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The role of plant oils/lipids as innovative fat replacers in various food products: A review

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ABSTRACT

Due to growing demands for palatable and nutritious food products, liquid plant oils are structured into oleogels and emulsion gels as fat replacers to mimic the physical state of saturated fats. This work reviews the methods of structuring plant oils into fat replacers and the functionality of these fat replacers, including emulsions and liquid oils, based on their recent applications in meat, bakery, and dairy products. Oleogel is made either by direct or indirect oleogelation, whereas the structuring of a biphasic system generates emulsion gels. The type of gelator and plant oil used influenced the colour, texture, and sensory properties of food products. The plant oil type also affected the fatty acid composition and oxidative stability of food. Textural properties were also altered where hardness was the most emphasised and affected, but the changes did not always deteriorate the overall acceptability of fat-replaced samples. Plant oil fat replacers efficiently enhance the fatty acid composition of food products by increasing unsaturated fatty acid content and reducing saturated and trans fatty acid content. However, most products were prone to lipid oxidation, which produced off-flavour compounds that compromised sensory acceptance, therefore, antioxidants could help. Oleogels, emulsion gels and emulsions were equally effective as fat replacers in various food products, and this indicated the successfulness of the oil structuring approaches. Therefore, the research on potential plant oil fat replacers should be expanded. The sensory analysis of reformulated food products is also recommended to better understand the effects of fat replacers on various food products.

1. Introduction

Cardiovascular diseases (CVD), obesity and other non-communicable diseases are major contributors to the fatality rate in the global population (Adhikary et al., 2022; Chong et al., 2024). These diseases are closely related and dependent not only on active and sedentary lifestyles but also on the intake of food components, especially fat, through various diets and eating habits (Alam et al., 2024; Krishnaswamy, 2016). For example, meat, bakery, and dairy products are widely favored by consumers worldwide due to their taste, convenience, and affordability. However, these products are known to contain high levels of saturated fatty acids (SFA), which have been associated with increased risks of CVD, obesity, hypercholesterolemia, and hypertension (Aramburu et al., 2024; Te Morenga & Montez, 2017). Despite these health concerns, saturated fatty acids (SFA) play a crucial role in food formulation, significantly contributing to taste, lubricity, texture, and overall sensory quality (Demirkesen & Mert, 2020; Ramel & Marangoni, 2019; Lee et al., 2018). Consequently, reducing or eliminating these fats from food products may compromise their desirable properties (Chen et al., 2020).

A promising strategy to address this issue is the partial or complete replacement of SFA with plant oils/lipids. Like traditional fats, plant oils/lipids contribute to the sensory attributes of food by influencing colour, aroma, and taste during cooking while also enhancing mouthfeel and satiety (Zhou et al., 2020). This makes them more suitable as fat

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replacers (FRs) compared to alternatives such as protein- or carbohydrate-based substitutes, which often lack the ability to fully mimic the sensory and functional properties of fat (Asyrul-Izhar et al., 2023a). Additionally, plant oils offer a more favorable fatty acid profile, as they are rich in unsaturated fatty acids (UFA), including monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) (Jurić et al., 2020; Wallis et al., 2022). These fatty acids have been associated with various health benefits, such as lowering low-density lipoprotein (LDL) cholesterol and reducing inflammation linked to CVD (Calder, 2001; Simonetto et al., 2019).

However, the direct replacement of solid fats with liquid oils negatively affects textural properties, compromising the structural integrity and overall sensory quality of food products since plant oils remain liquid at room temperature (Asyrul-Izhar et al., 2023a; Nur Illiyin et al., 2020). To overcome this limitation, solid-like structured plant oils have been developed as FRs, offering a balance between health benefits and the functional properties required for food formulation. Various strategies have been explored to modify fat content, enhance lipid profiles, and transform liquid oils into semi-solid/solid systems, including hydrogenation, interesterification, organogelation, and structured emulsions (Fadillah et al., 2024; Gao et al., 2024; Guo et al., 2023).

Despite the progress in structuring plant oils into FRs, challenges remain in optimizing their functional properties to ensure compatibility with different food matrices. The structuring method is critical in defining the physicochemical characteristics of FRs, influencing oil binding capacity, thermal stability, and sensory attributes. Hydrogenation effectively solidifies liquid oils but is associated with health concerns due to the formation of SFA and trans-fatty acids (TFA). Emerging strategies, such as oleogels and emulsion gels (EG), have shown potential in replicating the texture and mouthfeel of animal fat; however, their stability and mechanical properties are highly dependent on the type and concentration of the oleogelator and emulsifier used (Martins et al., 2020; Patel & Dewettinck, 2015; Sivakanthan, 2024; Lin et al., 2020; Yiu et al., 2023). Furthermore, the composition of plant oil-based FRs plays a crucial role in their nutritional and technological properties, as the type of plant oil used directly impacts the fatty acid profile, oxidative stability, and sensory characteristics of the final product (Badar et al., 2021).

Therefore, this review aims to evaluate the development of plant oil-based FRs, focusing on lipid types, structuring techniques, and their functionality in food applications (in meat, bakery, and dairy products). By analyzing recent advancements in formulation strategies, functional properties, and application outcomes, this work provides insight into the potential of plant oil-based FRs in promoting healthier and more sustainable fat alternatives in the food industry.

2. Plant lipids

2.1. Plant oils

Edible plant oils, a type of plant lipid, are extracted from the seeds (including germs and endosperms) and fruits of various plants (Lavenburg et al., 2021; Magri et al., 2020; Mukhopadhyay & Kabra, 2024; Zhou et al., 2020). They are primarily composed of triglycerides (98 %) and remain liquid at room temperature (Mumtaz et al., 2020). These triglycerides are composed of one glycerol molecule and three fatty acids (FAs), with UFA forming the majority of plant oil triacylglycerols (Jurić et al., 2020; Kesarwani et al., 2024).

FAs are a group of organic substances, or aliphatic carboxylic acids, that have a hydrocarbon chain of varying chain lengths, with a carboxyl group attached at one chain end (Mumtaz et al., 2020; Zhou et al., 2020). FAs are vital for organisms to function normally as they constitute the plasma membranes, serve as energy storage, and regulate cell growth, differentiation, and gene expression (Calder, 2015; McTavish & Mutch, 2024). They are classified based on chain length and saturation level into SFA, MUFA, and PUFA, with PUFA considered essential as they must be obtained from the diet (Custers et al., 2022; Abdelhamid et al., 2020). UFA play a key role in maintaining membrane fluidity, reducing blood cholesterol, and lowering CVD risk, with PUFA particularly linked to improved cardiovascular health (Abdelhamid et al., 2020; Nagy & Tiuca, 2017).

Among plant oils, palm oil is the most widely consumed, followed by soybean oil (SBO), canola oil (CNO), and sunflower oil (SFO), with others like olive oil (OO) and peanut oil being less commonly used (Zhou et al., 2020). The fatty acid composition (FAC) of these oils differs (Table 1), with palm oil being rich in palmitic and oleic acids, CNO containing high levels of oleic acid, and SBO and SFO being abundant in linoleic acid (Akkaya, 2018; Alves et al., 2019; Devi & Khatkar, 2018; Sagan et al., 2019). FAC is influenced by plant variety, climate, soil conditions, and analytical methods (Alves et al., 2019; Orsavova et al., 2015).

Different plant oils have been used to develop potential FRs in food products based on their availability and nutritional properties (Badar et al., 2021). SBO and SFO are selected generally, owing to their high world production besides their desirable FAC (Magri et al., 2020); while linseed oil, chia oil and corn oil are chosen due to their rich PUFA content (Badar et al., 2021; de Carvalho et al., 2020; Kavuşan et al., 2020; Li & Liu, 2019). Meanwhile, the low production and inefficient processing technology have limited the consumption of sesame oil (Yi et al., 2017).

