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EXPLORING STRUCTURED FATS, MICROENCAPSULATED OILS, AND FUNCTIONAL OILS: ADVANCING SUSTAINABLE INNOVATIONS IN FOOD PRODUCT: A REVIEW

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Abstract

In the context of increasingly stringent consumer demands for quality, sustainability, and nutritional benefits of food, dietary fats and oils have become a major area of interest for research and innovation. This review explores three directions in their utilization in food implementation. ***The structured fats*** *represent an emerging category of lipids obtained through chemical or enzymatic modifications, providing customized functionalities. Often used in bakery products, spreads, and processed foods to replace trans fats, to reduce caloric content, and to improve the nutritional profile, contributing to development of healthier and more sustainable food products.* ***The microencapsulated oils*** *might have significant benefits in food preservation by protecting active compounds from oxidation and degradation while ensuring controlled release of bioactive compounds. Such technologies are successfully applied in dairy products, processed meat, and baked goods, extending shelf life and improving food safety. Additionally,* ***functional oils****, fortified with natural antioxidants or vitamins, have become a cornerstone of the functional food industry. They contribute to reducing the risk of chronic diseases and improving overall health, being used in products such as margarines, cooking oils, and nutritional formulas. This review highlights the potential of structured fats, microencapsulated oils, and functional oils in optimizing novel food products, while emphasizing the need for further research to integrate in sustainable and efficient strategies.*

Key words*: antioxidant fortification, food preservation, functional oils, microencapsulation, structured fats.*

INTRODUCTION

The growing global demand for safe, nutritious, and sustainable food has accelerated the need for innovative lipid technologies capable of simultaneously addressing health, functionality, and environmental concerns. Fats and oils are important to the industry, not only as a source of energy and essential fatty acids, but also as key determinants of texture, flavour, stability, and overall sensory perception. Traditionally, animal-derived fats and partially hydrogenated vegetable oils have been widely used to achieve desired textural and structural properties in food products. However, conventional sources of lipids are increasingly challenged by nutritional concerns, particularly their association with high levels of saturated fats and trans fatty acids, both of which are linked to cardiovascular disease and other metabolic disorders. Simultaneously, environmental sustainability and consumer demand for plant-based, health-promoting alternatives have driven a paradigm shift toward the development of next-generation lipid ingredients. In this context, structured fats, microencapsulated oils, and functional oils have emerged as promising approaches that can reconcile technological functionality with nutritional and sustainability goals.

The aim of the current paper is to highlight the potential of structured fats, microencapsulated oils, and functional oils in optimizing novel food products, while emphasizing the need for further research to integrate in sustainable and efficient strategies.

MATERIALS AND METHODS

The systematic review methodology was applied using accessible scientific databases, including Google Scholar, Science Direct, Web of Science, Scopus, Springer Link, and MDPI. The identification process involved filtering based on keywords, publication year, and article type.

RESULTS AND DISCUSSIONS

1. Structured fats

Structured fats importance in the modern food industry strongly connected to their ability to improve product quality while ensuring safety and health requirements (Silva Lannes et al.,2013). The structured fats (Figure 1) have specific physicochemical properties, including controlled melting behaviour, improved oxide-tive stability, and customized crystallization patterns. From a nutritional standpoint, structured fats aim to reduce trans fats, lower saturated fat content, and incorporate functional fatty acids such as omega-3. The continuous development of sustainable technologies and adaptation to nutritional requirements contribute to their integration into a wide range of food products (Silva et al., 2013).

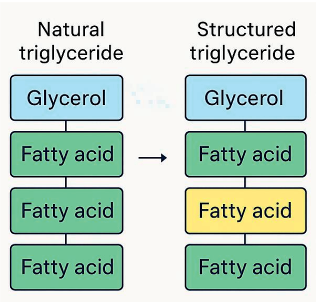

Figure 1. Structured fats (original)

1.1. Processing

The extraction of edible lipids from plant and animal sources has a long historical tradition. In the case of vegetable oils, the predominant raw materials are oilseeds from annual crops grown in temperate regions. These seeds are processed by mechanical pressing (screw press or expeller), a combination of pressing and solvent extraction, or by solvent extraction and expander techniques. Another important source of vegetable oils is oilseeds and oleaginous fruits, from which lipids are obtained either by direct pressing sometimes after preliminary treatments such as drying or sterilization or by cold pressing to better preserve the sensory properties. Animal fats, on the other hand, are generally recovered through wet or dry melting processes, which yield products such as lard (pigs), tallow (cattle and sheep), and milk fat or butter (cows). Once obtained, both animal and vegetable fats are usually subjected to refining steps, which can be chemical using alkaline solutions to remove impurities or physical, most often through distillation (O'Brien, 2024).

