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REINVENTING FAT (THE EVOLUTION AND EMERGING POTENTIAL OF STRUCTURED LIPIDS): A REVIEW

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Abstract
Structured lipids are a new, rapidly developing area in food science, biotechnology, and nutrition. The current evidence indicates that they can improve digestibility, oxidative stability, sensory quality, and targeted health benefits, and can help in the innovation of infant formula, medical foods, and functional bakery fats. Recent progress in the engineering of lipases, green lipids, and highly accurate lipidomic is steering the evolution of the new generation of custom lipids. Nonetheless, the barrier of cost, consumer confidence, and unbalanced regulations are still issues that should be overcome. Organized lipids will increase to be an ingredient of a robust functional food and nutraceutical innovation with coordinated scientific, industrial, and policy efforts, providing technological utility and quantifiable health advantages.

INTRODUCTION

Fats and oils are fundamental in human nutrition and the food industry, both as concentrated sources of energy, transport of essential fatty acids, a source of flavor and texture, and mouthfeel. However, conventional fats and oils tend to be associated with restrictions in terms of nutritional value, oxidative stability, and performance in food products. As an example, the popularity of partially hydrogenated oils has decreased because they contain trans-fatty acids and are harmful to cardiovascular health, and some natural fats do not allow them to achieve the desired level of structural or physicochemical properties needed in contemporary food systems (Singh et al., 2022).

In this regard, structured lipids (SLs) have become a new breed of modified lipids that are aimed at increasing the nutritional as well as functional values of fats and oils. Structured lipids have undergone the process of enzymatic, chemical, and biotechnological restructuring of triacylglycerols to change the fatty acid composition and distribution on the glycerol backbone. This alteration makes it possible to place medium-chain, long-chain, or other bioactive fatty acids in specific positions to produce lipids with enhanced digestibility and metabolic advantages, as well as with customized physicochemical features (Ribeiro et al., 2017).

Structured lipids have been of increased interest to the food industry because they have a wide range of uses in product development. Indicatively, it has been developed in infant nutrition, where lipids containing medium and long-chain triacylglycerols (MLCTs) and sn-2 palmitate analogues have been developed to more closely mimic human milk fat, resulting in better lipid absorption and supporting the proper growth of

infants(Chen et al., 2025). On the same note, engineered lipids synthesized through enzymatic interesterification have been discussed in terms of physicochemical, functional, and health-related properties, which can be used to substitute unwanted fats without compromising food quality (Singh et al., 2022). Also, inclusion of antioxidative ingredients in structured lipids was found to raise oxidative stability in food systems, including frying oils and infant formula emulsions (Gruczynska et al., 2015).

This review aims to give a comprehensive review of the recent developments in structured lipid production, functional qualities, uses, and nutrition. Special focus is given to enzymatic interesterification, which has transformed the sphere by providing a high degree of specificity and mild reaction conditions, and the new research trends based on sustainability, health, and consumer acceptance. This review will bring together existing knowledge and practical experience with the objective of identifying the potential of structured lipids as useful ingredients in the development of healthier, functional, and consumer-friendly food products.

Methods of Producing Structured Lipids

Structured lipids (SLs) are triacylglycerols that have had their fatty acid configuration or positional arrangement (sn-1, sn-2, sn-3) altered to provide properties desired physically, nutritionally, or functionally. The principal techniques of SLs production are chemical interesterification, enzymatic interesterification, and genetic/biotechnological.

Chemical Interesterification

In chemical interesterification (CIE), the rearrangement of fatty acids on the glycerol backbone is performed randomly with the help of chemical catalysts, including sodium methoxide, and leads to changes in triacylglycerol profiles and melting properties. Even though this process is quite cheap and effective, it is not positional-specific and yields side-products, including free fatty acids or partial-glycerides. Chemical interesterification has been found to alter the physical and thermal characteristics of oils and blends. As (Morselli Ribeiro et al., 2017) clearly demonstrated that chemically interesterified blends of high-oleic sunflower oil and fully hydrogenated soybean oil had higher solid fat content and different TAG distributions than enzymatic processes. Equally, (Okcu & Aktas, 2024) indicated that chemical restructuring of beef tallow, milk fat, and vegetable oils yielded fats that had an altered composition of fatty acids and melting properties suitable for food applications.