Moreover, when using plant oils as fat replacers, their oxidative stability is a critical consideration. Compared to saturated animal fats and fully hydrogenated oils, unsaturated plant oils are more prone to oxidation, leading to potential quality deterioration (Mozuraityte et al., 2016). Lipid oxidation is mainly driven by heat, light, and oxygen exposure, with oxygen being the primary factor responsible for oil degradation (Grosshagauer et al., 2019; Johnson & Decker, 2015). Autoxidation is one of the oxidation processes which occurs between UFA and oxygen (de Almeida et al., 2019), and generates primary oxidation products (hydroperoxides) which will decompose rapidly to secondary oxidation products (aldehydes, ketones, alcohols, hydrocarbons, esters, furans and lactones) that may be either toxic or off-flavour producing (Ghnimi et al., 2017; Tahergorabi & Jaczynski, 2017; Yang et al., 2024). This oxidative rancidity negatively affects food quality and limits the shelf life of products containing plant oils (Velasco et al., 2010). Therefore, ensuring the oxidative stability of plant oil-based FRs is essential in food formulation.

2.2. Plant waxes

Waxes are FAs-derived esters, either esters of medium- to long-chain FAs, or medium- to long-chain aliphatic alcohols, that can mimic the triglycerides' physical properties (Mumtaz et al., 2020; Doan et al., 2018). However, unlike triglycerides, waxes are constituted of SFA esterified with long-chain monohydric alcohols instead of glycerols (Mumtaz et al., 2020). Plant waxes, classified as natural waxes, are complex mixtures of long-chain (>C16) FA esters, fatty alcohols, free fatty acids, and hydrocarbons, resulting in diverse physical and chemical properties depending on their source (Cheng et al., 2022; Magri et al., 2020; Scharfe & Flöter, 2020). Nevertheless, all waxes are insoluble in water and soluble in specific organic solvents (Lan, 2019). The hydrophobic plant waxes are found in the amorphous layer on the outer surface of the plants, which serves to protect plants from environmental stresses (Lan, 2019). Several plant waxes, including carnauba wax (CNW), candelilla wax (CDW), and rice bran wax (RBW), have received "Generally Recognized as Safe" (GRAS) status from the FDA, allowing their use in various food applications (Manamela et al., 2024; Marangoni, 2012).

Both CDW and CNW are primarily extracted from the leaves of two small shrubs, *Euphorbia cerifera* and *Euphorbia antisyphilitica* (Meritaine da Rocha et al., 2018) and the Brazilian carnauba palm tree (Lan, 2019), respectively. With a melting point of around 83 °C, CNW is one the

Table 1
Fatty acid composition of plant oils.

Plant Oils	Lauric acid (C12:0)	Myristic acid (C14:0)	Palmitic acid (C16:0)	Stearic acid (C18:0)	Oleic acid (C18:1)	Linoleic acid (C18:2)	Linolenic acid (C18:3)	Refs.
Coconut	47.7-59.4	11.4-21.0	0.0-10.9	1.7-3.6	5.8-6.5	1.6-1.9	0.0-0.04	Devi and Khatkar (2018), Kim (2020), Orsavova et al. (2015)
Canola	–	–	4.5-4.8	2.1-3.3	59.7-67.5	15.1-23.2	4.5-7.1	Alves et al. (2019), Kaur et al. (2019), López-Marcos et al. (2024)
Corn	0.0-0.06	0.1-0.5	11.8-12.9	2.2-2.3	22.3-22.8	51.5-57.6	0.9-5.3	Alves et al. (2019), Boukid and Rosentrater (2024), Kaur et al. (2019)
Linseed	–	0.0-0.03	4.9-6.5	2.9-6.2	11.3-25.0	14.1-19.2	46.5-64.0	Stawarska et al. (2020), Alves et al. (2019), Kotliar et al. (2018)
Olive	–	0.0-0.02	10.9-15.1	2.6-4.3	68.9-75.7	4.8-8.5	0.3-0.6	Stawarska et al. (2020), Alves et al. (2019), Konuskan et al. (2019)
Palm	0.0-0.4	1.1-1.6	39.6-45.1	4.4-5.4	36.8-42.9	8.9-10.8	–	Alves et al. (2019), Devi and Khatkar (2018), Mumtaz et al. (2020
Soybean	–	–	8.9-12.2	3.8-6.5	22.9-29.1	44.1-53.6	2.7-10.6	Alves et al. (2019), Kaur et al. (2019), Mumtaz et al. (2020)
Sunflower	0.0-0.7	0.0-0.9	5.3-6.8	3.1-4.9	11.4-37.1	51.2-73.2	0.0-0.79	Alves et al. (2019), Devi and Khatkar (2018), Kaur et al. (2019), Kotliar et al. (2018), Stawarska et al. (2020)
Peanut	–	0.03	7.5-11.9	2.1-4.3	40.8-71.1	18.2-34.5	0.0-0.5	Fabiszewska and Białecka-Florjańczyk (2015), Konuskan et al. (2019), Mumtaz et al. (2020)
Sesame	–	0.0-0.02	9.3-10.0	5.2-6.5	36.3-41.5	40.9-44.2	0.0-0.4	Fabiszewska and Białecka-Florjańczyk (2015), Orsavova et al. (2015), Stawarska et al. (2020)
Pumpkin seed	–	0.1-0.2	11.5-13.1	5.7-12.8	24.9-41.5	37.8-54.2	0.1-0.5	Hu et al. (2024), Kotliar et al. (2018), Nosenko et al. (2019), Orsavova et al. (2015)
Rice bran	–	0.0-0.4	16.1-19.8	1.8-2.5	40.8-41.9	33.0-36.2	0.5-1.8	Ali et al. (2019), Kaur et al. (2019)

hardest plant waxes and hence often added to raise the melting temperatures of wax mixtures (Lan, 2019). It is commercially important with its extensive application in foods, confectionery coatings and other non-food applications (Tinto et al., 2017). Meanwhile, RBW is another plant wax with high melting properties (Endo & Shibata, 2019) that is obtained from rice bran, a by-product from rice milling (Dassanayake et al., 2009). Owing to its abundance and low cost in Asia, RBW is vastly applied in foods, including fruit and vegetable coatings, chewing gums, and confectionery (Islam et al., 2024; Sabale et al., 2009).

Traditionally, in food industries, plant waxes are used in chewing gums and as edible films or coatings for food to improve product shelf life and quality (Ribeiro et al., 2024). However, new emerging technologies such as oleogelation prompt the applications of certain plant waxes with good oil-binding capacity to produce potential FRs, typically oleogels, through wax crystal network formation (Lan, 2019). Since every plant wax has a complex composition that gives it different physicochemical properties, their general compositions must be identified to determine their functionality in wax-based oleogels, such as their rheological profiles and microstructures. Moreover, the strength of the effects on oleogels brought by waxes varies, hence, different waxes may be required at different amounts for them to exhibit their functions effectively. Among the complex compositions, hydrocarbons were determined to have the highest importance for oil gelation, followed by FAs, wax esters and lastly, fatty alcohols. Waxes with higher SFA and high melting FAs yield hard and viscous oleogels (Dassanayake et al., 2012; Dominguez & Carrín, 2024), while waxes consisting of homogeneous compositions such as RBW were likely to contain needle-like fibres or platelets (Limpimwong et al., 2017). Many studies have shown the successful application of oleogels formed with plant waxes as FRs in various food products, which will be discussed further later in this review.