1.1.1. Industrialization

The search for alternatives to natural butter began during the Industrial Revolution, initially in France. At that time, socio-economic pressures - including rural depopulation, economic crisis, and the threat of war with Prussia - caused a sharp rise in butter prices, as demand exceeded the available supply of milk. In 1869, at the request of Emperor Napoleon III, chemist Hippolyte Mège-Mouriès succeeded in producing the first commercial substitute for butter, which he called "margarine." Shortly thereafter, numerous modifications and patents based on his process appeared (Gotra et al., 2002). Until the end of the 19th century, animal fats were the main source of solid fats used in the manufacture of margarine, although this also created competition with the soap industry, which relied on the same raw materials (Meijaard et al., 2022). With technological advances, new modification methods have been adopted, the most important being hydrogenation, interesterification (by chemical or enzymatic means), and fractionation. The processes are designed to adjust the physicochemical characteristics of fats and oils: hydrogenation reduces the degree of unsaturation, interesterification redistributes fatty acid chains between triacylglycerols, while fractionation physically separates lipid fractions through selective crystallization and filtration (Kellens et al., 2007).

1.1.2. Hydrogenation

The technological basis for the hydrogenation of edible oils was laid at the beginning of the 20th century, starting with Paul Sabatier's catalytic studies and culminating in Wilhelm Normann's patent in 1903. From a chemical point of view, hydrogenation involves the conversion of double bonds in unsaturated fatty acids into single bonds, achieved by reacting the oil with hydrogen in the presence of a metal catalyst - traditionally nickel, which is still commonly used today. Depending on the extent of the reaction, the result can be fully saturated fats or partially hydrogenated products. However, during this process, double bonds can undergo geometric (cis-trans) or positional isomerization. This is of great importance because cis double bonds introduce bends in the fatty acid chains, lowering their melting points, while trans configurations produce nearly linear molecules with melting behaviors similar to those of saturated fatty acids (Tarrago-Trani et al., 2006). The industrial application of hydrogenation aims either to produce fats with a specific consistency (plastic or hard) or to improve oxidative stability. The properties of the final products are determined by the base oil, the type and concentration of the catalyst, the availability of hydrogen, and the process parameters. It should be noted that nickel catalysts can also promote side reactions that lead to the formation of trans fatty acids, which can substantially influence the structural and thermal properties of the resulting fats (Zeng et al., 2024).

1.1.3. Interesterification

As concerns about trans fatty acids have grown, interesterification has emerged as a valuable alternative to hydrogenation. This process does not change the overall composition of fatty acids, but redistributes fatty acids within and between triacylglycerol molecules, either randomly or in a controlled manner (Singh et al., 2022). The reaction can be carried out chemically or with enzymatic catalysts, and the result is fats with modified melting characteristics and textural properties suitable for spreads and other food applications. It is important to note that this method allows the production of soft, spreadable fat products without trans fatty acids. Although widely used today, the scientific basis for interesterification was first described as early as 1969 (Sivakanthan et al., 2020).

1.1.4. Fractionation

Fractionation is a reversible physical modification technique used to separate complex lipid mixtures into fractions with distinct physicochemical properties. The principle of separation is based on differences in melting behavior, solubility or volatility between lipid components and is implemented by methods such as fractional crystallization, fractional or short path distillation, supercritical extraction, adsorption, membrane separation or solvent-based techniques. In the context of fats and oils, fractional crystallization is the most relevant because it exploits the variable solubilities of triacylglycerols depending on their molecular structure and degree of unsaturation (Razam et al., 2013). At the industrial level, three main technologies are used: detergent fractionation, solvent fractionation, and dry fractionation, each of which allows the selective isolation of lipid fractions with specific functional or nutritional properties (Kellens et al., 2007).

1.2. Advantages of structured fats

Structured fats have several notable advantages that make them attractive for applications in various industries. From a technological standpoint, they exhibit superior physicochemical properties, including optimized melting behavior, desired viscosity, and improved oxidative stability.