2.2 Enzymatic Interesterification

Enzymatic interesterification (EIE) involves the catalysis of fatty acid exchange between TAGs or fatty acids and glycerol by the sn-1,3-specific lipases to allow regio- and fatty acid-selective modifications to be affected at milder conditions. This process is particularly applicable in synthesis of structured lipids such as human milk fat substitutes and the medium-long-medium (MLM) lipids as the enzymes can retain the essential fatty acids in sn-2 position. In terms of sn-2 fatty acid retention control, as (Zhang et al., 2021) discussed, enzymatic interesterification of palm stearin and palm olein provided a superior degree of control as compared to chemical reactions. Similarly, (Ai et al., 2023) demonstrated that, enzymatic interesterification of palm olein in a packed-bed reactor had effects on physical properties, crystal polymorphism, and texture, and decreased acyl migration. Another study by (Utama et al., 2019) also talked about enzymatic methods of preparing MLM-structured lipids and emphasized the nutritional and functional benefits of the enzymatic process.

2.3 Genetic and Biotechnological Approaches

Genetic engineering and biotechnological solutions aim to modify the fatty acids biosynthetic pathways of oil crops or microbes to produce oils with a fatty acid composition containing fewer downstream modulations. Gene editing and metabolic engineering allows the researcher to reduce or elevate the activity of desaturase or acyltransferase to enrich or position the quantity or position of specific fatty acids in TAGs. Recent research revealed that expression of the maize ZmSAD1 gene was altered to regulate the content of stearic and oleic acids in the seeds, which provides a method to produce oils with high nutritional value (Du et al., 2016). Moreover, experiments on rapeseed seeds with induced mutations in seed fatty acid reducer (SFAR) genes were useful to increase the quantity and composition of fatty acids, and they show that biotechnology can directly influence the production and composition of lipids (Karunarathna et al., 2020).

Functional Properties of Structured Lipids

3.1 Melting point modification:

Lipids of a structured type can be designed with modified melting and crystallization characteristics by altering the length of fatty acid chains, their saturation, and the glycerol backbone.(Zhou et al., 2023) prepared the MLM-type structured lipids out of the algal oil and demonstrated that following the modification, the melting peaks were lower than physiological temperature, which can enhance digestibility and processing behavior. It was also discovered by (Holser, 2012) working with solid lipid particles that the combination of the saturated triglycerides and unsaturated ones (with the addition of the unsaturated esters at the sn-2 location) could reliably predictably reduce the melting points. Therefore, one important parameter to be tuned when developing SLs in a particular application is the melting point (e.g., spreads, mouth-melting fats, etc.).

3.2 Oxidative stability:

Both production method and composition, in particular, the presence of unsaturated fatty acids and depletion of endogenous antioxidants, influence the oxidative stability of structured lipids. The review by (Amarowicz, 2012) the effect of structure on oxidative stability of structured lipids indicated that higher oxidative stability is often associated with lower oxidative stability of the source oil, in part because natural antioxidants such as tocopherols are frequently degraded during SL synthesis, but that exogenous antioxidants added (e.g., 0-tocopherol, rival natural) could help counteract oxidation. More recently, research on omega-3-enriched structured lipids (built on PSO: pomegranate seed oil or the like) demonstrated that the addition of rosemary extract enhanced various oxidative indices (peroxide value, p-anisidine value, etc.) at accelerated storage, making SLs stability levels, again, comparable to that of blends (Kumari Singh et al., 2024).

3.3 Digestibility and bioavailability:

By positioning fatty acids (particularly essential or functional ones at sn-2) more favorably, using medium-chain fatty acids in sn-1,3, or modifying the supramolecular structure to allow lipid droplets or fat matrices to release fatty acids more effectively, the structured lipids can enhance digestibility and bioavailability. The lipid-reduced iodine value in an MLM structure had changed thermal behavior, which was correlated with enhanced fat metabolism in vivo and obesity protection in mice (Zhou et al., 2023). Also, an investigation of compound chocolate products with structured lipids discovered that they retarded the free fatty acids during in vitro digestion, decreased absorption (resulting in reduced caloric uptake), and better serum lipid profiles in mice. The other paper discusses the impact of the intramolecular structure and physical state of lipids on digestion and absorption (Michalski et al., 2013).

3.4 Sensory and textural impact on foods:

The structured lipids determine such properties as hardness, spreadability, mouthfeel, gloss, melting feel, and consumers' acceptance of them in foods. In the case of SLs as partial cocoa butter substitutes, (Savchina et al., 2025) found that interesterified blends had melting and solid fat content (SFC) curves and polymorphic forms such as cocoa butter, providing similar texture and melting properties. Moreover, in the compound chocolate SL study, not only were the digestion and bioavailability enhanced, but sensory tests revealed that products containing SLs had satisfactory mouthfeel, flavor, and general sensory scores, such as those of the control products (Ledesma et al., 2022). So, although SLs could provide health or functional benefits, it is essential to maintain or optimize sensory characteristics to be accepted by consumers.