3. Plant oils as fat replacers (FRs)

3.1. General classifications and definitions of FRs

FRs are designed to replicate the sensory, textural, and functional properties of solid saturated fats in food products (Kumar, 2019). They are classified as carbohydrate-, protein-, or fat-based compounds used to reduce fat and calorie content by replacing, reducing, or eliminating undesirable saturated and trans fats (Asyrul-Izhar et al., 2023a; Zeece, 2020; Fellows, 2017; Chavan et al., 2016). Generally, FRs are categorised into fat substitutes (usually lipid-based FRs) and fat mimetics (mostly carbohydrate- and protein-based FRs) (Chen et al., 2024; Colla et al., 2018; Fellows, 2017; Mattes, 1998). Fat substitutes can replicate properties of fat (functional and sensory) in food since it has a similar chemical structure as fat, but is resistant to hydrolysis, and may replace fat fully or partially. Meanwhile, fat mimetic holds water to imitate the physical, textural or organoleptic properties of real fats but can only partially replace fat (Chavan et al., 2016; Czapalay & Marangoni, 2024; Mattes, 1998).

3.2. Liquid plant oil

Direct addition of liquid plant oils in food products is no doubt the easiest way to improve the nutritional profile of food products. Studies have shown the successful application of plant oils in food products to substitute animal fats (e.g. pork fat, beef fat and butter) and saturated plant lipids (e.g. margarine and shortening), resulting in products with improved fatty acid composition, and in some cases, reduced fat content (Nieto & Lorenzo, 2021; Chen et al., 2020; Kavuşan et al., 2020; Abd-ElGhany et al., 2020; Shin et al., 2020; Vieira et al., 2019; Baek et al., 2016; Lee et al., 2015). For example, introducing OO into meat emulsions led to a significant increase in the n-6/n-3 fatty acids ratio, thereby modifying lipid profiles (Nieto & Lorenzo, 2021). Furthermore, replacing pork fat with CNO notably decreased the SFA content in pork sausages, aligning with consumer preferences. (Baek et al., 2016).

Besides improving nutritional characteristics, chicken bologna sausages incorporating CNO exhibited similar physicochemical, textural, and sensory properties to the control sample, with microstructure comparable to the control (Tarté et al., 2020). Additionally, it was found that when CNO, OO, and SFO completely replaced pork back fat, these oils increased hardness without affecting the proximate composition, physicochemical, and technological properties of chicken sausages (Shin et al., 2020).

However, despite these promising outcomes, the direct addition of liquid oils is not universally effective or practical for all food applications. Some studies reported that incorporating liquid oils into product formulations negatively impacted oxidative stability, texture, and sensory attributes. For instance, sausages utilizing pumpkin seed oil as a fat replacer exhibit a softer texture and lighter colour compared to those made with beef fat (Uzlaşır et al., 2020). Similarly, pork batter supplemented with CNO results in undesirable texture and colour (Alejandre et al., 2019). Furthermore, studies by Pires et al. (2019) noted a decrease in sensory acceptance with higher levels of pork back fat replacement with echium oil in bologna-style sausage. This finding aligns with research conducted by Lee et al. (2015), which found that treatments without vegetable oil as fat replacers scored higher in saltiness, flavour, and overall acceptability.

3.3. Modification of plant oils

Traditionally, liquid plant oils were modified through hydrogenation and interesterification to improve their stability and functional properties (Paglarini et al., 2022). Hydrogenation is done to increase the stability of unsaturated liquid plant oils towards rancidity and to convert the oils into saturated solid fats by heating oils with hydrogen gas in the presence of a metal catalyst. Hydrogen atoms reduce the unsaturated carbon-carbon double bond in unsaturated fatty acids into saturated single bonds, thus increasing the melting point of the oils (Gupta, 2017; Tiefenbacher, 2019). Nevertheless, fully hydrogenated fats are too hard and waxy, limiting their application in foods. Hence, partial hydrogenation was done to achieve the solid fats of desired consistency for specific applications, but it was later found that this process generated a considerable amount of TFAs in treated oils (Fellows, 2017; Tiefenbacher, 2019).

Comparatively, interesterification is a more promising oil modification method than hydrogenation as the SFA content can be controlled, and no TFAs are produced (Bihola et al., 2025; Kadhum & Shamma, 2017). This process modifies the structure and functionality of fats and oils by altering the fatty acid composition or rearranging the position of fatty acids of triglycerides in fats and oils (Berry et al., 2019). Interesterification can be done either enzymatically or chemically, but the former is preferred since it is more controllable due to the use of substrate-specific enzymes that enable specific fatty acid composition of triglycerides to be achieved (Farfán et al., 2015). However, the explicitly high cost of enzymes (Kadhum & Shamma, 2017) is likely not favoured by most manufacturers, and interesterified fats tend to be less accepted by consumers due to their ability to chemically modify organic solvents at a molecular level (Martins, Vicente, et al., 2020), and the increasing consumers' demand for natural products (Fellows, 2017).

To address these challenges, efforts have focused on developing alternative methods for converting liquid oils into solid fats that provide desirable structural and textural properties while offering nutritional benefits without relying on hydrogenation or interesterification.

3.4. Emulsions and emulsion gels (EG)

Recently, emulsions and EG have been widely utilized as fat replacers in food products (Guo et al., 2023; Asyrul-Izhar et al., 2023b; Abd-El-Aziz, 2020; Pintado & Cofrades, 2020; Schmid et al., 2020). Plant oil emulsions are produced by dispersing one phase (oil or water) into another to form classical emulsions with the aid of emulsifiers or matrix materials (e.g. soy protein isolate, sodium caseinate, gelatine, myofibrillar protein) and polysaccharides (e.g. carrageenan, alginate and inulin) (Afshari et al., 2017; Lin et al., 2020). These emulsions can be classified into classical and pickering emulsions (de Carvalho-Guimarães et al., 2022; Gonzalez Ortiz et al., 2020). Classical emulsions include the most commonly known single emulsions, oil-in-water (O/W) and water-in-oil (W/O) emulsions, and the more complex multiple emulsions, oil-in-water-in-oil (O/W/O) and water-in-oil-in-water (W/O/W) emulsions (Lin et al., 2020). Pickering emulsions are, generally, emulsions that are stabilized with solid particles rather than conventional surfactants, as in classical emulsions (Xiao et al., 2016). However, since most emulsions do not exhibit a solid-like structure, their applications in food products are comparatively less.

To overcome this limitation, EG have been developed to integrate both emulsion droplets and a gel-like network (Balakrishnan et al., 2017; Rawal et al., 2024). EG exhibit solid-like mechanical properties, providing stability, textural enhancement, and the ability to act as carriers for fat-soluble compounds (Guo et al., 2023; Mantelet et al., 2019; Dickinson, 2013). EG can be made from any aforementioned types of emulsions, but despite the availability of a diverse emulsion type, O/W emulsions have always been more popular in research studies (Lin et al., 2020). An O/W EG is structured by first producing the emulsion using emulsifying agents, followed by adding the gelling agents into the emulsion, which then aggregates the oil droplets in the emulsion, or gelling the continuous water phase (Dickinson, 2013; Herrero et al., 2018; Patel & Dewettinck, 2016; Yalçinöz, 2024). Jiang et al. (2019) developed an EG from O/W Pickering emulsion without surfactant. Regenerated cellulose was used as an emulsifier to produce an O/W emulsion system, and the system was solidified by a curdlan gel. Meanwhile, a mixture of soybean protein isolate (SPI) and coconut oil was emulsified, and konjac flour was incorporated to form a protein/polysaccharide composite EG (Huang et al., 2022). The resulting solid fat substitutes exhibit a resemblance to pork fat in appearance and demonstrate favourable functional attributes in terms of mechanical properties and oral tribology. Additionally, an analogue of pork back fat was achieved through the stirring of soybean isolate emulsions and curdlan solutions, forming layer-by-layer EG. This EG closely matched the texture and colour of pork back fat, offering a novel approach for reducing fat content in meat products (Cui et al., 2022).

