SUMMARY OF PhD THESIS

Replacement of conventional fat with structured lipid systems: Investigation of rheological and structural properties in foods

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SUMMARY

Lipids are essential components of the human diet, serving as critical energy sources and carriers for fat-soluble vitamins, while also providing food with structural integrity, spreadability, and palatability that consumers expect. Traditionally, these functional attributes depend on the crystalline networks formed by saturated and trans-fatty acids. However, the strong correlation between high intake of these fats and risks such as coronary heart disease and oxidative stress has led to rigorous global regulations from the Food and Drug Administration, World Health Organization, and European Commission. This creates a complex challenge for the industry: substituting solid fats with liquid oils often results in structural instabilities, such as oil syneresis or loss of texture, unless the plastic properties of the fat phase are effectively maintained.

While tropical oils are frequently used as natural substitutes, they are not a perfect solution due to their association with environmental issues like deforestation and their own health implications. In response, advanced oil structuring through gelation has emerged as a transformative technological approach. By using structuring agents to trap liquid oils within a three-dimensional network, researchers can create "solid-like" fats - such as oleogels and bigels - that mimic the behavior of saturated fats using healthier unsaturated oils.

The primary strength of these structured lipid systems derives from their versatility and customizable nature, enabling precise control over texture and rheological properties in food systems. Beyond improving the nutritional profile, these matrices act as protective barriers for sensitive bioactive compounds, preventing their degradation during processing and storage. Because these systems are scalable and compatible with existing production lines, they offer an economically viable and "clean-label" strategy. Ultimately, these advanced lipid matrices bridge the gap between nutritional requirements and technological functionality, representing a key priority for future industrial innovation.

Meat and pastry products are widely consumed and typically use solid fats such as animal fats, margarine, shortenings, or tropical oils, which are high in saturated fatty acids and essential for texture, structure, and processing. From a nutritional perspective, replacing these fats with healthier liquid oils is desirable, but, such replacement must be achieved without losing the functional properties needed in food products. Given the high intake of these foods, improving fat quality can contribute meaningfully to overall dietary quality.

Structured lipid systems, particularly oleogels, offer a practical solution by structuring liquid oils into solid-like materials that can perform similarly to conventional fats. Sunflower oil is used as the lipid phase due to its favorable fatty acid composition, including essential polyunsaturated and monounsaturated fatty acids. Its wide availability, also makes it suitable for large-scale use. The feasibility of fat replacement is evaluated in different food matrices with varying structural complexity.

Accordingly, the aim of the present thesis is to evaluate the structural and rheological behavior of selected structured lipids, by obtaining and characterizing them and integrating in different categories of food products.

The main objectives of the doctoral research are:

O1. Reviewing the oxidative quality of bi-, oleo- and emulgels and their bioactives molecules delivery to better understand the differences between the systems as well as the advantages and limitations of each system.

O2. Evaluation the effects of substituting animal fat with sunflower oil in Vienna sausage production: The use of unstructured lipids to understand their impact on the food matrix and to better design structured lipid systems that address the observed limitations.

O3. Assessing candelilla wax and glycerol monostearate-based oleogels as animal fat substitutes in meat products during process dynamics: The assessment of the physical attributes in the dynamics of the process was conducted due to the significance of understanding the behavior of oleogels under processing and storage conditions, as well as their interaction with the meat structure.

O4. Investigating the complete replacement of conventional fat with oleogel on the structural behavior of pastry products in order to identify technological constraints and formulation requirements, supporting the reduction of saturated and partially hydrogenated fats in commonly consumed products.

Methodology

The meat product evaluation initially focused on the use of sunflower oil to understand the impact on meat products and was subsequently carried out on three distinct types of products, with different food matrix structures: traditional Romanian sausage (100% ground meat, results not shown), Bologna-type sausage (75% ground meat, 25% meat batter), and Frankfurter sausage (100% meat batter). This selection enabled the evaluation of fat replacement strategies across different structural matrices, and provided insight into how matrix composition affects the feasibility and functional performance of animal fat substitution.

A comparable strategy was applied to pastry products, which vary widely in processing and depend strongly on fat functionality. Five representative items: bow tie cookies, cheese crackers, apple pie, cookies, and jam-filled puff pastry - were chosen to examine how fat replacement efficiency is affected by product type and technological operations such as mixing, rolling, and baking. Studying multiple pastry models allowed for a thorough understanding of technological limitations and formulation requirements, while addressing the consumer-driven goal of reducing saturated and partially hydrogenated fats in widely consumed foods.