Applications in the Food Industry:

Infant formula

Lipids in structured form are extensively used in infant nutrition to mimic the composition and stereospecific structure of human milk fat, which contains palmitic acid at the sn-2 position in addition to the essential long-chain polyunsaturated fatty acids (LC-PUFAs). The given structure enhances the uptake of palmitate and calcium and decreases the creation of insoluble fatty acid soaps, thereby benefiting healthy bone formation and gastrointestinal comfort. Research has already shown that the absorption of fat and calcium in infants was improved by the intake of sn-2 palmitate-enriched enriched enzymatically modified structured lipids compared to regular fat-containing formula based on vegetable oils (van Erp et al., 2019). Structured

triacylglycerols are also used in commercial products to provide these advantages in infant formulas.

Medical and functional foods

Structuredlipids that include medium-chain triglycerides (MCTs) or mixed medium-long-medium (MLM) structures are considered to have fast digestion and absorption properties, and apply to patients with fat malabsorption, cystic fibrosis, or metabolic disorders. They can also be studied to provide nutraceuticals, as MCTs can serve as carriers to enhance the bioavailability of lipophilic compounds like omega-3 fatty acids and phytosterols. As an instance, the incorporation of MLM structured lipids containing MCTs and essential fatty acids into mayonnaise, cookies, and yogurt drinks did not affect the sensory quality (More et al., 2020). It is also proposed through animal research that these lipids can regulate lipid metabolism and prevent risks associated with obesity, which also demonstrates their therapeutic potential (Yue et al., 2020).

Bakery and confectionery

Organized lipids in bakery and confectionery products provide a healthier alternative to the hydrogenated fats and partially hydrogenated fats by maintaining the required texture, plasticity, and spread ability and minimizing the quantity of trans fats and saturated fats. They will copy the melting properties and solid fat content (SFC) of the bakery shortenings and confectionery fat that have been used traditionally, and they possess good mouthfeel and processing properties. The experience survey on the structured oils in baking showed that they had a positive experience in baking biscuits, cakes, and bread, and that the oils were not only capable of reducing the saturated fats, but also that their use did not affect the quality of the products negatively (Yue et al., 2020). Confectionery Structured fats Structured fats have been investigated as analogs of cocoa butter, which have the same polymorphic structure and melting behavior to provide snap, gloss, and flavor release in chocolate (Savchina et al., 2025).

5. Nutritional and Health Aspects

5.1 Role of SLs in energy metabolism

Structured lipids (SLs) are created to optimize the digestion, absorption, and utilization of fats in the diet, and thus influence the total metabolism of energy. SLs have the potential to meet both short-term and long-term energy requirements by balancing medium-chain fatty acids (MCFAs), which can be hydrolyzed immediately and directly transmitted to the liver to obtain immediate energy, with long-chain fatty acids (LCFAs), which also provide essential fatty acids and sustained energy (Utama et al., 2019). The benefit of MLM-type lipids is that the MCFAs in sn-1,3 is easily metabolized, and the LCFAs in sn-2 are absorbed and transported into tissues easily. It has been established that lipids arranged in MLM exhibited superior fat absorption, nitrogen equilibrium as well as superior in energy consumption in clinical nutrition when compared to their counterparts constructed of conventional fats (Guo et al., 2020).

5.2 Use in weight management, diabetes, cardiovascular health

Besides energy provision, SLs also have a brilliant future in the provision of chronic diseases such as obesity, diabetes and cardiovascular diseases. The MLM lipids contain fewer calories than the ordinary fats because of their special structure though they increase the degree of satiety and regulation and hence help in weight management. Consumption of SL in diabetic models has been associated with reduced blood glucose, enhanced lipid levels, and augmented antioxidant conditions, as well as it is thought to assist in the regulation of insulin sensitivity and oxidative stress (Yue et al., 2020). It has also been reported to have cardiovascular benefits, such as fewer atherosclerotic lesions, fewer inflammatory markers (e.g., VCAM-1, MCP-1), and better modulation of gut microbiota when MLM structured lipids were used instead of conventional fats in high-fat diets (PubMed). These results suggest that SLs are useful lipids that can be used to treat metabolic syndrome and other related diseases (Lopes et al., 2023).