These modifications enable the production of lipid systems with improved functional performance in food and non-food applications. From a nutritional standpoint, structured lipids can be designed to incorporate health-promoting fatty acids, such as medium-chain fatty acids and polyunsaturated fatty acids (PUFAs), thereby contributing to improved dietary profiles (Lopes et al., 2023). The inclusion of the fatty acids has been associated with a reduced risk of cardiovascular disease and beneficial effects on energy metabolism. In addition, structured fats can be engineered to achieve customized functionalities, including improved emulsification, solubility, and bioavailability of bioactive compounds. The properties extend their applicability across multiple sectors, from food and nutraceuticals to pharmaceuticals and cosmetics.

1.3. Applications of structured fats

In pastries and baked goods, structured fats contribute to crispness, aeration, and extended shelf life, improving dough consistency and reducing the need for hydrogenated fats (de la Horra et al., 2017).

Structured fats might support the desired consistency and stability in margarine and butter alternatives (Ghotra et al., 2002), providing a creamy texture while maintaining a balance between saturated and unsaturated fats (Munialo et al., 2023).
Processed foods, such as confectionery, dairy analogues, and plant-based meat, benefit from structured fats to maintain stability, prevent oil separation, and improve texture and taste.

2. Microencapsulated oils

Microencapsulation (Figure 2) is a technique that involves embedding tiny droplets of fats or oils (active material) in a protective layer or matrix, with the aim of preventing the production of chemical reactions that can modify the physicochemical and biological properties of the active material.
This process is widely applied in food (Yan et al., 2022), nutraceuticals, and pharmaceuticals to deliver essential fatty acids (like omega-3 and omega-6), protect sensitive oils from degradation, and mask undesirable tastes or odors (like fish oil).
Microencapsulation of dietary fats and oils aims to improve the stability, shelf life, and functionality of the encapsulated fats and oils by preventing oxidation, controlling their release, and enhancing their solubility in food and pharmaceutical applications (Zhang et al., 2022; Pogurschi et al., 2023).

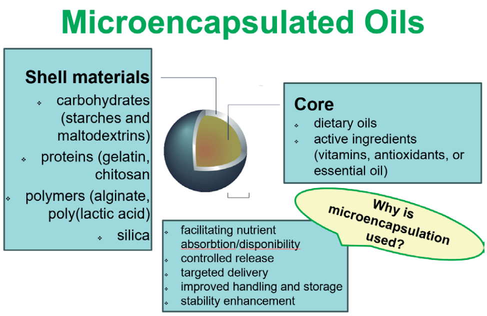

Figure 2. Microencapsulation of vegetable oil (original)

Oxidative degradation of oils is favored both by the action of oxygen in the air and light, and by the thermal stress applied to them (Mircea et al, 2023), causing changes in organoleptic characteristics (unpleasant taste and smell), as well as the formation of free radicals with harmful effects on the body (Alcântara et al., 2019).
In food area, the methods used to create these microcapsules are classified into physical methods (spray-drying, freeze-drying) and physicochemical (complex coacervation, ionic gelation) (Table 1). Both the active material and the encapsulation matrix must be taken into account when choosing the encapsulation method, as well as the final use of the product (Carvalho da Silva et al., 2022).

2.1. Methods of microencapsulation

2.1.1. Spray-drying

One of the most effective methods to improve their stability and facilitate their incorporation into various products is spray drying. This technique enables the transformation of liquid oils into free-flowing powders, enhancing shelf-life, handling, and solubility in aqueous systems.
Moreover, spray-drying contributes to the protection of sensitive lipophilic compounds such as polyunsaturated fatty acids (PUFAs), vitamins, and antioxidants, by forming a physical barrier that limits exposure to oxygen, light, and heat (Piñón-Balderrama et al., 2020).
Spray-drying is a process that includes several stages. In the first of them, the vegetable oil is emulsified with wall materials (maltodextrin, whey protein, gum arabic) to create a stable oil-in-water emulsion (Nosari et al., 2015).
This emulsification step is critical, as the droplet size distribution and interfacial stability directly affect the encapsulation efficiency and final powder quality. After that, the emulsion is sprayed into a drying chamber through a nozzle or rotary atomizer (the atomization stage).
Afterwards, the drying stage takes place, when hot air evaporates the water content, leaving behind micro-encapsulated oil particles. Finally, the dried powder is separated and collected using cyclones or bag filters (Gil-Chávez et al., 2020). The drying air temperature typically ranges between 150–200°C at the inlet and 70-90°C at the outlet, depending on the thermal sensitivity of the core and wall materials.
The characteristics that define both particles (size, physicochemical properties, stability) and

the process (encapsulation efficiency and yield) are dependent on the physical properties of emulsions and atomization parameters (inlet/outlet temperature, feeding flow, atomizer gas flow, atomizer gas type and nozzle size) (Silva et al., 2014).

