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Beyond Saturated Fat: A Comprehensive Review of Oleogels as Sustainable Alternatives in Food Systems

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ABSTRACT

Oleogels are a type of organogel that serves as an example of what can be done to provide a healthier way to create food products from solid or semi-solid fats that are either trans fat or saturated. Oleogels have unique properties and characteristics that allow for sensory attributes and textures found in baked goods, processed meats, cheeses, as well as candy products, while improving the nutritional value of these items. With oleogel the ability to create healthy food products will increase, contributing to better health overall by providing healthier food products in response to the current global health epidemic of obesity and related health problems. Research has shown that oleogels can substitute regular fats and still provide good taste and texture. Oleogels utilise plant-based gelators which reduce the amount of saturated fat while satisfying increasing demand for clean label and environmentally sustainable foods. Oleogels can also limit the amount of oil migration when used in creating food due to their ability to bind with oil, increasing the shelf life and stability of food products. While oleogels provide several advantages, there are challenges to be faced as they are introduced into the food industry, including oil stability, sensory acceptance and being able to produce at scale. There is the adverse effects of the mixed beliefs of different groups of consumers concerning the consumption of oleogels.

Keywords: gel; organogel; food; mechanisms; applications

1. INTRODUCTION

In the field of food science, oleogels represent a breakthrough in the creation of healthy, solid fat substitutes which retain the sensory properties that consumers expect. To create oleogels, a partially crystalline gel is formed that contains the oil in a solid form through the process of oleogelation. Various gelation agents may be used, such as natural waxes, fatty alcohols, or lecithin. The gelation agents are mixed with an edible oil (vegetable oil) and heated to break the molecular bonds between the gelation agent and the oil, then cooled to allow the gelation agent to crystallise. Once crystallised, the gelation agents create a 3D crystalline network, which forms the encapsulating structure that holds the oil in a gelled state and restricts the flow of the oil (allowing oleogels to mimic solid fat properties, despite being made from healthy, unsaturated liquid vegetable oils).

The reason for developing this technology is both global health issues and new government regulations. For example, WHO and European Union have imposed strict limits on the amount of trans fats and saturated fats can be eaten. This is because there are several studies shows they are related to chronic health problems like heart disease and Type 2 diabetes. this "bad" fats were necessary to make commercial food products like margarine, shortening, and processed baked goods because they provided structure, a creamy mouthfeel, and a good shelf life. If you take out the bad fats, the result is often a greasy product that does not look appetizing. Oleogels act as "fat mimetics," which means that food scientists can use oleogels to make food products that are low in saturated fats and do not have any trans fats, and, at the same time, have the same sensory experience that people expect from these types of products such as the "snap" when you bite into chocolate or the creamy texture when you spread.

Oleogels are becoming popoular as significant components in the expanding area of plant-derived substitute meats and vegan dairy products in addition to their role in conventional processed items. By replicating the fat marbling of meat products or the creaminess of heavy cream, plant-based food products are now being able to attain an "authentic" texture. The advantages of oleogels are, however, extend beyond the kitchen. Oleogels' ability to encapsulate substances, trap them within their three-dimensional structures and release them gradually over time has led to their increased adoption in the pharmaceutical and cosmetic industries. At present, oleogels are utilized for the encapsulation of bioactive ingredients so that medicinal applications benefit from controlled release, and for preventing the escape of oils in skin care formulations to ensure product integrity. Industrial applications of oleogels are also being investigated; businesses are exploring oleogels as potential ingredients in environmentally friendly lubricants, paint components, and biodegradable materials.

With ongoing developments in oleogel technology, we are moving towards cleaner product labels and more sustainable food creation than previously possible. Very little amounts of natural structuring agents (sometimes as low as 2% of a formulation) can optimize nutritional value & safety without excessive chemical manipulation or using unhealthy fats. If further progress occurs in this area, then oleogels will enhance the creation of a healthier global diet and show consumers how texture and heart health do not need to be mutually exclusive characteristics.

The purpose of this review is to summarize the different uses, major applications, physical/chemical properties, and advantages of oleogels. In addition, we will discuss the limitations that these semi-solid materials face when applied to food products and outline the trends that the future of oleogel usage in food product development may be headed toward.

2. THE PRINCIPLES OF OLEOGELATION

Oleogelation is simply the transition from an unstructured liquid to an orderly solid or gel state.