3.5. Oleogels

Oleogelation is an emerging oil structuring strategy that transforms liquid plant oils into viscoelastic gel-like structures through the formation of a three-dimensional (3D) network by oleogelators (Patel & Dewettinck, 2016). This technique provides a viable alternative to solid fat, enhancing the fatty acid profile and lowering cholesterol levels in food formulations (Manzoor et al., 2022). Additionally, oleogels function as carriers for lipophilic bioactive compounds, helping to maintain their stability during storage and delivery (Pinto et al., 2021). Recent studies have highlighted the potential of vegetable oil oleogels in food formulations, demonstrating promising results in product quality and functionality (Fu et al., 2025; Qiu et al., 2024; Tan et al., 2023).

Generally, oleogels could be produced by either direct or indirect oleogelation (Perța-Crișan et al., 2022). Direct oleogelation involves the direct dispersion of lipophilic oleogelators (waxes, ethyl cellulose (EC), γ-oryzanol and phytosterols, FA derivatives: monoacylglycerol, diacylglycerol, etc.) into the continuous liquid oil phase to immobilize the oil (Hashemi et al., 2024; Martins, Vicente, et al., 2020; Patel & Dewettinck, 2015). Waxes and FA derivatives are single-component (low molecular weight) gelators that structure liquid oil by forming lamellar crystalline structures (Martins et al., 2016). Meanwhile, EC can self-assemble in the oil bulk upon heating with subsequent cooling process and is the only polymeric (high molecular weight) gelator that can be used for direct dispersion due to its hydrophobicity (Martins, Vicente, et al., 2020; Sagiri & Rao, 2020). On the other hand, a combination of γ-oryzanol and β-sitosterol forms a network by self-assembling into tubular conformations (Martins et al., 2019).

Meanwhile, indirect oleogelation uses emulsion as a template to produce oleogels, where the continuous phase of emulsion, instead of that of liquid oil, is immobilized and structured (Perța-Crișan et al., 2022; Patel et al., 2015). This method is adopted when hydrophilic structuring agents or polymers (e.g. proteins and polysaccharides such as cellulose derivatives, hydrocolloid, gums, carrageenan, etc.) that have limited solubility in oil are used to induce gelation of oil in the presence of water (Flöter et al., 2021; Martins, Vicente, et al., 2020; Singh et al., 2017; Patel & Dewettinck, 2015). Hence, this approach highly depends on the ability of polymers to hydrate and form a network in water. Upon hydration, polymer conformations extend and open, which promotes molecular interactions and forms an interconnected, three-dimensional network (Sagiri & Rao, 2020).

For indirect oleogelation, an emulsion is first prepared, followed by the addition of oleogelators to gel the continuous phase of the emulsion. The water phase is then dried to expose the gelled network formed and to obtain the dried, physically trapped oil droplets (Magri et al., 2020). However, the dried emulsion is technically not an oleogel since the oleogelators are not the dispersed phase that constructs a 3D network, and the oil in the system is not structured but only held together in a network of emulsifiers and oleogelators (Feichtinger & Scholten, 2020). Therefore, oleogel is developed by mild shearing of the oil droplets to break the network of emulsifiers and oleogelators to yield a continuous oil phase in the system (Bascuas et al., 2021; Feichtinger & Scholten, 2020; Patel & Dewettinck, 2016; Patel et al., 2015).

It should be noted that EG and oleogels formed by emulsion templates are different in terms of water content as well as their production steps (Guo et al., 2023; Guo et al., 2020; Patel & Dewettinck, 2016). Oleogel comprised mostly oil (>90 %) and had a very low water content, whereas EG could have only half of the oil content of oleogel (Pintado & Cofrades, 2020; Patel & Dewettinck, 2016; Dickinson, 2013). It is also noteworthy that oleogelation does not involve any chemical modifications of oils for the conversion of liquid oils into gel-like oleogels (Patel & Dewettinck, 2016). This approach allows the formulation of food products with healthier nutritional profiles by adding oleogels as fat replacers that may mimic the functionality of saturated fats (textural, sensorial, rheological, and food matrix stability) in food products (Patel, 2017).

4. Application of plant oil-based fat replacers in food products

4.1. Meat Products

4.1.1. Meat batters/emulsions

Structured oils have been found to modify the fatty acid composition of meat batters (Fig. 1), particularly by decreasing SFA (Table 2). In a study by Ferrer et al. (2019), EC-based SBO oleogels were utilized to completely replace pork back fat in meat batters. The study noted that oleogel-based batters exhibited lower SFA, higher PUFA/SFA ratio, and reduced calorie content due to the lower fat content compared to the control. However, another study demonstrated that plant oil oleogel increased the yellowness, hardness, gumminess and chewiness of pork batters with increasing EC concentrations (Shao et al., 2020). Oleogel-included batters were lighter than pork fat batters but became darker with higher EC content. The batters also had better emulsion stability compared to pork fat batter, with SFO oleogel offering better stability than other oils (corn, peanut, flaxseed oils) used in this study. Oleogels could also induce stronger association between water and protein as well as reduce the mobility of water in batter, owing to the smaller fat globules produced in oleogel pork batters after chopping, which resulted in a more stable emulsion system (Igenbayev et al., 2024; Shao et al., 2020).

Beyond oleogels, liquid oil has also been evaluated as FRs in meat batters. Alejandre et al. (2019) observed that using liquid CNO resulted in a harder texture and undesirable colour compared to the control. In addition, CNO hydrogelled emulsion resulted in meat batters with higher fat loss during cooking. In contrast, CNO-EC oleogels produced a texture and color comparable to the control while also offering greater oxidative stability. However, regardless of the incorporation method, meat batters included with CNO had healthier FA profiles shown by the increased PUFA/SFA ratios.

EG is also used as a replacement for fat components in the meat system to improve the nutrition profile of these products. In the study by Demir et al. (2023), EG made with SFO and various legume flours (pea, lentil, bean, and chickpea) replaced 50 % and 75 % of animal fat in the model meat system. As expected, the fat content decreased in the experimental samples. The texture of the products was similar to the control, and there were no negative effects observed in the products, such as leaking water or oil. These attributes show encouraging outcomes in mimicking animal fat with plant-based EG.

4.1.2. Sausages and frankfurters

Sausages and frankfurters, commonly made with animal meat and

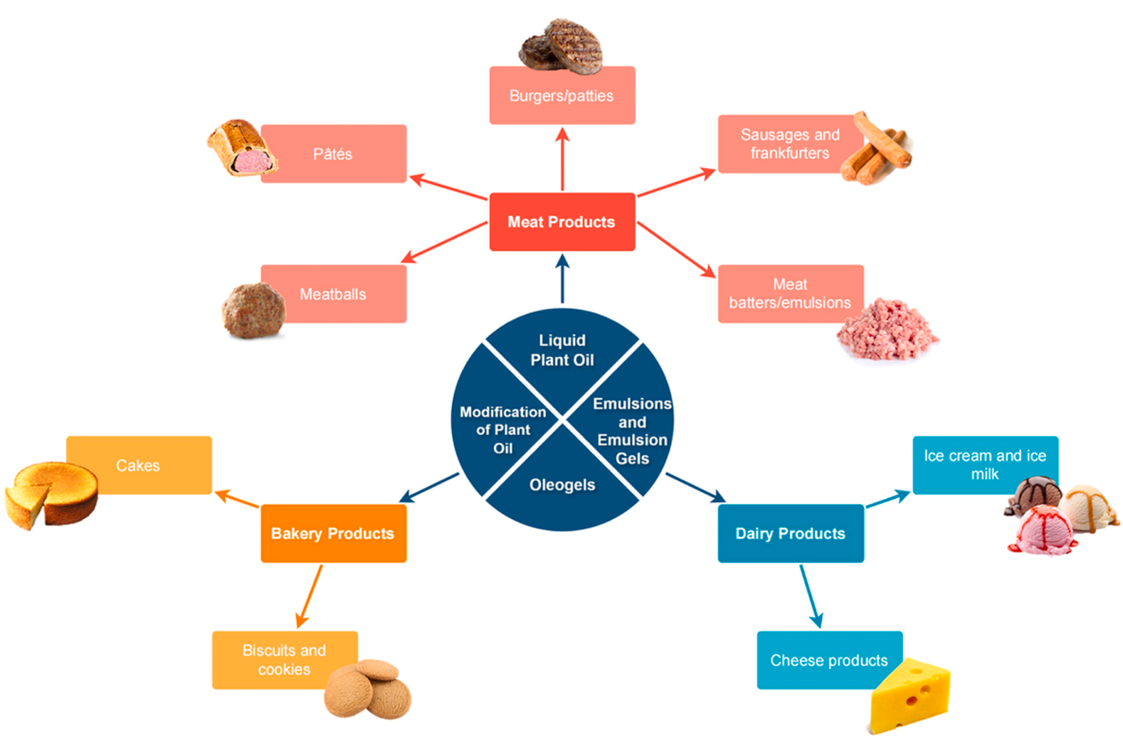

Fig. 1. Application of fat replacers in different food products.