Table 1. Methods, core substances, encapsulating matrices and applications for microencapsulated vegetable oils (Carvalho da Silva et al., 2022)

Method	Vegetable oil	Encapsulating matrix	Application	Reference
Spray-drying	Linseed oil	Different combinations of maltodextrin, gum arabic, whey protein and methyl cellulose	Food (bread)	Gallardo et al., 2013
	Linseed oil	Modified starch	Food	Barroso et al., 2014
	Green coffee oil	Different combinations of modified starch, gum arabic and maltodextrin	Food	Silva et al., 2014
	Cress seed oil	Whey protein	Food (biscuit)	Umesha et al., 2015
Freeze-drying	Olive oil	Different combinations of maltodextrin, carboxymethylcellulose and lecithin	Food	Calvo et al., 2012a
	Walnut oil	Different combinations of sodium caseinate, maltodextrin, lecithin and carboxymethylcellulose	Food	Calvo et al., 2012b
Complex coacervation	Corn oil	Xylitol and gelatin	Suggested application in food	Santos et al., 2015
	Palm oil	Chitosan/xanthan and chitosan/pectin	Food (yogurt and bread)	Rutz et al., 2017
	Pomegranate seed oil	Whey protein/gum arabic	Food	Costa et al., 2020
	Green coffee oil	Cashew gum/gelatin	Food (juice)	Oliveira et al., 2020
Ionic gelation	Chia oil	Sodium alginate and calcium chloride	Food (hamburger)	Heck et al., 2018 Heck et al., 2019

In addition, parameters such as emulsion viscosity, interfacial tension, and wall-to-core ratio play a major role in determining the morphology and stability of the final microcapsules. Different types of oil-in-water (o/w) emulsions, either monolayer or multilayer, have been used to encapsulate oils (Alcântara et al., 2019).

Multilayer emulsions, stabilized with bio-polymer complexes (chitosan-alginate, protein-polysaccharide systems), are particularly effective in improving oxidative resistance due to their denser interfacial layer.

Numerous and varied vegetable protein oils have been encapsulated by spray-drying (Santos et al., 2018) in different concentrations, such as avocado oil in a whey and maltodextrin matrix (Bae et al., 2008), chia oil with different wall materials (González et al., 2016a; Alcântara et al., 2019), flax oil in a hydrolyzed rice protein matrix (Gomes et al., 2020). The aforementioned studies evaluated oxidative stability, reporting a considerable improvement, primarily determined by the antioxidant capacity of the wall material used (Sundar et al., 2023).

Furthermore, the encapsulated oils demonstrated enhanced protection against lipid peroxidation over prolonged storage, suggesting that the microencapsulation technique not only delays oxidative degradation but also preserves the functional properties of the oils (Aniesrani et al., 2015). These findings support the feasibility of integrating microencapsulated oils into functional foods, nutraceuticals, and pharmaceutical formulations, with improved stability and controlled release properties.

2.1.2. Freeze-drying

Another common method in micro-encapsulation is freeze-drying, also known as lyophilization. It is carried out in several stages (Assegehegn et al., 2019) and consists of lowering the temperature of the material below its freezing point, simultaneously with the removal of the resulting water by sublimation at pressures below the triple point of water (Feng et al., 2020). In the first phase, the base material is mixed with the wall material. For lipophilic cores, emulsification ensures adequate dispersion. Subsequently, the mixture is frozen at low temperature (–40 to –80°C), with the formation of ice crystals, which represents the solidification stage.

Primary drying is the stage in which ice sublimation occurs and which starts from the upper surface of the sample and continues downwards. The slower the freezing, the larger the ice crystals formed and the easier the movement of water vapor, so that the drying time is shorter (Ishwarya et al., 2015). Also, an appropriate pressure value decreases the duration of the primary drying process. In the third stage, secondary drying (desorption) takes place, in which the bound water (residual moisture) is removed by slightly increasing the temperature. The pressure can be kept constant or can have lower values than in the drying stage. Finally, the former microcapsules are collected, often as a powder, and stored in a moisture-barrier containers to maintain their stability.