The study employed a multidisciplinary approach, combining physicochemical characterization, structural and compositional analyses, and stability assessments, as follows:

- Texture profile analysis (TPA) and rheological measurements to evaluate mechanical and viscoelastic properties;
- Fat loss determination to assess structural stability;
- Color analysis to quantify visual attributes;

- Fourier-transform infrared spectroscopy (FTIR) to investigate molecular interactions;

Results

Meat products

Vienna sausages: Texture analysis revealed no significant differences in hardness, cohesiveness, and gumminess between conventional and reformulated meat batters. However, after thermal treatments, meat pastes obtained with pork backfat exhibited higher hardness values (32.17 N and 35.67 N) than those processed with sunflower oil (10.93 N and 14.09 N). Fat loss assessments indicated optimal fat retention in sunflower oil-based samples, particularly in cooked sausages (5.77%), suggesting better stability during processing and consumption than in the conventional cooked sample (11.61%). Rheological analysis demonstrated higher values for viscoelastic properties in pork backfat samples than in those containing sunflower oil; for all samples, no crossover points were observed, as the storage modulus G′ was higher than the loss modulus G″ and both moduli increased with increasing frequency. Concerning the characterization of finished products, for uncooked sausages with casings, the sausages reformulated with sunflower oil had higher hardness values than conventional ones (53.90 N vs 40.93 N). Despite this difference, both samples prepared for consumption (cooked) without a casing exhibited similar hardness values (7.81 N and 7.43 N).

Bologna sausages: The enhanced oil-binding capacity of oleogels suggests their potential value as substitutes for saturated fats (>99%). In terms of meat composition textural analysis, the highest hardness value was registered for pork backfat composition - 25.23 N, followed by composition with candelilla wax oleogel - 13.08 N and glycerol monostearate oleogel - 12.27 N. However, adhesiveness, cohesiveness, springiness index, and gumminess showed similar values between samples. Reformulation of products with oleogels as a fat source abundant in mono- and polyunsaturated fatty acids resulted in uncooked products exhibiting reduced hardness values of 49.01 N (when candelilla wax oleogel was used) and 40.51 N (when glycerolmonostearate oleogel was used), compared to 65.03 N (with porkbackfat). Color results of the cross-section color can indicate the potential for consumer acceptance due to the reduced color differences between the conventional and oleogel samples.

Pastry products: The textural properties of oleogel were comparable to those of conventional fats, but frequency sweep measurements showed that the oleogel formulated with refined sunflower oil and carnauba wax had the highest storage modulus G’ and loss modulus G’’ values when compared to conventional fats (commercial margarine, butter, a mixture of 73% margarine and 27% lard, and puff pastry margarine). The textural properties of oleogel (2.34 N and 2.30 mJ) were significantly different from those of puff pastry margarine (9.78 N and 21.73 mJ), but compared to other conventional fats, the values of hardness (1.42–2.70 N) and

adhesiveness (4.40–5.17 mJ) were similar. For conventional and oleogel doughs the storage modulus (G') were higher than loss modulus (G″) and both increased with the applied frequency (Hz). In terms of the products textural profile, the prototypes formed with oleogel exhibited lower hardness values (2.37–15.64 N) than the conventional products (8.83–19.89 N), indicating the tenderizing effect produced by the oleogel. The fat losses determined during 14 days of storage showed a lower physical stability of the doughs and products formulated with oleogel, most probably due to the destabilization kinetics of the lipid system during the operations of the technological process.

General conclusion

The complete replacement of pork fat is technologically feasible, allowing the production of meat products with improved nutritional quality. Reformulated Vienna and Bologna-type sausages maintained physicochemical and textural properties comparable to conventional formulations. Sunflower oil-based oleogels structured with candelilla wax or glycerol monostearate effectively substituted animal fat, exhibiting solid-like rheology, high structural stability, and minimal oil loss. Oleogel incorporation significantly reduced saturated fatty acids and increased mono- and polyunsaturated fatty acids, improving the nutritional profile. Candelilla wax-based oleogels, most closely replicated the functional and textural characteristics of pork fat.

In pastries, oleogels enabled complete fat replacement in tender and puff-pastry products. Doughs showed textural properties comparable to commercial margarines and butter, and finished products were generally softer. Nutritionally, oleogel substitution reduced the content of saturated fatty acids by up to 80%.

Overall, structured lipid systems, particularly oleogels, offer effective strategies for improving nutritional quality without compromising technological performance. Recommendations include antioxidant incorporation to limit oxidation, processing below structurant melting points, sensory evaluation, and monitoring of stability under production and storage conditions.

Inovative contributions of the thesis

Processed meat products such as Vienna and Bologna sausages are widely consumed, making them ideal targets for fat reformulation to improve dietary quality. Similarly, pastries are extensively consumed, justifying research on fat replacement. This thesis emphasizes the importance of focusing on highly consumed foods to maximize practical impact. Studying five pastry products enabled evaluation of oleogel applicability across different processing technologies and highlighted technological limitations for further optimization.

The use of sunflower oil oleogels structured with candelilla wax or glycerol monostearate as fat replacers in Bologna sausages had not been reported previously. The research addressed this gap, providing original insights into the technological feasibility and functional performance of these lipid systems. Physical and structural

attributes were evaluated during processing and storage to understand their behavior in real food matrices.

Overall, the thesis provides an innovative contribution by integrating food technology, nutrition, and lipid chemistry, offering strategies to develop healthier, technologically feasible food products that maintain functionality while improving nutritional quality.