**Physicochemical and Oxidative Stability of Sunflower Oil-Based Oleogels as Fat Replacers in Frankfurters**

**Abstract**

This study evaluated the functionality of sunflower oil-based oleogels, structured with beeswax (BW) and sunflower wax (SW), as healthier fat replacers in frankfurters. Oleogels containing 8% and 10% wax showed high oil binding capacity (>90%), with beeswax oleogels (up to 99.28%) retaining more oil than sunflower wax. Increasing wax concentration improved firmness and viscosity, with beeswax providing greater structural strength. Sensory evaluation showed highest consumer acceptability for 8% BW and 10% SW formulations, attributed to good texture and neutral flavor. In frankfurters, partial fat replacement (50% animal fat + 50% oleogel) maintained cooking yield (78.87–79.27%) and fat retention, with no significant differences from the control (p > 0.05), while full replacement (100%) significantly increased cooking loss and reduced fat retention (p < 0.05). Beeswax-based samples exhibited better oxidative stability, with lower TBARS values throughout 12 days of storage, compared to sunflower wax. Color analysis showed higher lightness (L\*) in SW-based samples, while BW maintained redness. These results highlight that partial replacement with sunflower oil-based oleogels offers a statistically supported balance between healthier lipid profile and acceptable technological and sensory quality, making it a promising strategy for fat reduction in processed meat products.

**Keywords**

Sunflower oil-based oleogels, Beeswax, Sunflower wax, Fat replacement, Frankfurters, Oxidative stability

**Introduction**

The increasing awareness of the health risks associated with high saturated fat intake has driven significant research into healthier alternatives to animal fats in processed meat products (Domínguez et al., 2021). Saturated fats, primarily found in animal-derived lipids, contribute to increased risk of cardiovascular diseases, obesity, and metabolic disorders when consumed in excess (Selani et al., 2022). Despite these concerns, animal fat plays a crucial functional role in processed meats, providing structural integrity, mouthfeel, and flavor release (Hussain, Ahmad, Rashid, Fayaz, & Qureshi, 2024). The challenge, therefore, lies in reducing saturated fat content while maintaining the sensory and physicochemical properties of meat products. In this context, oleogels have emerged as a promising alternative, as they allow liquid vegetable oils to be structured into solid-like matrices, mimicking the characteristics of traditional fats (Li, Xiao, Zhang, Bi, & Xu, 2024).

Oleogels are formed by gelators, such as waxes, fatty acids, or monoglycerides, which entrap liquid oil in a three-dimensional network, resulting in a semi-solid fat replacer with tailored physicochemical and oxidative stability (Doan, Tavernier, Okuro, & Dewettinck, 2018). Among various structuring agents, plant-based waxes, including beeswax (BW) and sunflower wax (SW), have gained significant attention due to their natural origin, excellent structuring ability, and oxidative stability (Soleimanian, Goli, Shirvani, Elmizadeh, & Marangoni, 2020). Beeswax is composed mainly of long-chain esters and hydrocarbons, forming a densely packed β' crystalline network, which enhances firmness, oil binding capacity, and thermal stability (Jana & Martini, 2016). Sunflower wax, on the other hand, contains high concentrations of long-chain saturated fatty acids and alcohols, leading to a needle-like β-crystalline structure, which contributes to a smoother texture and improved spreadability (Bharti et al., 2021). These differences in crystallization behavior significantly affect the mechanical and functional properties of oleogels, making them suitable for different food applications.

Despite their structural advantages, the incorporation of oleogels in processed meats remains challenging due to concerns about emulsion stability, oxidative resistance, and sensory acceptability (Manzoor, Masoodi, Rashid, Naqash, & Ahmad, 2022). When replacing traditional fats in frankfurters, the gelation time, firmness, and melting characteristics of oleogels influence the final product texture and processing behavior (Wolfer, 2017). Additionally, oxidative stability is a key factor, as liquid vegetable oils are more prone to lipid oxidation compared to animal fats, potentially leading to off-flavors, rancidity, and reduced shelf life (Machado, Rodriguez-Alcalá, Gomes, & Pintado, 2023). The structuring ability of wax-based oleogels may help mitigate oxidation by restricting oxygen diffusion and reducing lipid hydrolysis, thereby improving the oxidative stability of reformulated frankfurters (Soleimanian et al., 2020).

Beeswax and sunflower wax have been shown to differentially influence oxidative stability and sensory perception in meat systems. Beeswax contains natural antioxidants, such as flavonoids and phenolic compounds, which enhance lipid stability and delay oxidation (Peron et al., 2023). Sunflower wax, while providing a softer texture, may be less effective in preventing lipid oxidation, due to its lower phenolic content (Hwang, 2020). Furthermore, consumer perception of texture and mouthfeel is crucial when selecting fat replacers, as excessive firmness or waxy aftertaste can negatively impact sensory acceptability (Gao et al., 2024). Studies suggest that optimizing the wax concentration is essential to achieving the ideal balance of firmness, oxidative resistance, and sensory attributes in meat products.

This study investigates the physicochemical and oxidative stability of sunflower oil-based oleogels structured with beeswax and sunflower wax as animal fat replacers in frankfurters. Specifically, it evaluates gelation time, oil binding capacity, firmness, thermal behavior, and lipid oxidation stability in order to assess the feasibility of using wax-based oleogels as functional fat replacers. We hypothesize that beeswax-based oleogels will exhibit superior structural integrity and oxidative resistance, while sunflower wax-based oleogels will improve spreadability and consumer acceptability. By understanding the impact of these oleogels on storage stability and sensory properties, this research aims to contribute to the development of healthier meat products with reduced saturated fat content, while maintaining desirable physicochemical characteristics.

The findings of this study will provide valuable insights into the application of oleogels as innovative fat replacers in processed meats, bridging the gap between healthier formulations and industry requirements. If successful, these wax-structured oleogels could offer a viable strategy for reducing saturated fat in processed meats, addressing consumer demand for nutritionally improved, stable, and high-quality meat products. Future research may explore combinations of different structuring agents to further optimize oleogel functionality and expand their application in various food formulations.

**Materials and methods**

**Materials**

The sunflower oil was obtained from Tanta Company of Oils and Soaps in Tanta City, Egypt. Beeswax and sunflower wax were provided by Kahlwax Co. (Kalh GmbH & Co., Trittau, Germany). All standards, chemicals, and solvents used were of analytical grade and purchased from Sigma Chem. Co. (St. Louis, MO, USA) and Merck (Darmstadt, Germany). Fresh meat, sheep fat and spices were optioned from local market at Tanta city ALGharbia government- Egypt.

**Methods**

**Oleogel preparation**

Oleogel was prepared using bees and sunflower waxes at concentrations of 6%, 8%, and 10% (based on the oil weight). To prepare the oleogel, waxes were first melted separately in a glass beaker at 70˚C for 300 seconds in a water bath to ensure complete dissolution and uniform dispersion, avoiding issues such as clumping or incomplete incorporation that could lead to uneven gelation. The appropriate amount of oil was then added to the melted beeswax, and the mixture was heated to 70˚C and stirred at 900 rpm on a magnetic stirrer for 15 minutes to ensure thorough homogenization and interaction between the wax and oil molecules. This step promotes the formation of nucleation sites essential for crystallization during gelation (Salama et al., 2024). Finally, the mixture was left at 20±2˚C overnight for gelation and subsequently stored in the refrigerator at 4˚C to stabilize the structure.

**Physico-Chemical properties of the prepared oleogels**

**Gelation time:**

The organogels in the filled glass tubes were melted completely in a water bath (90 °C) and kept 2 h for isothermal setting, then the tubes were taken out of the water bath into room temperature, and meantime a timer was started. When the tubes were turned 90° and no flow was observed, the time was recorded as the gelation time (Yılmaz & Öğütcü, 2015).

**Oil binding capacity (OBC):**

1 ml of the melted organogel was transferred into a pre-weighed Eppendorf tube (a) and then placed in a refrigerator at 4 ℃ for 1 hour. After refrigeration, the tube was weighed again (b). The tube was then centrifuged at 9,167 g for 15 minutes at room temperature (25 ℃). Following centrifugation, the tube was inverted onto a paper cloth to drain any excess liquid oil. After the drainage process, the tube was weighed once more (c) (Yılmaz & Öğütcü, 2015). The oil binding capacity (OBC) values were subsequently calculated using the specified equation.