2.1. Mechanism of Oleogel Formation

Oleogels are formed by the self-assembly of gelators, and this process can occur in one of two ways—

- formation of crystallites
- formation of self-assembled fibrillar networks (SAFINs)

2.1.1. Formation of Crystallites

Crystallization is an important step in the creation of many oleogels. Some gelators like fatty acids, fatty alcohols and waxes will undergo crystallisation upon cooling, resulting in a molten melted state and a resulting crystalline network and structure that traps liquid oils within the solid-like network. The process of crytallisation includes the two events of nucleation and crystallite growth to finally create a solid-like/non-fluid-like structure within the oil matrix. The kinetics of gelator crystallization significantly affect the gel strength, oil resistance, and microstructure of the oleogel. The use of differential scanning calorimetry (DSC) and X-ray diffraction (XRD) have both been used to study the crystallization kinetics of oleogels and confirmed gelator concentration and cooling rates of the oleogel greatly influence the heats of melting of oleogels.

2.1.2. Self-Assembled Fibrillar Networks (SAFINs)

SAFINs are formed when LMWGs, such as sterols and certain glycolipids, self-assemble into fibrillar structures via non-covalent interactions. The gelator molecules self-assembled into supramolecular entities, such as those of fibers,

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crystals or platelets, that then collectively create an unbroken continuum that immobilizes oil by way of capillarity (i.e., adhesion between the oil and the gel) and by physical (mechanical) entrapment. The forces that are promoting self-assembly are:

- Van der Waals Forces;
- Hydrogen Bonds;
- π–π interactions; and
- Lipid Crystallization.

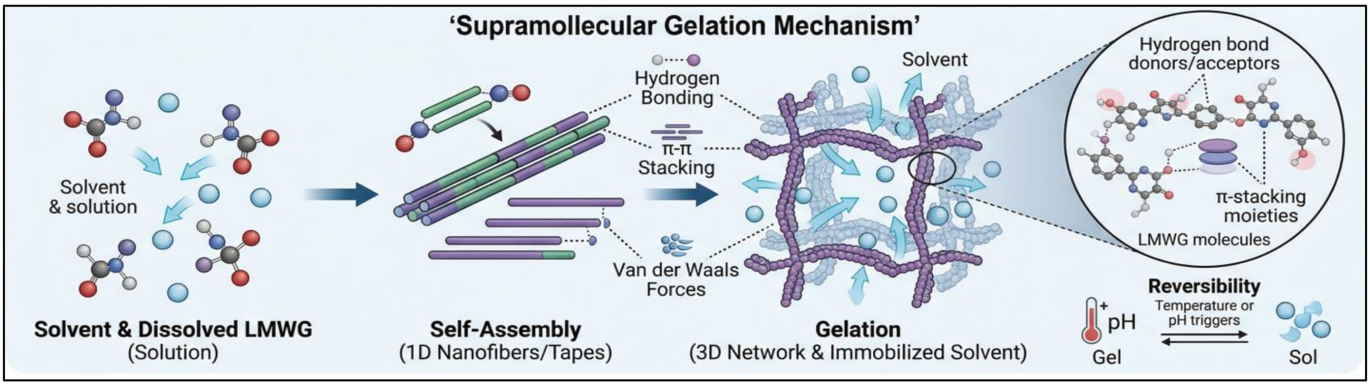

Figure 1: The Mechanism of Supramolecular Gelation

The relative strength of the above forces is responsible for forming the final microstructure and mechanical properties of an oleogel.

2.1.3. The Role of Gelators

Gelators are very important for determining the structure and properties of an oleogel. Research shows that increasing the gelator's (concentration) contributes to the gel's ability to bind to oil, to provide structural strength, and to exhibit appropriate rheological properties. The nature of the gelator itself will produce different oleogel physical structures. For example:

- Waxes produce crystalline networks;
- Polymers produce entangled networks; and
- Sterols produce fibrillar structures.

2.2. Thermodynamics of Oleogel Formation

For the gelation process to be spontaneous the Gibbs free energy of the system must be negative ($\Delta G < 0$).

$$\Delta G = \Delta H - T\Delta S$$

In the case of crystalline gelators like beeswax, a substantial change in the enthalpy of the system (ΔH) is observed during the exothermic process of crystal lattice formation. However, the unfavorable change in entropy (ΔS) of the system must be overcome by the gelation process (Valdivia-Culqui et al., 2024). Recent studies have shown that the energy barrier for the gelation process is significantly affected by the presence of bioactive compounds, which may enhance the process of nucleation (Ferdaus et al., 2025).