Microparticles that have been obtained by freeze-drying exhibit increased resistance both to thermal and oxidative degradation and satisfactory encapsulation efficiency (Malacrida et al., 2015; González et al., 2016b). Studies on samples obtained by lyophilization of pumpkin seed oil using whey protein, maltodextrin and gum arabic as wall material showed that this system can be used as a carrier of bioactive compounds, due to the stability of the emulsion, the carotenoid content and the good oxidative stability (Özbek et al., 2020). Favorable results were also obtained by microencapsulation of chia oil (Souza et al., 2017), differential scanning calorimetry showing that such particles are suitable for the formulation of long-life food products or in thermally processed products (bakery products).

Another example of lyophilization used in the food industry is the microencapsulation of Sichuan pepper essential oil for incorporation into sausages, in which soy protein isolate and hydroxypropyl-α-cyclodextrin were used as wall materials (Meng et al., 2022). The results obtained from the measurement of the oxidative capacity were comparable to those of samples in which antioxidants were added, which led to the conclusion that lipid oxidation was inhibited due to the encapsulated oil.

2.1.3. Complex coacervation

Coacervation is a complex physico-chemical process driven by several types of molecular interactions that collectively promote the separation of a polymer-rich phase (the coacervate) from a dilute aqueous phase (Napiórkowska et al., 2022) In the case of **complex coacervation**, the most significant driving force is the **electrostatic interaction** between oppositely charged biopolymers. For instance, a positively charged protein such as gelatin can interact with a negatively charged polysaccharide like gum arabic. When these polymers are mixed under conditions where their charges are balanced—typically near the isoelectric point—they form associative complexes that phase-separate from the solution, leading to coacervate formation.

In addition to electrostatic forces, **hydrophobic interactions** also play a key role (Timilsena et al., 2017). These occur when non-polar regions of polymers, which are poorly soluble in water, aggregate to minimize contact with the aqueous environment. Such interactions contribute significantly to the compaction and stabilization of the coacervate droplets. Another important factor is **hydrogen bonding**, which involves non-covalent interactions between hydrogen atoms bonded to electronegative atoms (like oxygen or nitrogen) and other electronegative atoms. These bonds form between specific functional groups on polymer chains, enhancing internal cohesion within the coacervate structure.

The actual process of coacervation generally unfolds in three main stages. First, the selected biopolymers are dissolved and mixed in an aqueous medium. The polymers must be capable of mutual interaction - either through charge-based attraction, hydrogen bonding, or hydrophobic forces - and must be added in appropriate ratios to favor coacervate formation. Following this, phase separation is induced by precisely controlling environmental conditions such as pH, ionic strength, and temperature (Timilsena et al., 2019**.** The pH influences the ionization of the polymers, directly affecting their charge profiles and compatibility. Ionic strength, typically adjusted via salt concentration, can screen or neutralize charges and thereby modulate electrostatic interactions. Temperature affects both polymer solubility and the kinetics of interaction, and must be carefully regulated to ensure efficient coacervation (Ma et al., 2019).

Once phase separation begins, a dense polymer-rich phase emerges as small coacervate droplets suspended in the continuous phase. The droplets may undergo **coalescence**, where smaller droplets merge into larger ones. To stabilize these structures and prevent them from fusing uncontrollably or breaking apart, the system may be subjected to **hardening treatments** such as cooling, pH adjustment, or chemical cross-linking. These measures help to preserve the integrity and functionality of the coacervate, particularly when it is used for encapsulation in food, pharmaceutical, or cosmetic applications.

2.1.4. Ionic gelation

Ionic gelation is a widely used technique in the encapsulation of bioactive compounds, particularly in the pharmaceutical and food industries. It is based on the ability of certain natural polyelectrolytes, such as alginate, pectin, chitosan, or carrageenan, to gel in the presence of multivalent counter-ions (Fernando et al., 2020). This gelation process occurs under mild conditions, without the need for high temperatures or toxic solvents, making it especially suitable for the encapsulation of thermally sensitive compounds such as vitamins, enzymes, essential oils, or probiotic microorganisms.