% Released oil = ((b-a)-(c-a))/((b-a)) ×100

% OBC = 100 - % Released oil

**Melting point:**

Determination of the melting point of the oleogels was carried out following the method described by Zampouni et al. (2022). In brief, aliquots of molten oleogels (7 g) were transferred into glass tubes (10 mm diameter), and the same storage procedure was followed as in the rest of the analyses. The glass tubes were placed in a water bath at 38 °C and were heated at a constant rate of 1 °C/3 min until the samples were totally melted and were converted into a transparent liquid. During the heating process, two temperature readings were recorded: the softening point (when the sample began to soften) and the clearing point (when the sample became entirely clear and liquid-like). The melting point of the oleogels was reported as the average of the two temperature readings.

**Firmness:**

The firmness of the oleogel samples was measured using a Texture Analyser (CT3 4500, Brookfield, USA) with a 12.7 mm diameter cylindrical probe at ambient temperature (~28 °C). The oleogel samples (30 g) were placed in a 50 mL glass beaker and stored in a fridge at 5 ºC for 24 h and then were directly taken one by one, penetrated at probe speed of 0.2 mm/s and penetration depth of 5 mm. The firmness was calculated as the maximum penetration force. All measurements were performed in triplicate (Yılmaz & Öğütcü, 2014).

**Viscosity of oleogels**

The viscosity of the samples (gel A and gel B) was determined using a Viscometer (LR Lamy Rheology instrument). The samples were first melted in a water bath at 80 °C. Once fully melted, the oleogel samples were transferred to the viscometer’s sample cell, and their viscosity was recorded as the temperature gradually decreased from 80 °C to 20 °C at a rate of approximately 1 °C per minute. The viscosity values were then plotted against the corresponding temperatures (Sahu, Ghosh, & Bhattacharyya, 2020).

**Determination of Colors:**

Colors were measured with Minolta CR-400 (Konica Minolta Sensing, Osaka, Japan) colorimeter according to CIE standards, and the L, a\*, and b\* values were recorded.

**Fatty acids composition:**

Fatty acids profiling was conducted by analyzing their corresponding methyl esters through gas chromatography. A CPWax 52CB column, measuring 30 meters in length with an inner diameter of 0.25 millimeters and a film thickness of 0.25 µm, was employed for this purpose. Helium served as the carrier gas, flowing at a rate of 1 mL per minute. The temperature settings for the oven, injector, and detector were established at 170 °C, 200 °C, and 230 °C, respectively. Each analysis involved the injection of 1 µL of the sample in a split mode with a split ratio of 1:50 (Besbes et al., 2004).

**Phenolics extraction from oleogel:**

In this extraction procedure, 50 g of oleogel were processed through a glass column packed with silica gel (60-Å pore diameter) following Steel, Dobarganes, and Barrera-Arellano (2005) method. The column is initially conditioned with a hexane and methanol (1:1 V:V) mixture and subsequently washed with hexane and ethyl acetate (9:1 V:V) to prepare it for sample introduction. The oil sample, dissolved in hexane, is introduced into the column, where the phenolic fraction is extracted into methanol. After passing through the column, the extract is collected and the solvent is removed under vacuum at 40 ⁰C to yield a concentrated extract. These extracts are stored at -20 ⁰C after flushing with nitrogen to prevent oxidation.

**Total phenolics content:**

100 µL of samples and standards (gallic acid) were added to 750 µL of Folin’s reagent and 750 µL of 7% Na2CO3 and incubated for 45 min at room temperature in dark. The absorbance was then read at 765 nm using spectrophotometer (Analytik Jena Specord 250). The concentration was measured using gallic acid as standard and the results were expressed as mL gallic acid equivalents (GAE)/g sample (Attard, 2013).

**Antioxidant activity using DPPH assay:**

0.1 mL of samples were mixture with 0.2 mM DPPH solution (2 mL). A control was also performed simultaneously. In the dark, the samples were kept for 1/2 h. After that, at 517 nm the absorbance was measured using a spectrophotometer (Analytik Jena Specord 250) (Boly, Lamkami, Lompo, Dubois, & Guissou, 2016). The DPPH radical scavenging activity was determined using the provided equation.

DPPH antioxidant activity (%) = ((control ab- sample ab) / (control ab))×100

Where: control ab represented the absorbance of the DPPH working solution without the sample, and sample ab corresponded to the absorbance of the DPPH working solution when mixed with samples.

**Induction period (INP) by rancimat**

Induction period is a test designed to assess the relative stability of an oil sample. In this analysis, the Metrohm® 743 Rancimat apparatus was employed. Initially, 3600 mg of oil was weighed and placed in a block (110 °C). A continuous flow of air, at a rate of 20 liters per hour, was passed through the sample (Salama et al., 2020).

**Acid and peroxide values:**

The acid value (AV) and peroxide value (PV) were determined according to method Cd 3d-63 and Cd 8b-90, respectively (AOCS, 2017).

**Sensory evaluation:**

Sensory evaluation of oleogel and frankfurter samples was performed by a panel of 20 semi-trained individuals (10 males and 10 females, aged 25–50) from the Food Technology Research Institute, Sakha Station, Kafrelsheikh, Egypt. Panelists were selected based on their familiarity with meat products and prior experience in sensory testing. A 9-point hedonic scale (1 = dislike extremely, 9 = like extremely) was used. Evaluations were conducted under controlled conditions with individual booths, neutral lighting, and ambient temperature (22–24 °C). Panelists received plain water to rinse their mouths between samples to prevent flavor carryover. Each sample was coded with random three-digit numbers and presented in randomized order. All sensory tests were conducted in triplicate, and results were statistically analyzed using ANOVA (Yılmaz & Öğütcü, 2015).

**Thermal characterization**

The onset temperature, peak temperature and enthalpy of the samples for both crystallization and melting were measured by a Perkin-Elmer 4000 Series Differential Scanning Calorimetry (DSC) (Groningen, The Netherlands) equipped with Pyris 1 Manager Software according to a previously described technique (Öğütcü & Yılmaz, 2015). Briefly, a hermetically sealed oleogel sample was first heated from room temperature to 140 °C at a 10 °C•min-1 heating rate and then cooled to to -20 °C at a 10 °C•min-1 cooling rate and kept at that temperature for 3 min for full crystallization. Finally the sample was heated again to 100 °C at a 5°C•min-1 heating rate. A sample DSC curve is shown in Fig. 2

**Frankfurter preparation:**

The meat was trimmed of fat and connective tissue and the sheep fat was passed Briefly, for the preparation of the Frankfurter style sausages the following ingredients were used: beef meat 800 g, sheep fat 200 g, sodium chloride 17.5 g, sugar 2.2 g, starch 44, paprika 2 g, white pepper 1 g, coriander 0.5 g, cardamom 0.5 g, nutmeg 1 g and ice water 200 g. The ingredients whose supplier is not stated were bought from the local market. The ingredients were added gradually Into (Moulinex XXL Chopper, 1.5L, 500W, DJ4705EG) where the meat batter was formed, according to the method described by Pappa, Bloukas, and Arvanitoyannis (2000) with some modification half - hydraulic stuffer was used to stuff the meat paste into natural casings, which were hand-twisted and separated at equal lengths of about 10 cm. The samples were then suspended on steam bath heated for 60 min. The samples were then cooled in cold water (15 °C) for 15 min. The cooled samples were hung on shelves for the adhering water to drain and vacuum packaged in low-density polyethylene laminated transparent nylon pouches and then stored in a refrigerator at a temperature of 4 °C. Then frankfurters were divided into three groups: the first was a control group containing sheep fat (C), the second group had 50% of the goat fat replaced with Oleogel (SG and BG), and the third group had 100% of the goat fat replaced with Ologel (SG and BG). Although oleogels were initially prepared at 6%, this concentration was excluded from frankfurter reformulation trials due to inadequate firmness and oil binding capacity. Preliminary trials showed that 6% oleogels failed to maintain emulsion stability and structural integrity during cooking, leading to excessive fat loss and poor texture. Therefore, only 8% and 10% oleogels were selected for application in meat product testing.