2.3. Kinetics of Oleogelation

Oleogel formation kinetics are generally modeled through the use of the Avrami Equation. The Avrami Equation explains how the solid fat content (i.e., degree of crystallinity) changes over time . Research conducted in 2025 indicates that the type of oil (e.g., pumpkin seed or almond) in addition to the cooling rate have a direct influence on the Avrami index (n). The Avrami index (n) typically ranges from 1.0 to 1.43 in wax-based systems and suggests these systems primarily have needle- or fiber-like growth patterns (Borriello, 2025).

3.CLASSIFICATION OF ORGANOGELATORS

The formation of an oleogel depends on the specific molecular interactions of "oleogelators." Organogelators are an interesting group of compounds that have the ability to convert organic solvents into a semi-solid viscoelastic gel. Organogels differ from hydrogels in that instead of water, they use organic solvents such as oil, alcohol, or hydrocarbons. Organogelators are classified according to their molecular weight and the nature of the interaction during gelation.

3.1. Low Molecular Weight Gelators (LMWGs):

Low molecular weight gelators (LMWGs) are mostly small molecules with a lipid basis (e.g., mono- and diglycerides) that can form self-assembled networks that retain oil. LMWGs typically consist of fatty acids and fatty alcohols (e.g., glyceryl monostearate). Phytosterols and their derivatives (e.g., phytosterol esters) comprise another major subset of LMWGs. Common examples of phytosterols and derivatives include β-sitosterol and γ-oryzanol. Fibre like structures are created from the assembly of these compounds and impart structural stability to oleogels. In addition to phytosterols and their derivatives, LMWGs can also be created from natural waxes (e.g., rice bran and beeswax) that crystallize and form networks within oils. The thermal characteristics and microstructural arrangements of oleogels are integral to their firmness and spreadability. In the image below, a sample of the chemical structures for a few LMWGs can be seen.

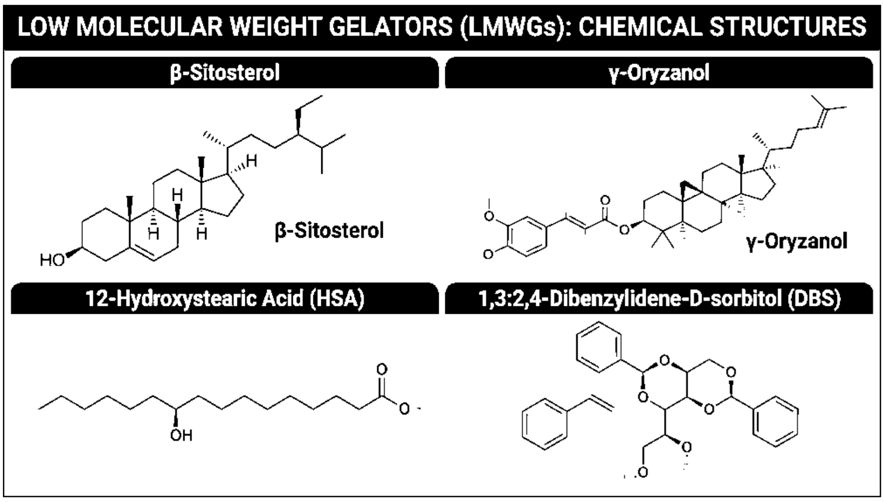

Figure 2: Chemical structures of a few low molecular weight gelators.

3.2. High Molecular Weight Gelators:

These gelators have the ability to self-entangle (crosslink) to make networks that are able to hold oils within their structure. They can be either synthetic polymers or naturally occurring polysaccharides. An example of this type of gelator is Ethylcellulose, which is a food grade polymer that will dissolve in oil at high temperatures and will form a gel when cooled. The oleogels produced from Ethylcellulose based on oleogels have been used to replace solid fats in many food applications, with satisfactory mechanical properties and thermal stability. There are polymer oleogels that are formulated using synthetic or natural polymers as gelators and have different rheological properties than those of lipid based oleogels, thus providing a wider range of texture and structure than lipid based oleogels. The viscoelasticity of these oleogels can be altered by adjusting the type and amount of polymer used, making them customizable for food applications. Examples of high molecular weight gelling agents (HMWG) based on polysaccharides and proteins that can entrap oils and form oleogels with specific viscoelastic properties, also use processes that involve the forming of three-dimensional networks, primarily from hydrogen bonding.