The underlying mechanism involves the cross-linking of negatively or positively charged polymer chains through the addition of ions with opposite charges. A classic example is the gelation of sodium alginate, an anionic polysaccharide derived from brown algae, in the presence of calcium ions (Ca^{2+}). The guluronic acid residues within the alginate chains contain carboxyl groups that readily bind with divalent calcium ions. This interaction promotes the formation of an "egg-box" structure, a three-dimensional network where calcium bridges form between adjacent polymer strands, leading to rapid gel formation.

The ionic gelation process typically begins with the preparation of an aqueous polymer solution, into which the active compound (such as a drug or oil) is dispersed or dissolved. This mixture is then introduced into a solution containing the cross-linking ions, either by droplet addition, extrusion, or emulsion techniques. As soon as the two solutions come into contact, gelation occurs spontaneously at the interface due to electrostatic interactions, resulting in the formation of gel beads, capsules, or films, depending on the method used (Kurozawa et al., 2017).

The properties of the resulting hydrogel matrix - including porosity, mechanical strength, and release behavior - can be finely tuned by modifying variables such as the polymer concentration, type and concentration of cross-linking ion, pH of the medium, and gelation time. For instance, increasing calcium concentration generally leads to stronger and more compact gels, which can enhance encapsulation efficiency but may slow down the release rate of the encapsulated compound.

Ionic gelation is particularly advantageous for designing controlled-release delivery systems in functional foods and nutraceuticals, where the bioactive compound must be protected during gastrointestinal transit and released at the appropriate site (Menin et al., 2018). Ionic gelation was used to microencapsulate rosemary-enriched chia oil, which was intended to replace 50% of the fat in hamburgers (Heck et al., 2018). Hamburgers produced with rosemary-enriched chia oil microparticles exhibited greater oxidative stability, especially after cooking. In addition, the incorporation of rosemary antioxidants into chia oil reduced sensory defects caused by lipid oxidation. In addition to previous studies, the volatile compounds and sensory properties of frozen hamburgers during storage were evaluated, which resulted in a decrease in volatile lipid and protein oxidation compounds and an increase in terpenes at the beginning (day 1) and end of storage (day 120), before and after cooking (Heck et al., 2019).

2.2. Wall materials for microencapsulation

The choice of wall material plays a primary role in protecting the encapsulated oil from oxidation and environmental factors.

Common materials used for micro-encapsulation include proteins (whey, casein), carbohydrates (maltodextrin, starches), and lipids (Akram et al., 2021).

2.3. Advantages of Microencapsulation of Dietary Fats and Oils

Microencapsulation of dietary fats and oils offers numerous advantages that contribute to improved stability, functionality, and application versatility (Bakry et al., 2016). One of the primary benefits is enhanced oxidative stability, as the encapsulating materials form a protective barrier that shields fats and oils from oxygen, thereby preventing rancidity and extending shelf life. Additionally, microencapsulation facilitates controlled release, allowing for the gradual or targeted delivery of lipids in both food and pharmaceutical formulations. Certain encapsulation techniques also improve the solubility and dispersibility of otherwise hydrophobic oils, enabling their easier incorporation into aqueous food and beverage systems.

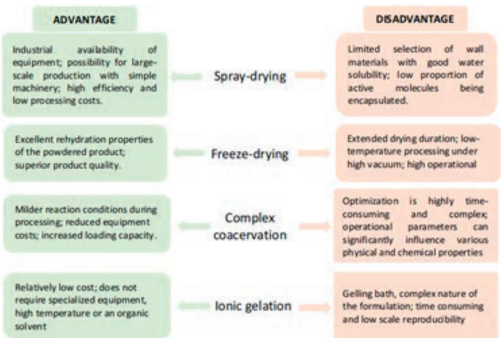

Figure 3. Advantages and disadvantages of the most used methods for microencapsulation of vegetable oil (original)

Moreover, the technique effectively masks unpleasant odours and flavours - such as the strong aroma of fish oil rich in omega-3 fatty acids - thus improving the sensory qualities of the final product (de Souza et al., 2020). Encapsulation further protects dietary oils from environmental stressors such as heat, light, and moisture, as well as from reactive interactions with other ingredients, preserving their quality and nutritional value (Pattnaik et al., 2023; Mircea et al., 2024).