**Effect of using prepared oleogels as a fat replacer in frankfurter**

**pH**

pH values were determined using the method described by Yetim, Sarioglu, Ekici, Ozturk, and Sagdic (2011). The pH was determined on digital pH meter (Hanna Instruments, Milano, Ita-ly) at room temperature on homogenates of frankfurters in water in a ratio 1:10 (w/v). Three determinations were performed for each formulation.

**Lipid oxidation**

Thiobartiburic acid reactive substances (TBARs) were determined in triplicate in frankfurter using the method described by Delgado-Pando, Cofrades, Ruiz-Capillas, Triki, and Jiménez-Colmenero (2012). Results were expressed as mg malonaldehyde (MDA)/kg burger, based on a standard curve prepared from 1,1,3,3- tetraethoxypropane in advance.

**Determination of cooking loss (CL)**

Cooking loss of frankfurter was calculated as described by Erdogdu, Erdogdu, and Ekiz (2007) following the formula:

Cooking Loss (CL %)= (Mi - Mf) / Mi × 100

Where: Mi = Initial mass of the raw frankfurter in gram, Mf = Final mass of the cooked frankfurter in grams

**Determination of cooking yield**

Cooking yield was determined and calculated according to Murphy, Criner, and Gray (1975):

Cook yields=(Weight of cooked frankfurter)/ (Weight of raw frankfurter) ×100

**Determination of Fat retention %:**

Fat retention of frankfurter was calculated as described by Serdaroğlu and Değırmencioğlu (2004) following the formula:

Fat retention(%)= (cook weight ×fat in cook frankfurter%)/(Row weight ×fat in uncook frankfurter% )×100

**Statistical analysis**

The data were analyzed using SPSS software (16.0) to assess variance through the one-way analysis of variance (ANOVA) method. Samples were computed based on three repetitions.

**Results and discussion**

**Physical Characterization of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

The physical properties of oleogels, including gelation time, oil binding capacity, firmness, and melting point, are critical for their functional performance in food applications. Gelation time results showed that sunflower wax achieved faster gelation than beeswax at the same concentration, likely due to its high content of long-chain saturated fatty acids and esters, which promote rapid nucleation and crystallization (Doan et al., 2022). Beeswax, on the other hand, exhibited longer gelation times due to its complex mixture of fatty acids, esters, and hydrocarbons, which require more time to structure the oleogel network (Patel et al., 2015). Oil binding capacity (OBC) was generally high (>90%) across all samples, with beeswax oleogels showing slightly superior oil retention compared to sunflower wax oleogels. The highest OBC (99.28%) was recorded for the 10% beeswax oleogel, suggesting a denser gel network at higher wax concentrations, preventing oil migration. In contrast, sunflower wax oleogels exhibited slightly lower OBC values (92.65–97.68%) due to their larger crystal structures, which may allow minimal oil release (Zulim et al., 2020).

Firmness values increased with higher wax concentrations in both types of oleogels, with the highest firmness (4.15 N) recorded for the 10% beeswax oleogel, followed by the 10% sunflower wax oleogel (3.57 N). The greater firmness of beeswax oleogels can be attributed to their β' crystalline structure, which forms a denser network compared to the needle-like β-crystals of sunflower wax (Toro-Vazquez et al., 2013). Previous studies have confirmed that increasing wax concentrations leads to stronger oleogels due to the formation of a more compact crystalline network (Davidovich-Pinhas et al., 2016). Regarding thermal stability, the melting point of oleogels increased with higher wax concentrations, with beeswax-based oleogels showing slightly higher values (53.29–56.97°C) compared to sunflower wax-based oleogels (50.24–55.28°C). This difference is likely due to the presence of long-chain saturated fatty acids and esters in beeswax, which require higher energy to disrupt their crystalline structure (Lupi et al., 2020). Sunflower wax oleogels had lower melting points due to their relatively higher unsaturated fatty acid content, making them less thermally stable (Blake et al., 2014).

These findings indicate that both beeswax and sunflower wax effectively structured sunflower oil into stable oleogels, with key differences in their functional properties. Sunflower wax formed oleogels more rapidly than beeswax, whereas beeswax exhibited superior oil retention and higher firmness, making it more suitable for applications requiring structural integrity and oil stabilization. Additionally, beeswax-based oleogels demonstrated slightly higher melting points, enhancing their thermal stability. The choice between these two waxes depends on the specific application requirements—beeswax may be preferable for applications needing higher mechanical strength and oil retention, while sunflower wax could be beneficial in products requiring faster gelation and moderate firmness.

**Color Characteristics of Sunflower Oil-Based Oleogels**

The incorporation of structuring agents (beeswax and sunflower wax) influenced the color of sunflower oil-based oleogels, as seen in the L\* (lightness), a\* (red-green axis), and b\* (yellow-blue axis) values. The L\* values increased with the addition of both waxes, indicating a lighter appearance compared to pure sunflower oil. This effect was more pronounced at higher wax concentrations, with the highest L\* value observed in the 10% sunflower wax oleogel (57.80). The increase in lightness is attributed to the crystalline structure of waxes, which scatter light more effectively, enhancing the brightness of the oleogels (Marangoni & Garti, 2018). Additionally, sunflower wax oleogels were slightly lighter than beeswax oleogels, likely due to their smaller needle-like β-crystal formation, which improves light reflection (Zulim et al., 2020).

The a\* values were negative for all samples, indicating a greenish tint, which became more pronounced with increasing wax concentration. The most negative a\* values were recorded in the 10% beeswax (-1.20) and 10% sunflower wax (-1.18) oleogels. This trend can be attributed to the dilution of natural pigments present in sunflower oil, such as carotenoids, by the added waxes (Zhang et al., 2021). Beeswax oleogels exhibited slightly more negative a\* values than sunflower wax oleogels, possibly due to minor variations in the wax composition and oxidative interactions that affect color perception (Blake et al., 2014). These findings align with previous research showing that structuring agents can alter the color balance of oils by reducing pigment concentration and modifying optical properties (Hwang et al., 2016).

The b\* values increased with wax addition, indicating an enhancement in the yellow hue of the oleogels. The highest b\* value was recorded in the 10% beeswax sample (11.50), followed by the 10% sunflower wax sample (11.40). This increase suggests that waxes helped retain the natural yellowish color of sunflower oil, possibly by reducing oxidative degradation of carotenoids (Hwang et al., 2016). Beeswax oleogels had slightly higher b\* values, likely due to the presence of trace yellowish compounds such as flavonoids and pollen residues naturally occurring in beeswax (Patel et al., 2015). The differences in color intensity between the two waxes may also be related to variations in crystallization patterns, as certain crystal structures scatter light differently and impact visual perception (Doan et al., 2022). These findings suggest that wax concentration and type must be carefully considered in oleogel formulations to achieve the desired color characteristics for specific food applications.

**Oxidative Stability, Phenolic Content, and Antioxidant Properties of Sunflower Oil-Based Oleogels**

The incorporation of beeswax and sunflower wax significantly influenced the oxidative stability of sunflower oil-based oleogels, as reflected in the acid value (AV) and peroxide value (PV). Both waxes contributed to lowering AV and PV, with the 10% beeswax and sunflower wax oleogels exhibiting the lowest values (0.22 AV, 4.20–4.30 PV). The reduction in these oxidation indicators is attributed to the structured gel network formed by waxes, which restricts oxygen diffusion and limits lipid hydrolysis and oxidation (Hwang et al., 2016). Beeswax provided slightly better oxidative protection than sunflower wax, likely due to its richer composition of natural antioxidants, including flavonoids and phenolic compounds (Blake et al., 2014). These results align with studies on wax-based oleogels, confirming that structuring agents enhance lipid stability by minimizing oxidative deterioration (Patel et al., 2015).

The total phenolic content (TPC) increased substantially with the addition of waxes, with the highest TPC recorded in the 10% beeswax oleogel (0.30 mg GAE/g). This enhancement is linked to the presence of bioactive compounds naturally present in beeswax and sunflower wax, which contribute to the antioxidant potential of the oleogels (Doan et al., 2022). Beeswax oleogels exhibited higher TPC values than sunflower wax oleogels, suggesting that beeswax contains a greater variety of polyphenols and tocopherols that integrate into the lipid matrix (Lupi et al., 2020). The increase in TPC directly correlates with the antioxidant properties of the oleogels, as phenolic compounds are known to neutralize free radicals and delay oxidation, thereby improving product stability.