4. OLEOGEL IN FOOD APPLICATION

The amount of interest in oleogels has dramatically increased over the last couple of decades primarily as a result of the mandated labeling of trans fats in food products. Oleogels form a gel-type structure that closely resembles the structure of solid fats in many ways. Recent research has demonstrated that oleogels have good functionality, structural properties, and sensory characteristics when used in high-fat food products such as margarine, baked goods, candy fillings, ice cream, and meat.

4.1. Fat replacers in processed foods

Oleogels have garnered considerable interest as a type of food ingredient that might help facilitate healthier processing of dietary fats in the human body. The structure of these gels provides mechanical obstruction to the digestive tract, which slows down the digestion of, and limits the amount of, dietary lipids absorbed into the body. By delaying digestion, oleogels will result in fewer calories being absorbed and less total fat intake by the individual. Further, because oleogels restrict the absorption of fat, they also reduce blood triglycerides and total cholesterol. This significant reduction can lead to much healthier lipid profiles in serum. As a result, replacing traditional fats with oleotropic gel substitutes will be able to provide individuals with an excellent and practical strategy for long-term cardiovascular health.

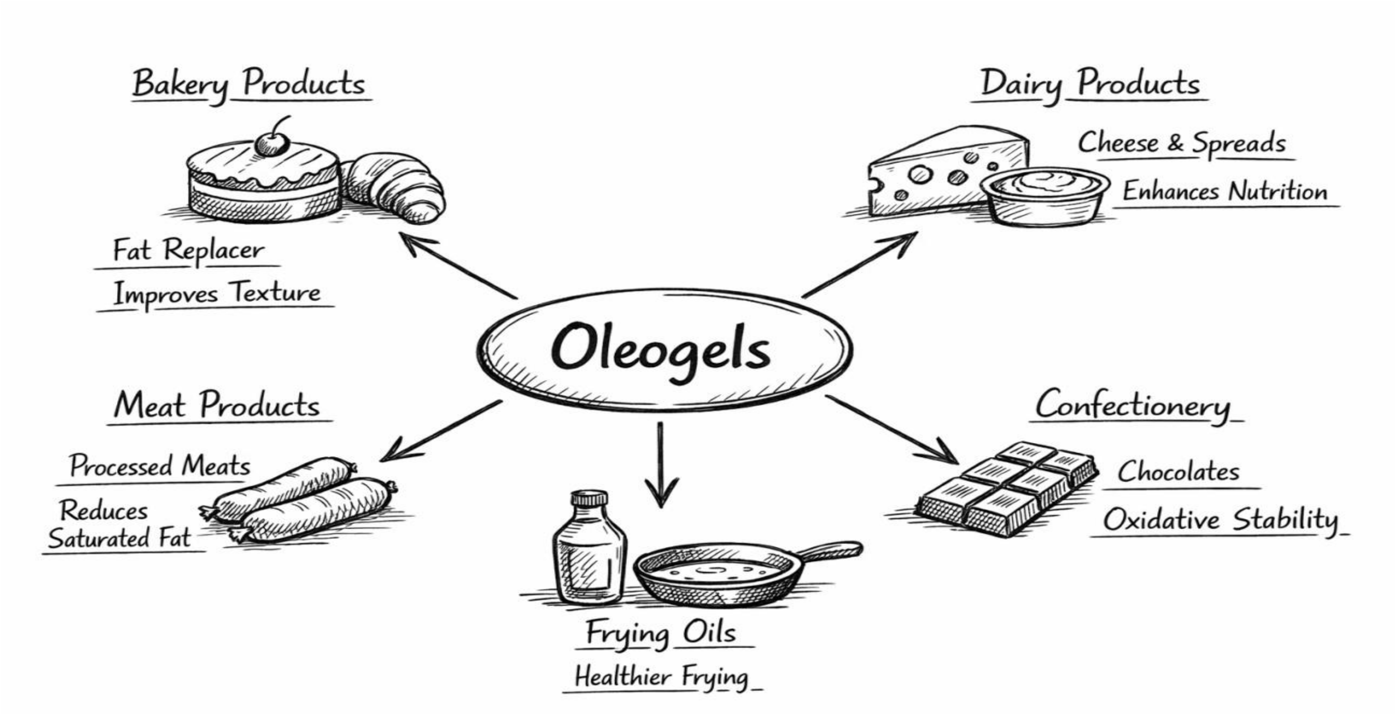

Figure 3: schematic representation of the applications and functional roles of oleogels in food systems