Table 2
Summary of the application of fat replacers in meat products.

Food products	Fat replacer	Plant oil	Gelators, emulsifiers, or stabilizers	Replacement level (%)	Main findings	Refs.
Meat batter	Oleogel	SBO	EC	100	Higher levels of PUFA and decreased lipid oxidation without compromising texture or overall acceptance.	Ferrer et al. (2019)
		CNO	EC, glycerol monostearate	100	Cooking loss, oxidative stability and FA profile were enhanced without affecting the texture.	Alejandre et al. (2019)
		SFO, peanut oil, corn oil, flaxseed oil	EC	100	Better emulsion stability and lower cooking loss. A lower EC concentration had less effect on textural properties. Oleogel prepared with SFO was the best FR.	Shao et al. (2020)
	Emulsion gel	SFO	Pea, lentil, bean, and chickpea flour	50, 75	Higher moisture and protein levels. Fat content decreased as anticipated. No significant differences were noted in pH, colour, water holding capacity, or texture.	Demir et al. (2023)
Sausages and frankfurters	Oleogel	Linseed oil	γ-oryzanol and β-sitosterol, BW	20, 40	It has a lower fat content and a better FA profile without affecting textural properties at 20 % γ-oryzanol and β-sitosterol oleogel inclusion.	Franco et al. (2020)
		SBO, high-oleic SBO	RBW	41.9	A healthier FAC was obtained without affecting most of the evaluated properties. Oleogel did not affect emulsion stability, and high-oleic SBO gave a better nutritional profile than SBO.	Tarté et al. (2020)
		CNO	EC, sorbitan monostearate (surfactant)	20, 40, 60, 80	Replacement levels did not affect textural properties. Cooking loss was reduced. Oleogel with 10 % EC and 1.5 % sorbitan monostearate produced sausages most similar to the control.	Barbut et al. (2016)
		OO, Chia oil	BW	80	Sausages had recommended ratios of PUFA/SFA and n-6/n-3 and had good oxidative stability during chilled storage.	Pintado and Cofrades (2020)
Sausages and frankfurters	Oleogel	SFO	Monoglycerides, BW	7, 10	The levels of PUFA and MUFA increased, enhancing the overall fatty acid composition while preserving satisfactory sensory characteristics.	Igenbayev et al. (2023)
		SFO, peanut, corn, and flaxseed oils	EC	10, 20, 30, 40, 50	The texture, lipid oxidation, and sensory characteristics of the modified sausages showed no significant variation compared to those without oleogel substitution. However, these reformulated sausages exhibited a healthier fatty acid profile and enhanced nutritional content.	Shao et al. (2023)
		OO	Monoglycerides	50	Oleogels produced sausages that are both sensorial-pleasing and microbiologically safe while offering a healthier nutritional profile.	Zampouni et al. (2022)
	Emulsion gel	OO, Chia oil	Soy protein isolate, gelatin	80	Sausages had recommended ratios of PUFA/SFA and n-6/n-3 and had good oxidative stability during chilled storage. EG produced sausages with similar hardness as the control.	Pintado and Cofrades (2020)
Sausages and frankfurters	Emulsion gel	SBO	Soy protein isolate, chia flour, sodium caseinate, inulin, carrageenan, sodium triphosphate	50, 100	Nutritionally better with enhanced FA profile and incorporation of EG at 50 % yielded the best results. Proximate composition was not affected at 50 % EG incorporation. Chia flour could improve textural properties.	de Souza Paglarini et al. (2019)
			Inulin, soy protein isolate		Increased fibre content without sacrificing sensory and textural properties at 50 % replacement level.	de Souza Paglarini et al. (2021)
		Camellia oil	Carrageenan, sodium caseinate	10, 20, 30, 40, 50	Increasing replacement levels reduced hardness. Sausages had higher L^* and b^* values and UFA content. The amount of fat and SFA were reduced.	Wang et al. (2018)
		Black cumin and flaxseed oil	PGPR, inulin, sodium caseinate, gelatin	50, 75, 100	Sausages had lower fat content and better FA profiles. GE at 50 % produced sausages that were closest to the control and had the lowest TBARS values throughout the storage period.	Kavuşan et al. (2020)
		OO	Chia mucilage	100	Samples with EGs showed low liquid exudation, less cohesion, and higher elasticity, but no significant differences were found in sensory evaluation for texture attributes.	Ferreira Ignácio Câmara et al. (2021)
Sausages and frankfurters	Emulsion gel	OO, Walnut, and Chia Oils	Soy protein isolate, transglutaminase, and chitosan	100	The reformulated product achieved a notable decrease in the n-6/n-3 ratio, along with an increase in the PUFA/SFA ratio. Colour analysis revealed increased lightness and yellowness, with a slight decrease in redness in the reformulated product.	Cîrstea (Lazăr) et al. (2023)
		Chia oil, linseed oil, OO	Sodium caseinate	100	Reduced fat content, TBARS value not affected. Linseed oil emulsion improved FAC without affecting technological and sensory properties.	de Carvalho et al. (2020)
	Emulsion	Chia oil, linseed oil, OO	Sodium caseinate	100	Reduced fat content, TBARS value not affected. Linseed oil emulsion improved FAC without affecting technological and sensory properties.	de Carvalho et al. (2020)
		Hazelnut oil	Sodium caseinate	50, 100	Healthier FA profile with comparable textural, overall sensory quality.	Urgu-Öztürk et al. (2020)

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Table 2 (*continued*)