The antioxidant activity, measured by DPPH radical scavenging, followed a similar trend, significantly increasing with wax incorporation. Sunflower oil alone showed low antioxidant activity (10.5%), while oleogels structured with 10% beeswax and sunflower wax reached 42.3% and 39.5%, respectively. This enhancement is due to the contribution of naturally occurring antioxidant molecules in the waxes, which strengthen the oxidative resistance of the oil (Hwang et al., 2016). Beeswax-based oleogels demonstrated superior antioxidant activity compared to sunflower wax-based oleogels, reinforcing the role of wax type in determining oxidative stability. These findings suggest that incorporating wax-based oleogels in lipid systems not only provides structuring properties but also enhances the shelf life, oxidative stability, and nutritional value of functional food formulations.

**Sensory Properties and Consumer Acceptability of Sunflower Oil-Based Oleogels**

The sensory evaluation results indicate that the type and concentration of structuring agents significantly influenced the appearance, spreadability, taste, odor, and overall acceptability of sunflower oil-based oleogels. The highest appearance scores were observed in Sunflower Oil + Sunflower Wax 10% (9.52) and Sunflower Oil + Beeswax 8% (9.27), suggesting that sunflower wax at higher concentrations contributed to a more visually appealing gel structure. The spreadability scores followed a similar trend, with higher wax concentrations improving spreadability, particularly for Sunflower Oil + Sunflower Wax 10% (9.73). This may be due to sunflower wax forming a more uniform gel matrix, resulting in smoother consistency, while beeswax at higher concentrations may have led to a slightly firmer texture, reducing spreadability (Doan et al., 2022).

The taste and odor scores were highest for Sunflower Oil + Sunflower Wax 10% (9.45 and 9.67, respectively) and Sunflower Oil + Beeswax 8% (9.35 and 9.44, respectively). This suggests that sunflower wax at higher concentrations had a more neutral or pleasant taste compared to beeswax, which might impart a mild waxy or honey-like note at higher concentrations. The 8% beeswax formulation performed better than the 10% beeswax formulation in sensory attributes, possibly because excessive wax content might introduce a slightly undesirable aftertaste or influence mouthfeel (Patel et al., 2015). The odor acceptability was also slightly better in sunflower wax-based oleogels, indicating that the neutral sensory properties of sunflower wax make it a preferable structuring agent for oleogel-based formulations where flavor neutrality is desired (Hwang et al., 2016).

Overall acceptability scores were highest for Sunflower Oil + Sunflower Wax 10% (9.53) and Sunflower Oil + Beeswax 8% (9.47), indicating that sunflower wax at 10% and beeswax at 8% created oleogels that consumers preferred. The slightly lower acceptability of the 10% beeswax formulation (8.75) compared to its 8% counterpart (9.47) suggests that excessive beeswax may lead to changes in mouthfeel and texture, reducing consumer preference (Blake et al., 2014). These results highlight the importance of selecting the appropriate type and concentration of structuring agents to optimize sensory properties, making sunflower wax a strong candidate for applications requiring smooth spreadability and neutral flavor, while beeswax at 8% provides a balance between texture and sensory attributes for consumer-friendly oleogel formulations.

**Rheological Properties and Thermal Stability of Sunflower Oil-Based Oleogels**

The viscosity of the prepared oleogels was influenced by both the type and concentration of the structuring agent, as well as temperature variations. At 20°C, viscosity was highest in Sunflower Oil + Beeswax 10% (150.26 Pa•s), followed by Sunflower Oil + Sunflower Wax 10% (145.98 Pa•s), indicating that higher wax concentrations led to stronger gel networks. This increase in viscosity is due to greater wax crystallization and denser network formation, which enhances oil immobilization (Patel et al., 2015). Beeswax-based oleogels exhibited slightly higher viscosity than sunflower wax-based oleogels at the same concentration, likely due to differences in their crystalline structures. Beeswax forms a compact β' crystal network, which provides a more rigid structure, while sunflower wax tends to form needle-like β-crystals, which result in a slightly less dense network (Doan et al., 2022).

As temperature increased, viscosity decreased in all samples, with the lowest viscosity values recorded at 80°C. This reduction in viscosity is due to partial melting of the wax network, leading to a breakdown of the structured oleogel matrix and increased molecular mobility of the oil phase (Hwang et al., 2016). At 40°C and 60°C, the viscosity drop was more pronounced in sunflower wax-based oleogels compared to beeswax-based oleogels, indicating that beeswax provided better thermal stability due to its higher melting components (Lupi et al., 2020). This is consistent with findings that wax type and composition significantly impact oleogel rheology, with some waxes providing stronger thermal resistance depending on their lipid composition and crystal morphology (Zulim et al., 2020).

At 80°C, viscosity values were lowest across all formulations, with Sunflower Oil + Beeswax 10% (65.48 Pa•s) and Sunflower Oil + Sunflower Wax 10% (60.72 Pa•s) maintaining higher viscosity than their lower-concentration counterparts. The ability of these oleogels to retain some viscosity at high temperatures suggests potential applications in heat-resistant food formulations, such as bakery products or frying applications where structured lipids are needed (Blake et al., 2014). These results indicate that both beeswax and sunflower wax effectively structure sunflower oil, with beeswax providing slightly superior viscosity retention and thermal stability, making it a stronger candidate for applications requiring enhanced textural properties and heat stability.

**Thermal Behavior and Crystallization Characteristics of Sunflower Oil-Based Oleogels**

The onset temperature (To), peak temperature (Tp), and endset temperature (Te) of the prepared oleogels increased with higher wax concentrations, indicating that increasing the structuring agent content enhances thermal stability. The 10% beeswax oleogel exhibited the highest onset temperature (50.14°C), peak temperature (54.57°C), and endset temperature (60.25°C), followed closely by the 10% sunflower wax oleogel with values of 49.87°C, 53.84°C, and 58.85°C, respectively. This suggests that a stronger crystalline network was formed at higher wax concentrations, requiring more thermal energy for melting (Doan et al., 2022). The slightly higher thermal stability of beeswax-based oleogels compared to sunflower wax-based oleogels can be attributed to the compact β' crystal structure of beeswax, which promotes a denser and more stable gel matrix, while sunflower wax forms elongated needle-like β-crystals, which have slightly lower melting stability (Lupi et al., 2020).

The enthalpy change (ΔH), representing the energy required for melting, increased with higher wax concentrations, indicating a more structured gel network. The highest enthalpy change was observed in the 10% beeswax oleogel (14.87 J/g), followed by the 10% sunflower wax oleogel (13.25 J/g), suggesting that beeswax-based oleogels require more energy for complete phase transition. This is due to the increased number of crystalline domains and stronger interactions within the lipid network at higher wax concentrations (Zulim et al., 2020). Additionally, beeswax oleogels consistently displayed slightly higher enthalpy changes than sunflower wax oleogels at the same concentration, reinforcing that beeswax forms a more rigid and stable gel structure, contributing to improved thermal resistance (Patel et al., 2015).

Overall, these findings indicate that both beeswax and sunflower wax effectively enhance the thermal stability of sunflower oil by forming structured oleogels with defined crystalline properties. Beeswax at 10% concentration provided the most thermally stable oleogel, suggesting its suitability for applications requiring heat resistance, such as bakery fillings and frying applications (Hwang et al., 2016). Meanwhile, sunflower wax-based oleogels also showed significant structuring capacity, making them an alternative for products where a smoother, less rigid texture is desired. The results confirm that wax type and concentration play a crucial role in determining the thermal behavior and melting properties of oleogels, which are critical for their functionality in food formulations.

The optimal beeswax concentration was 8%, providing a balance of firmness (3.59 N), high oil binding capacity (98.68%), oxidative stability (DPPH: 38.7%), and superior sensory acceptability (9.47/10) without excessive rigidity, making it ideal for structured food applications. In contrast, the 10% sunflower wax concentration was the best, offering the highest spreadability (9.73/10), smooth texture, and strong thermal stability (melting point: 55.28°C, enthalpy: 13.25 J/g) while maintaining a firm but consumer-friendly consistency (3.57 N). Beeswax is better suited for applications requiring higher oxidative stability and structural integrity, whereas sunflower wax is more appropriate for spreadable formulations and softer textures, such as bakery fillings and emulsified products.

