, and firmness, enhancing overall acceptance of processed meat[23]. Yılmaz et al.[45] demonstrated that the higher melting point of oleogels (53.22 °C compared to 44.63 °C in beef fat) favored greater juice release during cooking, resulting in significantly improved juiciness in beef sucuk (fermented sausage). This effect was attributed to higher moisture retention, the oral perception of the oleogel, and the release of melted fat.

In contrast, Igenbayev et al.[43] reported significantly lower juiciness in sausages formulated with a 10% replacement using monoglyceride-beeswax-sunflower oil oleogels, due to the lower WHC of beeswax, attributed to its hydrophobic nature. Additionally, protein-lipid interactions generated a stiffer matrix, negatively affecting texture. However, when oleogels were prepared with oil blends (olive, flaxseed, and fish), no significant textural differences were observed in pâté or burger formulations[6,20].

6.4 Overall acceptability

The sensory acceptability of meat products may depend on the lipid source used in oleogels[5,20]. Sesame oil-based oleogels, owing to their characteristic flavor and aroma profiles, can significantly enhance acceptance when used to replace 50% of the fat in burgers[5]. In contrast, oleogels formulated with fish oil tend to significantly decrease acceptability, most likely due to the sensory attributes of this oil[20]. Furthermore, oleogels structured with beeswax better preserve sensory quality compared with those produced using other organogelators, such as sunflower wax[45] or ethylcellulose[20–21]. Nevertheless, their sensory performance has not yet consistently surpassed that of conventional animal fats, such as tallow[45] or pork backfat[20–21,43,46,48].

Low substitution levels (10%) may already produce significant differences in acceptability[43]. Most studies indicate that replacing up to 50% of animal fat with oleogels maintains acceptability levels comparable to those of control products[19,23,28,42]. However, higher substitution levels (≥ 60%) may compromise acceptability in pâtés[25], although certain storage or ripening strategies may mitigate these effects in fermented sausages[46].

At the highest level, complete fat replacement (100%) may result in no differences or even yield products comparable to the control[6,21,45]. Overall, the evidence suggests that the composition of the oleogel, followed by the substitution level, are the primary factors influencing sensory acceptability; moreover, potential negative effects can be mitigated through adjustments in seasoning.

7 Limitations

Further research is required to optimize sensory properties and lipid and protein oxidative stability. Additionally, it is essential to investigate how beeswax and the oil phase influence protein-water and protein-fat interactions, microstructure, and the thermal gelation process, as well as the mechanisms that determine the texture of reformulated meat products. Long-term studies are needed to determine shelf-life, digestibility, bioavailability, and overall nutritional quality. The application of advanced lipidomics tools will be key to understanding the structural changes induced by technological processes, including heating, cooking, and storage.

8 Future perspectives

The incorporation of natural antioxidant sources—such as essential oils and plant-derived extracts obtained from herbs, fruits, vegetables, cereals, trees, and agro-industrial by-products—represents a safe, functional, and health-promoting strategy for integration into beeswax-structured lipid systems. Future research should determine the optimal concentrations of these bioactive compounds and investigate their interactions within meat matrices, particularly with the protein network and other formulation components. Understanding these interactions is essential for optimizing the structural, oxidative, and sensory properties of the final product.

Although most available evidence focuses on beeswax from *A. mellifera*, a complementary approach considers waxes and derivative products from stingless bees—species of ecological, economic, and cultural importance—representing a source of bioactive molecules with biotechnological potential, including antioxidant and antimicrobial activities[83–85]. Their application in structuring vegetable oils for the development of oleogels and bigels remains unexplored. Future studies should focus on the extraction and characterization of these native waxes, correlating their crystalline morphology with the functional properties of structured lipid systems, thereby opening new avenues for the development of functional meat products.

9 Conclusions

Beeswax-structured oleogels and bigels constitute an effective strategy for partially replacing animal fat in functional meat products, improving the lipid profile by reducing SFA and increasing PUFA, including *n*-3 PUFA, without compromising technological or sensory quality, particularly at substitution levels of up to 50%. Their effectiveness depends on lipid selection, beeswax concentration, substitution level, meat matrix formulation, and the conditions of processing and storage. The oxidative stability remains the main limitation. The industrial implementation of beeswax oleogels requires careful consideration of their functionality, availability, and cost, as well as the physical state of these systems during processing and in the final product, ensuring compliance with current regulations (European Food Safety Authority, Food and Drug Administration, and Novel Food Regulation). Innovation is possible through new formulations that meet consumer expectations and capitalize on the demand for healthier options. Current trends reflect a preference for natural ingredients, sustainable solutions, and transparent labeling.

Conflict of interest

The authors declare no conflict of interest.

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Ethical statement

There are no human or animal subjects in this article.

Authors contribution

Zuemy Hernández-Nolasco: Writing-original draft, writing-review & editing, investigation, conceptualization, visualization, project administration. Mariana Inés Acateca-Hernández: Writing-original draft, writing-review & editing, investigation, conceptualization, visualization. Natalia Real-Luna: Writing-review & editing, resources. Aleida Selene Hernández-Cazares: Writing-review & editing, supervision, project administration, resources.

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