5.3 Potential risks or limitations

Structured lipids, as well as being beneficial, have their threats and drawbacks, though. Oxidative stability is one of the primary issues, as polyunsaturated fatty acids (PUFAs) enrichment increases SLs vulnerability to lipid peroxidation, which would ultimately shorten shelf life and produce harmful oxidation products unless antioxidants have been added to stabilize the product (Amarowicz, 2012). Another issue is the cost of production and scalability because enzymatic

treatments are more costly and require special technology than other fat-modifying techniques. Also, although SLs are safe, the long-term outcomes of the new structures on lipid metabolism and cardiovascular health in high-risk groups, including infants and elderly people, are to be verified further in clinical practice. The reviews note that it is crucial to optimize the production processes, antioxidant fortification, and human testing thoroughly before it can be applicable across all food industries (Nagachinta & Akoh, 2013).

6. Advances in Research and Emerging Trends

6.1 Lipase engineering and immobilization techniques

New protein engineering technologies, directed evolution, and site-specific mutagenesis have produced lipases with enhanced thermostability, changed substrate selectivity, and enhanced positional selectivity to make structured lipids. Parallel immobilization approaches, like covalent anchoring on polymer support, adsorption on nanomaterials, and enzyme encapsulation in sol–gel networks, are increasing the lifespan, reusability, and biocompatibility of the enzymes with continuous reactors, enabling enzymatic interesterification to be more economical (Zhou et al., 2022).

6.2 Sustainable production (green chemistry, renewable raw materials)

Sustainability is a concept that has attracted research studies, and solvent-free reactions, supercritical carbon dioxide processing, and enzymatic catalysis have replaced severe chemical reactions. These approaches not only lead to a reduced environmental impact but also allow the valorization of renewable feedstocks, such as algal oils, waste cooking oils, or seed by-products, which can assist in supporting a circular bioeconomy. Scientists underline that the carbon footprint of organized lipid production can also be reduced with the assistance of the implementation of one of the concepts of green chemistry and renewable substrates, without the loss of functionality (Guo et al., 2020).

6.3 Precision nutrition and personalized lipid design

Precision design of structured lipids according to age, genetics, and health status is possible through the integration of lipidomics, nutrigenomics, and big data. E.g., infants needing sn-2 palmitate-enriched customized triacylglycerols, or MCT-PUFA hybrids in patients with metabolic disorders, are examples of how lipids can be tailored to a particular nutritional or therapeutic requirement. There are new technologies, including machine learning-based lipid-gene interaction models, which are likely to boost the creation of personalized lipid products soon (Lopes et al., 2023).

7. Challenges and Future Perspectives

7.1 Cost and scalability

Even though the enzymatic interesterification process is very specific and environmentally friendly, the high prices of immobilized lipases, short working life, and the requirement of special bioreactor systems limit its large-scale application. The chemical methods are still cheaper, but not selective, and produce undesired by-products. To bridge this gap in economics, studies of reusable biocatalysts and continuous operations, as well as low-cost supports, are underway (Zhou et al., 2022).

7.2 Consumer acceptance and labeling issues

Consumer perception becomes critical even if technological hurdles are overcome. There will be misgivings over products that are advertised as modified fats or engineered lipids. Consumer trust must be gained through transparent labeling, proper acquisition of health benefits, and regulatory sanctions against health claims to succeed in the market. According to acceptance studies, presentation of SLs as either being functional or human-milk-fat-mimicking enhances acceptance, particularly in the infant and medical nutrition category (Zam, 2015).

7.3 Regulatory frameworks for SLs in different countries

Structured lipids regulatory control is sporadic. Strategized lipids in the EU need to, in many instances, undergo EFSA novel food rules, whereas in the US, they can be evaluated under GRAS notifications. In Asia, especially in China and Japan, infant formula SLs are more mature, but extensive clinical validation is required for the medical or nutraceutical applications. The harmonization of the global systems would also eliminate delays in approvals and international trade on SL-based products (Osborn & Akoh, 2002).

7.4 Future potential in functional foods and pharmaceuticals

In the future, structured lipids will have greater use in functional foods and pharmaceuticals, with infant formulas and clinical nutrition being only a part of it. They can be made into healthier fat options in bakery and confectionery due to their potential to control their melting, oxidative stability, and digestibility, and their potential use in pharmaceuticals due to their bioactive delivery property. Structured lipids are also underway to being used to encapsulate vitamins, polyphenols, and even drugs in nano-emulsions and lipid nanoparticles, providing controlled release and improved bioavailability (Osborn & Akoh, 2002). This bi-purpose application, as both food ingredients and biomedical carriers, serves to highlight their versatility in the next few decades (McClements & Grossmann, 2021).

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