**Impact of Beeswax and Sunflower Wax on the Fatty Acid Composition of Sunflower Oil-Based Oleogels**

The incorporation of 8% beeswax and 10% sunflower wax into sunflower oil led to notable changes in fatty acid composition, particularly in saturated (SFA), monounsaturated (MUFA), and polyunsaturated fatty acids (PUFA). The palmitic acid (C16:0) content increased in both wax-structured oleogels, rising from 5.80% in pure sunflower oil to 7.24% in the beeswax oleogel and 6.19% in the sunflower wax oleogel. This increase is expected, as beeswax and sunflower wax contain higher amounts of saturated fatty acids, contributing to improved oxidative stability and gel network formation (Patel et al., 2015). Additionally, minor increases in stearic acid (C18:0) and arachidic acid (C20:0) were observed, with higher levels in beeswax-based oleogels, reflecting the wax’s inherent fatty acid composition (Zulim et al., 2020).

Regarding monounsaturated fatty acids (MUFA), the oleic acid (C18:1) content increased from 27.27% in sunflower oil to 30.92% in the beeswax oleogel and 31.50% in the sunflower wax oleogel. The palmitoleic acid (C16:1) and gondoic acid (C20:1) levels also increased, which suggests that wax components contributed additional monounsaturated fatty acids, possibly from long-chain wax esters breaking down into free fatty acids during oleogel preparation (Doan et al., 2022). These increases in MUFA enhance oil stability and nutritional benefits, as oleic acid is associated with improved lipid metabolism and cardiovascular health (Lupi et al., 2020). The slightly higher MUFA content in the sunflower wax oleogel compared to the beeswax-based formulation suggests differences in wax composition and the degree of wax-lipid interactions during structuring.

The polyunsaturated fatty acid (PUFA) content decreased with wax incorporation, particularly linoleic acid (C18:2), which dropped from 63.59% in sunflower oil to 55.74% in the beeswax oleogel and 57.14% in the sunflower wax oleogel. This reduction is likely due to wax components contributing more saturated and monounsaturated fatty acids, thereby reducing the relative proportion of PUFAs (Hwang et al., 2016). Despite this decrease, linolenic acid (C18:3) increased, particularly in sunflower wax-based oleogels (0.53%), which may be attributed to minor bioactive lipid components in sunflower wax (Blake et al., 2014). The overall shift in fatty acid composition highlights that wax structuring enhances oxidative stability by lowering PUFA content while increasing SFA and MUFA, making the oleogels more resistant to lipid oxidation while retaining essential fatty acids.

**Effect of Sunflower Oil-Based Oleogels on the pH Stability of Frankfurters During Storage**

The initial pH values (Day 0) were similar across all samples, ranging from 5.44 to 5.45, with no significant differences between the control (100% animal fat) and oleogel-based frankfurters. This indicates that replacing animal fat with sunflower oil-based oleogels did not significantly alter the initial acidity of the product, which is essential for maintaining quality and sensory attributes (Hwang et al., 2016). The pH values of meat products are typically influenced by protein content, fat composition, and interactions with added structuring agents (Patinho et al., 2022). Since beeswax and sunflower wax are neutral compounds, their presence did not immediately impact pH levels at the beginning of storage.

As storage progressed (Day 6 and Day 12), a notable increase in pH was observed in all samples, with the control frankfurter (100% animal fat) reaching the highest pH (6.83) by Day 12. In contrast, frankfurters containing sunflower oil-based oleogels exhibited significantly lower pH values (5.68–5.80 on Day 12), suggesting that the inclusion of oleogels delayed the alkalization process. The lower pH in oleogel-based formulations is likely due to a reduced formation of alkaline nitrogenous compounds, such as ammonia and biogenic amines, which are produced by microbial activity and lipid oxidation in traditional high-fat meat products (Lorenzo et al., 2018). The better pH stability of oleogel-formulated frankfurters may be attributed to the antioxidant properties of sunflower oil and the waxes, which slow down oxidative and microbial degradation, thereby maintaining a more stable acidic environment (Doan et al., 2022).

Among the oleogel-based formulations, frankfurters containing sunflower wax exhibited slightly higher pH values than those containing beeswax by Day 12. This may be due to differences in antioxidant activity between beeswax and sunflower wax, as beeswax is known to contain flavonoids and phenolic compounds, which provide superior oxidative stability (Blake et al., 2014). The 100% sunflower oil + beeswax 8% formulation maintained the lowest pH (5.73), indicating its greater effectiveness in stabilizing the product against pH fluctuations. These findings suggest that substituting animal fat with sunflower oil-based oleogels not only improves the nutritional profile of frankfurters but also enhances their pH stability, potentially extending shelf life and maintaining quality during storage (Zulim et al., 2020).

**Lipid Oxidation and Oxidative Stability of Frankfurters Formulated with Sunflower Oil-Based Oleogels**

The TBA values, expressed as mg of malondialdehyde (MDA) per kg, measure lipid oxidation in frankfurters over 12 days of storage. At Day 0, the control frankfurter (100% animal fat) exhibited the highest TBA value (0.26 mg MDA/kg), while samples containing sunflower oil-based oleogels had significantly lower values (0.14–0.18 mg MDA/kg). This indicates that the replacement of animal fat with oleogels enhanced oxidative stability from the beginning of storage, likely due to the higher antioxidant potential of sunflower oil and structuring waxes, which help limit the formation of oxidative by-products (Hwang et al., 2016). The 100% BG (100% Sunflower Oil + Beeswax 8%) sample exhibited the lowest initial TBA value (0.14 mg MDA/kg), suggesting that beeswax may have contributed more effectively to reducing oxidation compared to sunflower wax due to its natural phenolic compounds and flavonoids, which act as antioxidants (Doan et al., 2022).

By Day 6, the control sample showed a sharp increase in oxidation (0.85 mg MDA/kg), whereas frankfurters containing oleogels exhibited significantly lower TBA values (0.25–0.32 mg MDA/kg). The 50% BG (50% animal fat + 50% Sunflower Oil + Beeswax 8%) and 100% BG (100% Sunflower Oil + Beeswax 8%) samples maintained the lowest oxidation levels, followed by sunflower wax-based formulations (50% SG and 100% SG). The reduction in lipid oxidation in oleogel-based frankfurters can be attributed to the gel network formation by waxes, which limit oxygen diffusion and reduce oxidative degradation (Patinho et al., 2022). Furthermore, beeswax and sunflower wax act as stabilizers, forming a protective barrier around lipid molecules, preventing oxidation reactions that commonly occur in traditional high-fat meat products (Lupi et al., 2020).

At Day 12, oxidative deterioration in the control frankfurter continued to increase sharply (1.28 mg MDA/kg), surpassing the acceptable threshold for lipid oxidation in processed meats. However, all oleogel-based formulations maintained significantly lower TBA values (0.26–0.34 mg MDA/kg), demonstrating that sunflower oil-based oleogels effectively delayed lipid oxidation throughout storage. The beeswax-based formulations (50% BG and 100% BG) exhibited the lowest TBA values (0.26–0.27 mg MDA/kg), reinforcing beeswax's superior antioxidant potential compared to sunflower wax (Blake et al., 2014). These findings suggest that substituting animal fat with sunflower oil-based oleogels not only improves the nutritional profile of frankfurters but also enhances their shelf life and oxidative stability, making them a viable alternative for reducing saturated fat content in processed meats while preserving quality.

**Effect of Sunflower Oil-Based Oleogels on Cooking Loss in Frankfurters During Storage**

Cooking loss refers to the percentage of weight loss during heat processing, primarily due to moisture and fat loss, which affects product yield, texture, and juiciness. At Day 0, frankfurters containing 100% sunflower oil-based oleogels (100% SG and 100% BG) exhibited significantly higher cook loss (32.54–33.77%) compared to the control (20.26%) and mixed formulations (50% SG and 50% BG). The increased cook loss in 100% oleogel formulations may be due to the lower solid fat content and weaker fat-protein interactions, as traditional animal fat contributes to emulsion stability by retaining water and fat more efficiently (Patinho et al., 2022). However, beeswax-based oleogels (100% BG) exhibited slightly lower cook loss (32.54%) compared to sunflower wax-based oleogels (33.77%), suggesting that beeswax provides better structural stability in meat matrices, potentially due to its higher viscosity and gel network strength (Doan et al., 2022).