Food products	Fat replacer	Plant oil	Gelators, emulsifiers, or stabilizers	Replacement level (%)	Main findings	Refs.
		CNO	Porcine plasma protein hydroxylates	15, 30, 45, 60	Increased emulsion stability and reduced cooking loss and fat content. At 45 %, the FA profile was enhanced without affecting overall acceptability.	Chen et al. (2020)
		Peanut and linseed oil	Powdered gelatin, egg white powder, chicory, and lipophilic emulsifier polyglycerol polyricinoleate	50, 100	Total fat content dropped by up to 40 %, and energy content by up to 27 % in reformulated products. Reformulation also increased n-3 content and improved emulsion stability and cooking behaviours, with acceptable sensory features.	Nacak et al. (2021)
Sausages and frankfurters	Emulsion	OO, walnut, and chia oils	Soy protein isolate, transglutaminase, and chitosan	100	A significant decrease in the n-6/n-3 ratio and an increase in the PUFA/SFA ratio were compared to the control. Colour measurements showed increased lightness and yellowness, with a slight decrease in redness.	Cîrstea (Lazăr) et al. (2023)
	Structured lipid	IPKO	-	25, 50, 75, 100	Enhanced nutritional quality by lowering long-chain SFA without affecting overall acceptability. Up to 50 % could increase PUFA content with minimized effects on oxidative and textural qualities.	Kılıç and Özer (2019)
		IPKO	-	25, 50, 75, 100	FAC was improved with higher medium-chain FAs content and lower long-chain SFA content. TBARS values were not affected at the end of the fermentation process.	Kılıç and Özer (2017)
	Liquid plant oil	CNO, flaxseed oils	-	20	CNO enhanced pH, water holding capacity, and texture profile, while flaxseed oils showed the highest yellowness. Replacing pork fat with plant oil significantly boosted omega-3 content and improved fatty acid profiles.	Baek et al. (2016)
		CNO, OO, SFO	-	100	No significant effects on chemical composition, emulsion stability, cooking yield, and WHC. OO produced sausages that were most similar to the control.	Shin et al. (2020)
Sausages and frankfurters		Pumpkin seed oil	-	5, 15, 30	Acceptable TBARS values were obtained. At 5 %, pH, WHC and emulsion stability were similar to control.	Uzlaşır et al. (2020)
Burgers or patties	Oleogel	Sesame oil	BW	25, 50	BW at 10 % produced oleogel most similar to animal fat. Burgers treated with this oleogel had reduced L^*, cooking loss and fat absorption. Overall acceptability was better than that of the control.	Moghtadaei et al. (2018)
		OO, linseed oil, fish oil	EC, BW	100	Improved FA profile and maintained moisture content. BW was a better oleogelator as burgers had closer sensory properties to control.	Gómez-Estaca, Pintado, et al. (2019)
		Hemp oil	RBW, CDW	100	Successfully replicated the texture properties of pork fat. However, sensory evaluation exhibited lower levels of juiciness and taste intensity.	Hamidioglu et al. (2022)
		SBO	EC, adipic acid. CNW, adipic acid	50	Oleogel with 2 % oleogelator and 4 % adipic acid was the best oleogel formulation. The oleogel burgers had the nearest sensory characteristics to the control.	Adili et al. (2020), Aliasl Khiabani et al. (2020)
	Emulsion gel	OO	PGPR, inulin, gelatin	25, 50, 100	The textural properties were affected, and L^* was higher. Similar cooking and sensory characteristics were obtained up to 50 % gelled emulsion inclusion.	Serdaroğlu et al. (2017)
Burgers or patties	Emulsion gel	Chia oil	Chestnut flour	5, 10	Yellowness, TBARS, and PUFA were higher. Hardness, chewiness, and shrinkage were lower.	Lucas-González et al. (2020)
		Algae oil	kappa carrageenan	70 %	Reduced amount of n-6 fatty acids, increased amounts of long chain n3 fatty acids.	Alejandre et al. (2017)
	Emulsion	Tiger nut oil	Calcium sulphate, sodium alginate, disodium diphosphate	50, 100	Total replacement increased L^* and b^*. FAC and oxidative stability were improved without affecting textural properties (except springiness).	Carvalho Barros et al. (2020)
		OO, CNO	Soy protein isolate	100	Recommended ratios of PUFA/SFA and n-6/n-3 were achieved. Sensorial properties were not affected and cooking characteristics were better.	Afshari et al. (2017)
		OO, linseed oil	Soy protein isolate	100	Burgers were nutritionally better with comparable sensory attributes as the control. Discolouration and TBARS values of raw samples were reduced.	Gómez et al. (2018)
Pâtés	Oleogel	CNO	EC, glycerol monostearate	100	Oleogel pâtés exhibited comparable textural, physical, and sensory properties to traditional pâté made with pork fat while reducing saturated fat content by 60 %.	Barbut et al. (2019b)
		CNO	EC, glycerol monostearate	20, 40, 60, 80, 100	L^* was reduced while a^* was increased. The textural and sensory properties were maintained. Oil retention was good up to 60 % oleogel incorporation.	Barbut et al. (2021)
Pâtés	Oleogel	OO, linseed, and fish oils	EC, BW	60, 100	Optimal fatty acid profile. Technological and sensory properties were maintained, but reformulation increased lipid oxidation.	Gómez-Estaca, Herrero et al. (2019)
		Linseed oil	BW	30, 60	Nutritionally better FAC with higher omega-3 FA and lower SFA contents. Proximate composition and overall sensory acceptance were nearest to control at 30 % oleogel inclusion.	Martins, Lorenzo, et al. (2020)

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Table 2 (*continued*)

Food products	Fat replacer	Plant oil	Gelators, emulsifiers, or stabilizers	Replacement level (%)	Main findings	Refs.
Meatballs	Emulsion	OO	Soy protein isolate	25, 50, 75, 100	Reduction of cholesterol and SFA, and increased UFA content. Improved cooking loss and emulsion stability. Total replacement did not affect TBARS value and sensory attributes.	Abd-El-Aziz (2020)
	Liquid plant oil	CNO	-	25, 50, 75, 100	Proximate composition was not affected, and FAC was improved. The replacement level did not significantly alter colour, texture, oxidative stability, and sensory acceptance.	Vieira et al. (2019)
	Oleogel	Black Cumin Seed Oil, SFO	CNW	25, 50, 75	Resulting in changes in colour, cooking parameters, lipid oxidation, and texture.	Palamutoğlu (2021)

Note: Soybean oil (SBO), canola oil (CNO), sunflower oil (SFO), olive oil (OO), palm kernel oil (IPKO), ethyl cellulose (EC), rice bran wax (RBW), beeswax (BW), carnauba wax (CNW), candelilla wax (CDW), polyglycerol polyricinoleate (PGPR)

fat, are popular meat products. Fat plays a crucial role in determining their composition and texture, significantly influencing sensory characteristics (Ferdaus et al., 2024).

The introduction of oleogels, emulsions, and EG as fat replacers has shifted research focus away from liquid plant oils and interesterified oils as substitutes for saturated fats in food products. However, some recent studies continue to explore these conventional FR (Table 2). For instance, liquid plant oils, such as CNO, OO, and SFO, have also been evaluated in chicken sausages. Shin et al. (2020) reported that replacing pork back fat with these oils did not affect the proximate composition, emulsion stability, cooking yield, or water-holding capacity of chicken sausages. However, the reformulated sausages were softer and had lower redness (a^* value). Among the tested oils, OO produced sausages with textural properties closest to those made with pork back fat, likely due to its higher MUFA content and lower PUFA levels (Jimenez-Lopez et al., 2020). SFA and PUFA determine the physical state of lipids, where native PUFA-rich plant oils are always in the liquid form, whereas SFA-rich pork back fat has a higher solid fat content and hence, behaves as solid at room temperature (Tarté et al., 2020). Additionally, the incorporation of conventional SBO (40 %) did not affect the proximate composition, textural characteristics and sensory properties of bologna-type sausages (Tarté et al., 2020). However, sausages were significantly softer, less adhesive and less chewy with the incorporation of pumpkin seed oil (5 %, 15 %, 30 %), despite the greater penetration hardness and work of penetration (Uzlaşır et al., 2020). In addition, increasing oil levels also significantly increased lightness (L^*) and yellowness (b^*) but decreased a^*. Colour is an important quality indicator for meat products because high-quality meat products are usually bright and pinkish-red in colour, which is favoured by consumers. Meanwhile, the hardness, springiness and emulsion stability of frankfurters made with liquid CNO were reduced (Chen et al., 2020). In contrast, frankfurters were even harder and less desirable when liquid CNO was incorporated (Barbut et al., 2016). These inconsistent findings highlight the variable effects of different liquid oils in meat matrices.

Additionally, the potential of enzymatic interesterified palm kernel oil (IPKO) as a beef fat replacer in frankfurters (Kılıç & Özer, 2017) and Turkish dry-fermented sausages (sucuks) (Kılıç & Özer, 2019) was investigated. IPKO significantly increased the amount of medium-chain FAs and decreased long-chain FAs as well as UFA, which improved the oxidative instability of both products. At 75 % IPKO inclusion, softer frankfurters were produced but with preserved colour, proximate composition and sensory properties, whereas sucuks were affected. Overall, the influences of IPKO on the properties of these sausages were dependent on their type of sausages (Kılıç & Özer, 2019). It was suggested that up to 50 % beef fat replacement with IPKO can maintain desirable oxidative stability and quality of frankfurters (Kılıç & Özer, 2017) but without an improved FA profile, whereas the texture of IPKO-incorporated sucuks must be improved (Kılıç & Özer, 2019).