Importantly, microencapsulation has been shown to enhance the bioavailability of essential fatty acids and fat-soluble vitamins, improving their absorption in the human body.

Lastly, the conversion of encapsulated oils into powder form simplifies their handling, facilitates their inclusion in dry formulations, and allows for convenient packaging in capsules or sachets.

2.4. Applications of Microencapsulation of Dietary Fats and Oils

Dietary fats and oils microencapsulated has diverse applications across several industries, notably in the food, pharmaceutical, animal feed, cosmetic, and packaging sectors (Choudhury et al., 2021).

In the food industry, encapsulated oils are widely employed in functional foods and beverages to fortify products with essential fatty acids such as omega-3 and omega-6, without compromising taste or texture (Fernandes et al., 2024). In dairy and bakery products, including yogurt (Rajam et al., 2015; de Moura et al., 2019), cheese, and baked goods, microencapsulation enhances nutritional value while maintaining oxidative stability (Karimi et al., 2020). In infant formulas, it ensures the delivery of essential fatty acids like DHA and ARA while minimizing oxidation (Mehta et al., 2022).

In the pharmaceutical and nutraceutical industries, microencapsulation is utilized in dietary supplements to produce stable, odor-free omega-3 capsules and in drug delivery systems to control the release of fat-soluble vitamins such as A, D, E, and K.

In animal feed, encapsulation maintains the stability and bioavailability of essential fatty acids and nutrients, ensuring optimal nutritional delivery.

3. Functional oils

Functional oils are edible lipids that have been modified or naturally contain high levels of bioactive components (antioxidants, vitamins, essential fatty acids) to provide health benefits beyond basic nutrition. These include oils naturally rich in polyphenols (extra virgin olive oil), oils enriched through fortification or microencapsulation (fish oil enriched with omega-3 polyunsaturated fatty acids), and oils infused with vitamins or antioxidant compounds. Types can be classified according to the bioactive substances involved (polyphenols, tocopherols, carotenoids, sterols), the oil matrix (vegetable vs. marine oils), and the delivery format (liquid oils, butters, encapsulated forms). Recent analyses highlight encapsulation carriers such as polysaccharides, proteins, alginates, and hybrid matrices (Kumar et al., 2024; Yehmed et al., 2023).

3.1. Fortification and enrichment process

Fortification or enrichment of oils can be achieved through physical, chemical, or biotechnological methods. Physical methods include micro- or nanoencapsulation, adsorption on porous supports, emulsification, or mixing oils with natural extracts rich in bioactive substances. Chemical methods may involve esterification or conjugation, although these are less common in food applications due to regulatory and safety constraints. The enrichment process aims to increase both the bioactive stability and bioavailability of the oil. For example, microencapsulation techniques such as spray drying or nanostructured lipid carriers can retain over 90% of PUFA content during storage (Perez-Palacios et al., 2022). Another example is the adsorption of fish oil with vitamin D3 on mesoporous silicon to stabilize both components (Ciriminna et al., 2021). Furthermore, the addition of tocopherols, phenolic acids, or β-carotene improves the oxidative stability of mixed oils (Wang et al., 2024).

3.2. Advantages of functional oils

Functional oils, enriched with bioactive substances such as ω-3/ω-6 polyunsaturated fatty acids (PUFAs), tocopherols, carotenoids, sterols, and phenolic compounds, offer physiological, nutritional, technological, and public health benefits.

A key advantage is their role in cardiovascular protection, as enrichment with unsaturated fatty acids, sterols, or tocotrienols lowers LDL cholesterol, improves the lipid profile, and reduces inflammation (Patted et al., 2024; Kamisah et al., 2024). They also support metabolic regulation, as ω-3 polyunsaturated fatty acids improve insulin sensitivity, reduce triglycerides, and modulate lipid metabolism (Kumar et al., 2024).

Functional oils have antioxidant and anti-inflammatory effects, with phenolic compounds, carotenoids, and tocopherols improving antioxidant capacity and protecting against neurodegenerative disorders (Romano et al., 2022; Olivares-Tenorio et al., 2024). They also improve gut health and immune responses, as the bioactive substances in seed oils regulate microbial populations and strengthen the intestinal barrier (Gupta, 2022). Oils fortified with vitamins A and E also reduces micronutrient deficiencies (Hormenu et al., 2024).