As storage progressed (Day 6), a slight increase in cook loss was observed across all samples, but the 100% sunflower oil-based formulations continued to exhibit significantly higher values (33.33%) compared to the control and 50% fat-replacement samples (21.26–22.37%). The 50% oleogel formulations (50% SG and 50% BG) demonstrated similar cook loss values to the control frankfurter, indicating that partial replacement of animal fat with sunflower oil-based oleogels maintains acceptable cooking stability. The higher cook loss in 100% sunflower oil-based formulations is likely due to reduced emulsion stability, as oleogels may not fully mimic the structural properties of animal fat, leading to increased water and oil separation during cooking (Lorenzo et al., 2018). The slightly better performance of beeswax-based oleogels (50% BG and 100% BG) over sunflower wax-based oleogels suggests that beeswax forms a more cohesive gel network, improving water retention and reducing moisture loss (Blake et al., 2014).

By Day 12, cooking loss in the control and 50% oleogel formulations remained stable (20.73–21.13%), whereas the 100% sunflower oil-based formulations continued to show significantly higher cook loss (32.79–34.97%). The increase in cook loss over time may be due to protein denaturation, emulsion destabilization, and structural weakening as storage progresses (Hwang et al., 2016). The 100% sunflower wax formulation (100% SG) exhibited the highest cook loss (34.97%), reinforcing that sunflower wax-based oleogels may not retain moisture as effectively as beeswax-based formulations. These findings indicate that partial fat replacement (50% animal fat + 50% oleogel) is optimal for maintaining cooking stability, while 100% fat replacement leads to higher moisture loss, particularly in sunflower wax-based formulations. Overall, beeswax-based oleogels performed better in retaining moisture and minimizing cook loss compared to sunflower wax-based oleogels, making them a preferable choice for improving the textural and cooking properties of reformulated meat products.

**Effect of Sunflower Oil-Based Oleogels on Cooking Yield of Frankfurters During Storage**

Cooking yield is an essential parameter that reflects the ability of meat products to retain moisture and fat during heat processing, influencing product texture, juiciness, and overall quality. At Day 0, the control frankfurter (100% animal fat) exhibited the highest cooking yield (79.74%), while samples containing 100% sunflower oil-based oleogels (100% SG and 100% BG) exhibited significantly lower yields (66.23–67.46%). This reduction in cook yield is expected, as animal fat forms a more stable emulsion matrix, contributing to improved moisture and fat retention during heat treatment (Patinho et al., 2022). The 50% fat-replacement formulations (50% SG and 50% BG) exhibited similar cook yield values (78.70–78.86%) to the control, suggesting that partial substitution of animal fat with sunflower oil-based oleogels does not significantly affect water and fat retention.

By Day 6, a slight decrease in cook yield was observed across all samples, with the 100% sunflower oil-based formulations maintaining the lowest yields (66.23–66.67%). The 50% SG and 50% BG formulations continued to demonstrate similar retention capacity to the control (77.63–78.74%), reinforcing the stability of partially replaced formulations in maintaining desirable cooking properties. The higher cooking loss observed in 100% oleogel-based formulations (previously noted in cook loss data) likely contributed to the lower cook yield, as oleogels do not form the same fat-protein interactions as animal fat, leading to higher moisture loss during heating (Lupi et al., 2020). The slightly higher cook yield in 100% BG (67.46–67.21%) compared to 100% SG (66.23–65.03%) suggests that beeswax-based oleogels provide better emulsion stability, possibly due to their denser gel network and higher viscosity, which aid in water retention (Doan et al., 2022).

By Day 12, cooking yield values remained stable for the control and 50% oleogel formulations (78.87–79.27%), while 100% sunflower oil-based formulations continued to show significantly lower yields (65.03–67.21%). The higher reduction in cook yield observed in 100% SG (65.03%) compared to 100% BG (67.21%) reinforces previous findings that beeswax may enhance moisture retention better than sunflower wax, likely due to its stronger lipid structuring ability (Hwang et al., 2016). These findings suggest that partial fat replacement (50% animal fat + 50% oleogel) is the optimal formulation for maintaining cook yield, while 100% fat replacement results in higher moisture and fat loss, particularly in sunflower wax-based formulations. Overall, beeswax-based oleogels performed better in retaining cooking yield than sunflower wax-based oleogels, making them more suitable for fat-reduced frankfurter formulations.

**Effect of Sunflower Oil-Based Oleogels on Fat Retention in Frankfurters During Storage**

Fat retention is a critical quality parameter in meat products, as it influences juiciness, texture, and mouthfeel. At Day 0, the control frankfurter (100% animal fat) exhibited the highest fat retention (18.52%), whereas frankfurters containing 100% sunflower oil-based oleogels showed significantly lower fat retention (8.74–9.38%). This reduction is expected, as animal fat forms a more stable emulsion matrix with proteins, which helps retain lipids during processing and cooking (Patinho et al., 2022). In contrast, oleogels have a weaker interaction with muscle proteins, leading to a higher release of fat during cooking (Doan et al., 2022). Among the oleogel-based formulations, beeswax-based oleogels (50% BG and 100% BG) exhibited slightly higher fat retention than sunflower wax-based oleogels, suggesting that beeswax provides a more cohesive lipid network, which limits fat release during processing (Blake et al., 2014).

By Day 6, fat retention values remained relatively stable in all formulations, with minor changes due to protein-lipid interactions and gradual moisture loss. The control sample retained the highest fat content (18.40%), while 100% sunflower oil-based formulations (100% SG and 100% BG) showed the lowest fat retention (9.30% and 8.66%, respectively). The slightly higher fat retention in 50% BG (11.43%) compared to 50% SG (12.36%) suggests that beeswax provided better structural integrity than sunflower wax, which aligns with findings that beeswax-based oleogels exhibit stronger gel networks, reducing fat migration (Lupi et al., 2020). Despite the differences, partial fat replacement (50% animal fat + 50% oleogel) maintained fat retention closer to the control, indicating that a balanced fat replacement strategy can preserve fat-holding capacity in reformulated frankfurters.

By Day 12, fat retention remained highest in the control frankfurter (18.43%), while 100% oleogel-based formulations continued to exhibit lower values (9.19% in 100% SG and 8.46% in 100% BG). The gradual decline in fat retention over time may be attributed to oxidative degradation and structural weakening of the oleogel matrix, leading to increased fat release (Hwang et al., 2016). The slightly better fat retention in 100% SG compared to 100% BG suggests that sunflower wax, despite its higher cook loss, may form a more oil-entrapping network at later storage stages. However, beeswax-based oleogels (50% BG and 100% BG) still showed greater stability in fat retention compared to sunflower wax-based oleogels, reinforcing their suitability for fat replacement applications in processed meat products. These results indicate that partial fat replacement (50% animal fat + 50% oleogel) is optimal for maintaining fat retention, while 100% replacement leads to significant fat loss, particularly in beeswax-based formulations.

**Effect of Sunflower Oil-Based Oleogels on the Color Stability of Frankfurters During Storage**

Color is a crucial sensory attribute in meat products, influenced by fat composition, oxidation, and pigment stability. The lightness (L) values\* varied significantly among formulations, with 100% SG (100% Sunflower Wax + Sunflower Oil) exhibiting the highest L (60.77) at Day 0\*, indicating a brighter and lighter appearance compared to other formulations. This could be due to the lower opacity of sunflower oil compared to animal fat, leading to a more translucent effect (Patinho et al., 2022). However, by Day 6 and Day 12, the L values of 100% SG significantly decreased (46.18),\* suggesting oxidative discoloration and structural breakdown of the oleogel network, leading to light scattering changes (Doan et al., 2022). The control sample (100% animal fat) maintained the highest L (62.40) by Day 12\*, demonstrating better color stability, likely due to the protective effects of saturated fat in limiting oxidation.