Emulsions, EGs and oleogels were also widely incorporated into sausages. Lamb sausages with 100 % replacement of back fat by chia oil, linseed oil or OO emulsions had higher L^* and b^* but lower a^*. Sausages included with emulsions of chia oil and linseed oil had recommended ratios of omega-6/omega-3 (n-6/n-3) and PUFA/SFA. In addition, chia oil and OO emulsion sausages had the highest PUFA and MUFA contents, respectively. This led to the lowest oxidative stability, taste and odour scores reported for chia oil emulsion sausages. Chia oil sausage was also the hardest and most chewy after 60 days of storage (de Carvalho et al., 2020). Similarly, CNO pre-emulsified with porcine plasma protein hydroxylate increased the hardness, gumminess, and chewiness of frankfurters, as well as water and fat binding capacities at increasing replacement levels (Chen et al., 2020). Overall, emulsion-incorporated sausages were springier and chewier than control samples but still had acceptance test scores within the acceptable limit. Linseed oil emulsion was shown to be the best FR by yielding lamb sausages with improved FAC and similar sensory qualities as the control (de Carvalho et al., 2020). In contrast, pre-emulsified hazelnut oil only increased the cohesiveness of beef sausages (Urgu-Öztürk et al., 2020). Pre-emulsion sausages had higher fat contents, attributed to the improved fat-holding ability, and increased UFA and reduced SFA contents. Pre-emulsified hazelnut oil inclusion did not deteriorate the textural and overall sensory qualities of sausages. However, the colour parameters of reformulated sausages were affected, as reported in the aforementioned studies (de Carvalho et al., 2020; Tarté et al., 2020; Uzlaşır et al., 2020). Moreover, pre-emulsified hazelnut oil reduced oxidative and storage stabilities (loss of water and oil during storage) of sausages. A combination of pre-emulsified hazelnut oil and hazelnut powder (up to 3 %) was suggested to produce nutritionally better sausages similar to control sausages in terms of texture, sensory and technological qualities, and storage stability (Urgu-Öztürk et al., 2020).

The integration of EG systems into sausage formulations can also effectively promote a healthier lipid profile while maintaining high technological and sensory standards. Nacak et al. (2021) explored the use of EG, containing peanut and linseed oils, to replace beef fat in emulsified sausages. Total fat content decreased by up to 40 %, and energy content dropped by up to 27 % in the reformulated products. Saturated fatty acids and cholesterol decreased, while mono and polyunsaturated fatty acids increased noticeably in sausages with EG. The reformulation increased n-3 content and improved emulsion stability and cooking behaviours, although it altered colour and texture. Pork back fat replacement with SBO-EG (EG made with SBO) produced Bologna sausages that are lighter, lower in a^*, and have improved FAC. The oxidative stability of EG sausages was not affected, and the sausages had more stable, homogeneous and dense structures compared to the sausages with a simple reduction of 50 % pork back fat (de Souza Paglarini et al., 2019), probably due to the WHC of hydrocolloids in the EG (Glisic et al., 2019). At 100 % pork back fat replacement, moisture and fat contents of sausages were increased and decreased, respectively, and sausages were harder and chewier. However, sausage with 50 % SBO-EG had a similar texture and rheological properties as the control (de Souza Paglarini et al., 2019).

On the other hand, SBO-EG added with inulin (16.5 %) increased the fibre content of Bologna sausages and had a similar effect on colour and emulsion stability. Consumer test scores and correspondence analysis results for inulin-added SBO-EG sausage were similar to those of full-pork back fat sausage. However, the oxidative stability of sausage was significantly reduced during chilled storage. Another important finding in this study was that the simultaneous reduction of pork back fat and salt content in sausages reduced emulsion stability, juiciness and sensory qualities. Overall, inulin-enriched SBO-EG was concluded as a potential FR for healthier and stable meat products (de Souza Paglarini et al., 2021).

Moreover, a stable EG using soy protein isolate, transglutaminase, and chitosan formed a solid-like structure with extra virgin OO, walnut, and chia oils. Substituting pork backfat with this gel improved Bologna sausage lipid healthiness by reducing saturated fatty acids, n-6/n-3 ratio, atherogenic index (AI), and thrombogenic index (TI). The reformulated sausage meets European regulations for "high unsaturated fat" and "high omega-3 content". While texture improved slightly, colour changes were minimal.

The replacement of pork back fat with camellia oil gelled emulsion up to 50 % also maintained the sensory quality of Harbin sausages, with increased moisture content and L^* and b^* values. Harbin sausages had an improved FA profile, though with reduced oxidative stability. Moreover, the sausages were significantly softer with increasing fat replacement levels (Serdaroğlu et al., 2017; Wang et al., 2018). This may be explained by the stronger correlation between moisture content and textural properties compared to fat content and textural properties (Franco et al., 2020). Camellia oil gelled emulsion was suggested as a feasible FR to reduce SFA content in Harbin sausage without apparent effects on sausage properties (Wang et al., 2018).

Fresh chicken sausages reformulated with O/W gelled emulsion (consisting of black cumin and flaxseed oil blend) also had higher moisture in addition to lower fat contents and enhanced FAC. In contrast to previous studies, fresh sausages were softer, had lower emulsion stability, and were darker than beef fat sausages at the end of storage due to the colour of black cumin oil (Kavuşan et al., 2020). Sausages with 50 % gelled emulsion were the most similar to the control in terms of texture, though they had lower oxidative stability and hardness, while higher gelled emulsion content (70–100 %) yielded the softest sausages. However, the inclusion of EG (80 %) did not affect the hardness of pork back fat-replaced dry, fermented meat products (fuets). This may be due to the different production steps involved for fuets and fresh sausages (Pintado & Cofrades, 2020).

Oleogel is also a popular strategy currently. The reformulated Harbin red sausage, utilizing a combination of peanut oil and EC oleogel to partially replace pork fat, demonstrated similar texture, lipid oxidation levels, and consumer acceptance as the original. Additionally, these reformulated sausages boasted a healthier fatty acid profile and increased nutritional value (Shao et al., 2023). Meanwhile, CNO-EC oleogel (CNO structured with EC) and its replacement levels (20–80 %) indistinctly altered the instrumental hardness, springiness, or chewiness of beef frankfurters. However, panellists claimed that oleogel beef frankfurters were firmer and oilier but less juicy. Water loss during cooking was noted to decrease with increasing levels of oleogel in frankfurters. Oleogel frankfurters were also lighter and had lower redness than beef fat frankfurters. In summary, the oleogels could be used to exploit the texture and sensory properties of frankfurter to achieve the standards of control (Barbut et al., 2016; Ferdaus et al., 2024).

Beeswax (BW) oleogel was found to yield dry-cured sausages with notably lower hardness, gumminess and chewiness, in addition to higher springiness at increasing replacement levels (20 % to 40 %). In comparison, γ-oryzanol-β-sitosterol oleogel insignificantly altered all textural parameters, except for decreased chewiness at a 40 % incorporation level. These results indicated that BW oleogel was more influential on the textural properties of the sausages than γ-oryzanol-β-sitosterol oleogel. All modified dry-cured sausages had significantly lower overall acceptability, but the sausages with 20 % oleogels obtained a positive acceptability compared to 40 % oleogel sausages. This suggests the potential of these oleogels as pork back fat replacers, up to 20 %, in dry-cured sausages (Franco et al., 2020).