From a technological standpoint, functional oils offer greater stability and bioavailability. Natural antioxidants improve oxidative stability (Wang et al., 2024; Stefanidis et al., 2023), while encapsulation preserves bioactive substances and improves their absorption (Perez-Palacios et al., 2022; Kumar et al., 2024).

At the population level, functional oils contribute to preventive nutrition by reducing the risk of noncommunicable diseases (Romano et al., 2022; Hormenu et al., 2024) and by addressing nutritional deficiencies in vulnerable groups (Kamisah et al., 2024; Gupta, 2022). They also align with consumer demand for natural and health-promoting foods (Kumar et al., 2024; Olivares-Tenorio et al., 2024).

3.3. Industrial Applications

Cooking oils enriched with functional compounds offer additional health benefits during culinary use. Palm oil enriched with plant sterols has been proposed for everyday cooking as a cholesterol-lowering strategy (Kamisah et al., 2024). Oils fortified with natural antioxidants also reduce degradation during frying (Kumar et al., 2024).

Margarines and butters are common delivery systems for functional oils. Clinical studies show that margarines enriched with α-linolenic acid, EPA, or DHA improve the fatty acid composition of erythrocytes (Egert et al., 2012). Antioxidant-enriched margarines also increase plasma antioxidant levels and reduce lipid oxidation (Jurek, 2022).

Functional oils are also used in dietary supplements and nutraceuticals for athletes, the elderly, and populations with low ω-3 intake. Encapsulated fish oil is widely used in supplements, with ongoing research focusing on masking the taste and improving shelf life (Perez-Palacios et al., 2022).

CONCLUSIONS

Structured fats, obtained through processes such as interesterification, fractionation, or oleo-gelification, enable the design of customized lipid systems with improved melting profiles, oxidative stability, and textural properties, while reducing the presence of harmful trans fats. These systems are particularly relevant for bakery, confectionery, and dairy analog products, where fat functionality strongly influences product quality. By manipulating the composition of triacylglycerol or incorporating biopolymers and natural structuring agents, researchers can generate fat systems that mimic the technological performance of traditional lipids while aligning with modern dietary recommendations. In parallel with the development of structured fats, microencapsulation technologies have attracted substantial attention in the delivery and stabilization of oils rich in polyunsaturated fatty acids (PUFAs), such as omega-3 and omega-6 fatty acids. Although these lipids are well recognized for their beneficial health effects, including cardiovascular protection and anti-inflammatory activity, they are also highly susceptible to oxidation, leading to rapid quality degradation and the formation of undesirable flavours. Microencapsulation offers an effective strategy to protect sensitive oils from oxidative deterioration, control their release in the gastrointestinal tract, and improve their incorporation into a wide range of food matrices. Techniques such as spray drying, complex coacervation, liposome formation, and nanoemulsion systems provide versatile platforms for stabilizing bioactive oils and extending their shelf life, thereby improving both the nutritional and functional quality of foods. Functional oils are another rapidly expanding field, encompassing not only natural oils with inherent bioactive properties, but also modified oils enriched with specific compounds such as phytosterols, carotenoids, tocopherols, and medium-chain triglycerides. These lipids contribute to health promotion through various mechanisms, including cholesterol-lowering effects, antioxidant activity, and improvements in energy metabolism. At the same time, they present opportunities for the development of functional foods that align with consumer trends emphasizing personalized nutrition, wellness, and disease prevention.

Beyond their physiological benefits, functional oils can also be applied to improve product stability, modify sensory attributes, and replace less desirable lipid fractions in processed foods. The convergence of these innovations - structured fats, microencapsulated oils, and functional oils - illustrates a broader movement toward sustainable optimization in food product design.

In this context, sustainability extends beyond environmental considerations to encompass nutritional sustainability, consumer acceptance, and industrial feasibility. By developing lipid systems that are healthier, more stable, and better suited to contemporary processing technologies, the food industry can simultaneously address public health challenges, respond to consumer demands for clean-label and plant-based products, and reduce dependence on unsustainable lipid sources. In addition, the integration of new lipid technologies supports circular bio economy strategies by enabling the valorization of underutilized raw materials, such as agricultural by-products or food processing residues, into high-value lipid ingredients. Despite these advances, challenges remain in terms of increasing production, ensuring profitability, and maintaining product quality and sensory performance in various food systems Aspects such as regulatory approval, consumer perception, and optimization of technological parameters must be carefully considered.

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