The redness (a) values\* were highest in the 50% SG formulation (11.89) at Day 0, suggesting that partial fat replacement with sunflower wax-based oleogels initially enhanced red color intensity. However, by Day 6 and 12, the 100% SG formulation exhibited the highest a values (11.33),\* while the control and beeswax-based samples showed lower redness values (8.14–9.88). This could indicate a greater oxidation effect in 100% SG, where lipid oxidation byproducts interacted with meat pigments, leading to shifts in red intensity (Lorenzo et al., 2018). In contrast, beeswax-based formulations (50% BG and 100% BG) maintained more stable a values\*, suggesting that beeswax offers better oxidative protection to color pigments than sunflower wax (Hwang et al., 2016). The decline in a values over storage\* is commonly associated with metmyoglobin formation and oxidation of heme pigments, which are influenced by fat composition and antioxidant capacity (Blake et al., 2014).

Regarding yellowness (b) values,\* all formulations exhibited relatively stable b values throughout storage, with minor fluctuations.\* The control sample, 50% SG, and 50% BG maintained the highest b values (~19.05–21.45),\* while 100% SG and 100% BG showed slightly lower values over time. This could be due to differences in pigment retention and lipid stability in formulations containing higher proportions of sunflower oil, which lacks the natural yellow hue of animal fat (Doan et al., 2022). By Day 12, the highest b values were observed in the 100% SG sample (20.41),\* which may be due to oxidative changes leading to the formation of secondary yellow-pigmented compounds. These findings suggest that partial replacement (50% SG and 50% BG) better preserves color characteristics, whereas full replacement (100% SG and 100% BG) may lead to increased oxidative discoloration over time.

**Conclusion**

This study demonstrates that sunflower oil-based oleogels structured with beeswax and sunflower wax offer a viable alternative to animal fat in frankfurters, enhancing their nutritional profile while maintaining structural and sensory integrity. Beeswax-based oleogels provided superior oxidative stability, oil retention, and firmness, making them suitable for applications requiring structural integrity. In contrast, sunflower wax-based oleogels contributed to better spreadability, higher lightness values, and improved sensory perception, making them ideal for formulations requiring smooth texture and neutral taste. Partial fat replacement with 50% oleogel retained cooking yield and fat retention, whereas full substitution resulted in higher cooking loss and lower fat retention, suggesting that balanced incorporation is necessary for optimal product stability. The increased oxidative stability in oleogel-based formulations indicates their potential to enhance product shelf life, making them a promising alternative in fat-reduced meat products. Future research should focus on the impact of different wax combinations on oleogel structuring and their long-term stability in food applications.

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**Conflict of interest:** No

**Table 1: Physical Properties of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax at Different Concentrations**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Properties | SFOBW6 | SFOBW8 | SFOBW10 | SFOSFW6 | SFOSFW8 | SFOSFW10 |
| Gelation time | 6.19±0.54a | 5.28±0.36b | 3.27±0.27c | 2.59±0.21d | 1.49±0.11e | 1.15±0.09f |
| Oil binding capacity | 95.34±1.62b | 98.68±1.26a | 99.28±1.39a | 92.65±1.25b | 94.68±1.62b | 97.68±1.56a |
| Firmness (N) | 2.87±0.456c | 3.59±0.26b | 4.15±0.36a | 2.64±0.26c | 2.99±0.31c | 3.57±0.16b |
| Melting point | 53.29±0.94b | 55.62±0.78a | 56.97±0.88a | 50.24±0.63c | 52.96±0.73b | 55.28±0.64a |

Values are means ± SD; means having the different case letter(s) within a row are significantly different at P≤0.05. SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 2. Color Properties (L\*, a\*, b\*) of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Color | SFO | SFOBW6 | SFOBW8 | SFOBW10 | SFOSFW6 | SFOSFW8 | SFOSFW10 |
| Color L | 55.23 ± 0.30b | 56.10 ± 0.40a | 56.80 ± 0.35a | 57.50 ± 0.30a | 56.30 ± 0.45a | 57.00 ± 0.40a | 57.80 ± 0.30a |
| Color a | -1.02 ± 0.05a | -1.10 ± 0.04a | -1.15 ± 0.06a | -1.20 ± 0.04a | -1.08 ± 0.05a | -1.12 ± 0.06a | -1.18 ± 0.05a |
| Color b | 10.54 ± 0.15b | 11.00 ± 0.20a | 11.20 ± 0.22a | 11.50 ± 0.18a | 10.80 ± 0.20b | 11.10 ± 0.25a | 11.40 ± 0.22a |

Values are means ± SD; means having the different case letter(s) within a row are significantly different at P≤0.05. SFO= Sunflower oil, SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 3. Chemical Characteristics, Total Phenolic Content, Antioxidant Activity, and Oxidative Stability of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Properties | SFO | SFOBW6 | SFOBW8 | SFOBW10 | SFOSFW6 | SFOSFW8 | SFOSFW10 |
| AV | 0.25 ± 0.03a | 0.24 ± 0.02a | 0.23 ± 0.02a | 0.22 ± 0.02a | 0.24 ± 0.03a | 0.23 ± 0.02a | 0.22 ± 0.02a |
| PV | 5.20 ± 0.12z | 4.80 ± 0.10b | 4.50 ± 0.11c | 4.20 ± 0.09d | 4.90 ± 0.12b | 4.60 ± 0.10c | 4.30 ± 0.09d |
| TPC | 0.02 ± 0.00d | 0.25 ± 0.01b | 0.28 ± 0.01a | 0.30 ± 0.01a | 0.20 ± 0.01c | 0.22 ± 0.01c | 0.25 ± 0.01b |
| DPPH | 10.50 ± 0.20e | 35.20 ± 0.50c | 38.70 ± 0.60b | 42.30 ± 0.70a | 32.50 ± 0.50d | 35.80 ± 0.55c | 39.50 ± 0.65b |
| Rancimate | 4.10 ± 0.08e | 6.50 ± 0.12d | 7.80 ± 0.14c | 9.00 ± 0.15a | 6.20 ± 0.13d | 7.40 ± 0.14c | 8.60 ± 0.15b |

Values are means ± SD; means having the different case letter(s) within a row are significantly different at P≤0.05. SFO= Sunflower oil, SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 4. Sensory Evaluation Scores of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sample** | **Appearance (10)** | **Spreadability (10)** | **Taste (10)** | **Odor (10)** | **Acceptability (10)** |
| SFOBW6 | 7.85 ± 0.30d | 8.10 ± 0.25d | 7.93 ± 0.20d | 8.00 ± 0.20c | 8.00 ± 0.22c |
| SFOBW8 | 9.27 ± 0.20a | 9.53 ± 0.18a | 9.35 ± 0.15a | 9.44 ± 0.15a | 9.47 ± 0.15a |
| SFOBW10 | 8.93 ± 0.25ab | 8.87 ± 0.22b | 8.57 ± 0.18b | 8.77 ± 0.20b | 8.75 ± 0.18b |
| SFOSFW6 | 8.02 ± 0.28c | 8.26 ± 0.26c | 8.08 ± 0.20c | 8.19 ± 0.22c | 8.15 ± 0.25c |
| SFOSFW8 | 8.76 ± 0.22b | 8.95 ± 0.20b | 8.79 ± 0.18b | 8.83 ± 0.18b | 8.88 ± 0.20b |
| SFOSFW10 | 9.52 ± 0.15a | 9.73 ± 0.12a | 9.45 ± 0.12a | 9.67 ± 0.10a | 9.53 ± 0.12a |

Values are means ± SD; means having the different case letter(s) within a column are significantly different at P≤0.05. SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 5. Viscosity of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax at Different Temperatures**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample** | **Viscosity at 20°C (Pa·s)** | **Viscosity at 40°C (Pa·s)** | **Viscosity at 60°C (Pa·s)** | **Viscosity at 80°C (Pa·s)** |
| SFOBW6 | 125.54 ± 3.53d | 95.34 ± 2.80c | 60.47 ± 2.03e | 35.24 ± 1.50e |
| SFOBW8 | 135.80 ± 3.82b | 110.43 ± 3.24b | 75.54 ± 2.55c | 50.36 ± 2.06c |
| SFOBW10 | 150.26 ± 4.06a | 125.36 ± 3.65a | 90.68 ± 2.87a | 65.48 ± 2.36a |
| SFOSFW6 | 115.44 ± 3.27c | 90.22 ± 2.77d | 55.35 ± 1.84f | 30.14 ± 1.43f |
| SFOSFW8 | 130.74 ± 3.68b | 105.44 ± 3.14b | 70.69 ± 2.32d | 45.57 ± 1.84d |
| SFOSFW10 | 145.98 ± 3.99a | 120.66 ± 3.53a | 85.44 ± 2.68b | 60.72 ± 2.26b |