4.2. Bakery products:

The bakery and confectionery industries have found oleogels to be a very successful alternative to traditional fats. In baked products such as cakes, cookies, etc... oleogels can replace conventional shortenings without sacrificing flavour, texture, or overall acceptability to consumers. In addition to providing flavour, oleogels can also serve as effective binders and increase the structural integrity of the finished product while providing longer storage life.

4.3. Chocolates and confectionary

Furthermore, oleogels show similar promise in the confectionery market with respect to chocolate formulations and fillings. By using products derived from nature, manufacturers can create healthier confections using no hydrogenated fats while still having the desired sensory properties. Although the current regulatory environment worldwide limits oleogels from being labeled as “standard chocolate,” they are used on a large scale in chocolate-flavoured coatings and spreads. Overall, oleogels offer a versatile and healthier substitute for saturated fats, thus providing the food industry with a functional mechanism for improving product stability, as well as nutritional content, while maintaining high quality.

4.4. Meat and dairy alternatives

Plant-based meats and dairy substitutes are being changed through oleogels. Oleogels can imitate the texture and juiciness of fat and provide the same "mouthfeel" as animal fats do. Plant-based contain liquid vegetable oils in a solid-like structure and therefore they can be utilized to make meat analogs that closely resemble meat. An added benefit of using these oleogelied products is that oleogels enhance fat distribution and can help create the visual look of marbling in steaks by using extrudable fat technology. Using this type of fat technology will not only enhance the appearance of plant-based products but will also mitigate the negative off-tastes that are typically present in plant proteins. The ability of oleogels to improve the palatability and tenderness of plant-based products is reliant upon the interaction between the oleogel and the proteins derived from the plant. Because the proteins in plants exhibit amphiphilicity, they stabilize the oleogel and the plant protein mixture; however, in order to obtain a stable mixture, a careful evaluation of raw material, molecular level characteristics and processing conditions must occur. The challenge that remains unfulfilled is the replication of the melting temperature gradient of animal fats as animal fats melt during cooking; the ultimate goal of oleogels as they relate to the plant-based product market is to close the sensory gap between them and traditional animal products. As the demand for high-quality meat alternatives continues to rise, research into these textural properties will continue to be important. Oleogels are a significant innovative tool designed to eliminate the sensory difference between plant-based substitutes and animal-based products.

5. Advantages of Oleogels in Food Applications:

Oleogels are a new way to create an alternative to traditional solid fats (like saturated and trans fats) in the Food Industry. They are made by "trapping" liquid vegetable oils inside a three-dimensional network of structuring agents (oleogelators), creating a solid-like product with all the nutritional benefits of liquid oils. The advantages of using oleogels in food applications are mentioned as below –

5.1. Better Nutritional Value

The main advantage associated with oleogels is their ability to replace saturated and trans fatty acids with unsaturated fatty acids. Since oleogels are primarily made up of liquid vegetable oil such as sunflower oil, soybean oil, and olive oil, they are rich in MUFAs and PUFAs, and this is the reason they help in maintaining the right levels of cholesterol. A study was carried out in 2021 where an oleogel made from an unsaturated fatty acid such as linseed was used to replace the fat of pork patties. By substituting 25% and 75% of the solid fat with an 8% γ-oryzanol–β-sitosterol oleogel, both ended up with improved fatty acid profiles . In addition, Oleogels provide a firm texture to food products without creating harmful trans fatty acids during partial hydrogenation.

5.2. Customizable Texture and Functionality

Oleogels give the “mouthfeel” of solid fats, as well as providing the solid structure, which cannot be obtained only through the use of liquid oils. Oleogels also inhibit oil migrations (the movement out of a product). This is significant when it comes to chocolate and peanut butter. With baked items, the oleogels create the appropriate shortening effect to provide flaky textures and proper dough consistency.

5.3. controlled release of bioactive compounds:

Oleogels are a great way to deliver bioactive materials because they can protect delicate components from breaking down while helping to control when those materials break down and are released into their final form. A semi-solid matrix of oleogel-type materials allows you to enclose or encapsulate lipophilic bioactive materials, which will result in increasing the stability and 'bio-availability' of those materials. Through various studies conducted in the past few years, we have learned that oleogel-based systems can be used to deliver functional molecules used in food products, emphasizing the ability of oleogels to encapsulate many different types of bioactive substances.

Feature	Traditional Solid Fat (Saturated)	Oleogel
Physical State	Solid at room temperature	Semi-solid / Gel-like
Main Lipid	Saturated fatty acids	Unsaturated fatty acids
Health Impact	Higher risk of CVD	Cardioprotective
Structure	Crystalline fat network	3D network of gelators

Table 1: Comparison: Traditional Fat vs. Oleogel

6. LIMITATIONS

Food researchers have focused their efforts on the properties of oleogels, which have many advantages including being able to modify texture; increasing both oxidative and structural stability; and providing enhanced nutritional function. Because of these properties oleogels offer excellent potential as substitutes to the traditional hard stocks of fat by simulating their textural characteristics while not adversely affecting the fatty acid composition of food items. However, the commercialisation of foods containing oleogel is in its infancy, primarily because there is still very little knowledge about how oleogels behave during processing when combined with food ingredients. In addition, while many gelators are considered food grade, and as such, Generally Recognized as Safe (GRAS), they do not have well established applications within the food industry nor a clear understanding of their regulatory compliance.

Another significant impediment to the use of oleogels in foods is the limited number of studies on their sensory and organoleptic characteristics. As a consequence, some foods containing oleogels develop undesirable flavour characteristics, such as bitterness and/or off-flavours resulting in reduced consumer acceptance. In addition, the production of oleogels often involves processing at elevated temperatures, which poses the possible risk of oil oxidation and the loss of bioactive components. Although elevated temperature processing is essential to ensure the right conditions for gel development, appropriate processing practices and the use of antioxidants may help mitigate these adverse effects and improve the overall quality of the final product.

7. FUTURE OPPORTUNITIES

The focus of future research on oleogels will be converting them from an experimental additive into a mainstream fat alternative on an industrial scale. As demand increases for healthy options without trans fats, scientists will focus on optimizing the gelator combinations and how oleogels are processed (including the use of the emulsion-template method). By making these technologies available, scientists hope to create sustainable plant oils with a range of melting points so that they can compete directly with animal-based fats both texturally and economically.

To achieve success in the marketplace, however, many hurdles will need to be crossed. The majority of the structural advantages of oleogels have been identified; however, continued sensory testing will be necessary to eliminate characteristics (such as "off-flavors" or bitterness) found in existing formulations. Future studies will probably involve clinical trials to determine the impact of these fats on human metabolism, as well as conducting lifecycle analysis to demonstrate the environmental benefit (sustainability) of oleogels. Ultimately, the transition to large-scale production will require the continued refinement of the textures and flavors of oleogels to ensure they meet the high expectations of consumers.

Overall, oleogels are positioned to fill the gap between nutritional and sensory enjoyment and will be instrumental in the development of food technologies that are sustainable.

8. CONCLUSION

Oleogels have changed the food science industry due to their innovative way to resolve the age-old debate between health and sensory aspects of food. By encapsulating liquid plant oils within a 3d stable network structure; oleogels can provide similar functionality to that of saturated and trans fats. Apart from being able to solve major manufacturing problems such as oil migration and fat blooming in candy manufacturing, oleogels also deliver the attributes of "mouthfeel", juiciness and stability (structural) of bakery items and plant-based meat alternatives. Currently, oleogels are still in an evolving state from the laboratory to being commercially viable around the globe. While the health impacts of oleogels are well-known (i.e., improved cardiovascular profiles, decreased lipid digestibility), other areas such as the lack of sensory consistency or regulatory clarity through industry-wide releases are creating barriers to adoption. Specific sensory issues (off-flavor, bitterness) and the possibility of oil oxidizing from high temperature processing need to be controlled using precise temperature regulation and the use of antioxidants. As a result of ongoing research into optimizing gelator combinations, increasing scalability and improving oleogels will be at the forefront of sustainable food technology. In addition, oleogels are also bridging the gap between clean label consumer demands and consumer expectations with food texture. Ultimately, the successful adoption of oleogels in the food system as sustainable alternative will depend on a balanced consideration of technological innovation, regulatory compliance, and consumer trust.

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