Values are means ± SD; means having the different case letter(s) within a column are significantly different at P≤0.05. SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 6. Thermal Properties of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample** | **Onset Temp (°C)** | **Peak Temp (°C)** | **Endset Temp (°C)** | **Enthalpy Change (J/g)** |
| SFOBW6 | 48.23 ± 0.55a | 52.50 ± 0.43b | 57.86 ± 0.60c | 10.45 ± 0.38e |
| SFOBW8 | 49.32 ± 0.45a | 53.78 ± 0.35a | 58.94 ± 0.54b | 12.66 ± 0.40c |
| SFOBW10 | 50.14 ± 0.34c | 54.57 ± 0.35a | 60.25 ± 0.46a | 14.87 ± 0.57a |
| SFOSFW6 | 47.85 ± 0.43b | 51.86 ± 0.46c | 56.53 ± 0.57d | 9.88 ± 0.36e |
| SFOSFW8 | 48.96 ± 0.44a | 52.95 ± 0.37b | 57.72 ± 0.45c | 11.56 ± 0.37d |
| SFOSFW10 | 49.87 ± 0.35a | 53.84 ± 0.30a | 58.85 ± 0.46b | 13.25 ± 0.45b |

Values are means ± SD; means having the different case letter(s) within a column are significantly different at P≤0.05. SFOBW6= Sunflower oil-beeswax oleogel 6%, SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOBW10= Sunflower oil-beeswax oleogel 10%, SFOSFW6= Sunflower oil-sunflower wax oleogel 6%, SFOSFW8= Sunflower oil-sunflower wax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 7: Fatty acid composition of Sunflower Oil-Based Oleogels Structured with Beeswax (8%) and Sunflower wax (10%)**

**Table 7. Fatty Acid Composition of Sunflower Oil-Based Oleogels Structured with Beeswax and Sunflower Wax**

|  |  |  |  |
| --- | --- | --- | --- |
| Fatty acids | SFO | SFOBW8 | SFOSFW10 |
| Luric acid | 0.18±0.02a | 0.12±0.01b | 0.07±0.00c |
| Palmitic acid | 5.80±0.21c | 7.24±0.34a | 6.19±0.15b |
| Palmitiolic acid | 0.02±0.00c | 0.13±0.01b | 0.19±0.02a |
| Stearic acid | 3.50±0.12a | 3.62±0.11a | 3.09±0.25a |
| Oleic acid | 27.27±1.11b | 30.92±1.25a | 31.50±1.57a |
| Linoleic acid | 63.59±1.67a | 55.74±1.58b | 57.14±1.34b |
| Linolenic acid | 0.08±0.00c | 0.30±0.09b | 0.53±0.10a |
| Arachidic acid | 0.10±0.01c | 0.25±0.02b | 0.29±0.05a |
| Behenicacid | 0.55±0.02c | 0.59±0.04b | 0.73±0.03a |

Values are means ± SD; means having the different case letter(s) within a row are significantly different at P≤0.05. SFOBW8= Sunflower oil-beeswax oleogel 8%, SFOSFW10= Sunflower oil-sunflower wax oleogel 10%.

**Table 8. pH Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time (Day)** | **Sample** | | | | |
| **Control frankfurter (100% animal fat)** | **50% animal fat +**  **50%** Sunflower Oil + Sunflower Wax 10% | **100%** Sunflower Oil + Sunflower Wax 10% | **50% animal fat +**  **50%** Sunflower Oil + beesWax 8% | **100%** Sunflower Oil + beesWax 8% |
| **pH** | **0** | 5.45±0.01a | 5.44±0.01a | 5.44±0.01a | 5.45±0.01a | 5.44±0.01a |
| **6** | 6.30±0.1a | 5.68±0.01b | 5.68±0.01b | 5.56±0.01b | 5.56±0.01b |
| **12** | 6.83±0.01a | 5.80±0.02b | 5.74±0.02b | 5.68±0.01b | 5.73±0.01b |

**Table 9. TBA Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time (Day)** | Sample | | | | |
| **Control** | **50% SG** | **100% SG** | **50% BG** | **100% BG** |
| **TBA**  **MDA/ Kg** | **0** | 0.26±0.04a | 0.17±0.01b | 0.17±0.01b | 0.18±0.01b | 0.14±0.01b |
| **6** | 0.85±0.02a | 0.32±0.01bc | 0.32±0.02b | 0.29±0.02cd | 0.25±0.01cd |
| **12** | 1.28±0.02a | 0.34±0.01b | 0.34±0.02b | 0.26±0.01c | 0.27±0.01c |

**Table 10. Cook loss Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time (Day)** | Sample | | | | |
| **Control** | **50% SG** | **100% SG** | **50% BG** | **100% BG** |
| **Cook loss (%)** | **0** | 20.26±0.3b | 21.30±0.4b | 33.77±0.7a | 21.14±0.4b | 32.54±1.0a |
| **6** | 21.78±0.4b | 22.37±0.7b | 33.33±0.6aa | 21.26±0.4b | 33.33±0.7a |
| **12** | 21.00±0.6b | 21.13±0.4b | 34.97±0.5Aa | 20.73±0.7b | 32.79±1.2a |

**Table 11. Cook yield Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time (Day)** | Sample | | | | |
| **Control** | **50% SG** | **100% SG** | **50% BG** | **100% BG** |
| **Cook yield (%)** | **0** | 79.74±0.3b | 78.70±0.4b | 66.23±0.7a | 78.86±0.4b | 67.46±1.0a |
| **6** | 78.22±0.4b | 77.63±0.7b | 66.23±0.6a | 78.74±0.4b | 66.67±0.7a |
| **12** | 78.94±0.5b | 78.87±0.4b | 65.03±0.5a | 79.27±0.7b | 67.21±1.2a |

**Table 12. Fat retention Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time (Day)** | Sample | | | | |
| **Control** | **50% SG** | **100% SG** | **50% BG** | **100% BG** |
| **Fat retention (%)** | **0** | 18.52±0.06a | 12.24±0.08b | 9.38±0.06d | 11.45±0.14c | 8.74±0.14f |
| **6** | 18.40±0.07a | 12.36±0.09b | 9.30±0.11d | 11.43±0.11c | 8.66±0.14f |
| **12** | 18.43±0.1a | 12.42±0.05b | 9.19±0.03d | 11.64±0.07c | 8.46±0.08f |

**Table 13. Color Changes in Frankfurters Containing Sunflower Oil-Based Oleogels During Storage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Storage time/ Day** | **Sample** | | | | |
| **Control** | **50% SG** | **100% SG** | **50% BG** | **100% BG** |
| **L** | **0** | 55.62±0.07b | 50.37±0.4c | 60.77±0.3ab | 55.53±1.7 | 58.21±1.1ab |
| **6** | 61.00±0.8a | 64.07±2.6a | 48.90±0.8c | 55.22±1.5b | 54.83±1.9b |
| **12** | 62.40±1.2a | 57.69±0.6b | 46.18±0.7c | 59.69±0.4ab | 57.58±1.2 b |
| **a** | **0** | 9.49±0.5b | 11.89±0.2a | 9.36±0.1b | 9.27±0.2b | 9.56±0.04b |
| **6** | 9.27±0.7ab | 7.44±0.7b | 10.41±0.9a | 9.74±0.3ab | 9.71±1.0ab |
| **12** | 9.46±0.2c | 10.10±0.2b | 11.33±0.3a | 8.14±0.2d | 9.88±0.1bc |
| **b** | **0** | 21.34±0.2a | 21.05±0.2a | 18.39±0.1b | 21.45±0.2a | 19.95±0.5b |
| **6** | 19.46±0.1Cab | 18.08±0.8c | 19.95±0.7ab | 18.86±0.2ab | 20.83±0.6a |
| **12** | 19.05±0.1a | 19.31±0.3a | 20.41±0.8a | 20.41±0.8a | 18.99±0.2a |

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