Pork back fat in fuets was partially replaced (80 %) with EG or oleogel made from mixtures of OO and chia oil (8:2). Reformulated fuets had better FA profile, higher moisture content, lower fat content and cooking yield when compared with pork back fat fuet (control), although they had less favourable sensory attributes. It was noted that both EG fuet and oleogel fuet had similar proximate composition (except higher protein content in EG fuet), cooking yield, FAC and sensory quality. This showed that both FRs exhibited similar effects on the said properties of fuets. The hardness of all samples increased during chilled storage due to water loss, though oleogel fuet had smaller textural changes than the control. Generally, fuet made with oleogel was softer and more yellow than the control, whereas EG fuet had a comparable hardness to the control and was less yellowish than oleogel fuet (Shao et al., 2023).

4.1.3. Burgers/patties

Burgers and meat patties are highly consumed in many countries. In a study by Hamidioglu et al. (2022), hemp oil-based oleogels were explored as substitutes for animal fat in meat patties. Hemp oil exhibited higher levels of PUFA and lower oxidative stability compared to oleogels. Despite this, oleogels successfully mimicked the texture properties of pork fat, particularly in terms of spreadability and adhesiveness. However, sensory analysis of cooked meat patties fully replaced by oleogels showed that samples containing 100 % pork fat had superior juiciness and taste intensity. In another study, oleogels composed of a mixture of oils (OO, linseed oil and fish oil) and EC or BW were incorporated into pork burgers. This formulation reduced the SFA content while increasing PUFA and MUFA levels. However, it also led to reduced oxidative stability and a higher fat content. The oleogel-incorporated patties were softer and exhibited a more intense colour, with increased redness and yellowness. Nevertheless, both oleogels negatively impacted the flavour and overall acceptability of pork burgers, though those made with BW were more acceptable (Gómez-Estaca, Pintado, et al., 2019).

The partial substitution of sesame oil-BW oleogel had similar findings when raw beef burgers were softer at a higher substitution level, which may be contributed by higher moisture content and the smaller fat globules in oleogels as compared to animal fat. However, cooked oleogel burgers were darker and softer (except for 50 % oleogel burger), as well as being less gummy and chewy. A higher lipid oxidation and cooking shrinkage were also observed. Nevertheless, the positive effects of oleogel incorporation were the reduction in cooking loss and the fat uptake of beef burgers. Panellists preferred oleogel burgers over control burgers, which may be a consequence of the unique flavours of sesame oil. Moreover, sesame oil had higher oxidative stability than animal fat despite being highly unsaturated, attributed to the presence of lignans, including sesamin and sesamolin (Li et al., 2024; Moghtadaei et al., 2018).

Further research explored soybean oil (SBO)-EC oleogels reinforced with adipic acid (Adili et al., 2020). An optimized oleogel (2 % EC and 4 % adipic acid) exhibited superior crystallinity, thermal behaviour, and oil-binding capacity. The oleogels resulted in less chewy burgers, but the oleogel with higher EC concentration (6 %) yielded a softer burger compared to the control burger, while the optimized oleogel yielded the opposite. Both burgers had increased L^* and b^* but decreased a^*. Both burgers with oleogels had lower overall acceptability than the control, but the optimized oleogel burger had a higher score.

A similar approach was adopted by Aliasl Khiabani et al. (2020), where SBO oleogels were prepared using CNW instead of EC. The optimized CNW oleogel (2 % CNW and 4 % adipic acid) exhibited similar properties to the optimized EC oleogel. However, a high concentration (6 %) of EC and CNW affected hardness differently. Beef burgers in which 50 % bovine fat was replaced with CNW oleogels were firmer, with the 2 % CNW–4 % adipic acid oleogel increasing hardness more significantly. Despite their firmer texture and reduced juiciness, these burgers closely resembled the control in colour and sensory acceptability. Consequently, the optimized CNW oleogel was identified as the best fat replacer in this study.

In addition to oleogels, emulsions have been explored as fat replacers in burgers/patties. Formulated with an OO-gelled emulsion were lighter, more yellowish, and contained higher fat than control samples (Serdaroğlu et al., 2017). At 50 % animal fat substitution, the reformulated patties exhibited similar cooking characteristics and sensory qualities to the control. However, complete fat replacement deteriorated the most evaluated characteristics of chicken patties. Similar findings were also observed in the utilization of EG formulated with chestnut flour and chia oil as partial fat replacers in pork burger formulation (Lucas-González et al., 2020).

A recent approach where tiger nut oil emulsion was used to replace beef fat produced healthier beef burgers with improved oxidative stability and FAC (balanced increase in MUFA and PUFA with reduced SFA) (Carvalho Barros et al., 2020). At 100 % beef fat replacement, burgers had higher moisture content and lower fat content, as well as higher cooking loss. Tiger nut oil emulsion burgers were lighter and yellower and had similar textural (except springiness) and sensory characteristics as the control burgers. In addition, all beef burgers received comparable purchase intention and positive acceptance by consumers. Thus, indicating tiger nut oil emulsion as a prospective FR.

Similarly, the total replacement of beef fat with an emulsion of CNO and OO blend yielded harder and less springy, low-in-fat beef burgers with comparable overall acceptability as the control, but better FAC and nutritional profile. When prebiotic fibres (inulin and β-glucan mixture) were included in the burger formulation, the beef burgers had better cooking yield, moisture content, hardness and juiciness, while reduced flavour and chewiness (Afshari et al., 2017). Another study showed that OO/ linseed oil emulsion developed modified beef burgers that were lighter in colour and had higher fat and PUFA contents than the control beef burger (Gómez et al., 2018). Modified burgers were also more yellowish on the first two days of the retail display simulation. Surprisingly, oxidative stability was greatly improved due to the antioxidant-rich grape seed extract in the OO/ linseed oil emulsion, though cooking loss was increased. Despite being softer and less chewy, the sensory qualities of modified burgers were not influenced by beef fat replacement. This demonstrated the prospective combined use of healthy oils and functional ingredients as FR.

4.1.4. Pâtés

It was previously proven that 100 % pork fat replacement in pâté (a spreadable meat-based product) with CNO oleogels had similar textural properties as 100 % lard pâté but with weak oil retention properties (Barbut et al., 2019a). A subsequent study suggested that replacing 60 % of pork fat with CNO oleogels in chicken liver pâté was optimal, as it maintained good oil retention and textural properties while reducing saturated fat by 40 % with minimal impact on sensory attributes (Barbut et al., 2020). No significant increase in sensory and instrumental hardness was observed up to 60 % oleogel incorporation. However, the pâté became darker, with increased yellowness and redness. Additionally, a greater number of larger fat globules were observed at higher oleogel levels, suggesting a potential risk of reduced stability and increased oil separation.

In contrast, 60 % pork fat replacement with linseed oil-BW oleogel yielded pâtés with poorer sensory properties compared to pâtés with 30 % oleogel (Martins, Lorenzo, et al., 2020). This discrepancy may be due to differences in the fat content of the pâté formulations. While the gelation of linseed oil was successful with 8 % BW, the oleogel did not provide the same meat-binding properties as pork fat. Similar to previous findings, pâtés incorporating oleogels were darker and more yellow. Additionally, their hardness, gumminess, and adhesiveness were reduced compared to the control. Among the formulations tested, Pâté with 30 % oleogel incorporation had the nearest acceptance and preference results to those of the control, whereas pâté with 60 % oleogel had the furthest. This may be related to the strong and unfavourable odour exhibited by a high amount of linseed oil in the pâté.

4.1.5. Meatballs

In terms of meatballs, replacing chicken fat with CNO in roasted chicken meatballs improved the PUFA/SFA and n6/n3 ratios, enhancing their nutritional profile, enhancing their nutritional profile (Vieira et al., 2019). Additionally, the presence of citric acid (an antioxidant) in CNO contributed to greater oxidative stability in raw meatballs. However, CNO incorporation resulted in slightly darker roasted meatballs compared to the control, and a full replacement of chicken fat led to a softer texture. Overall, replacing up to 70 % of chicken fat with CNO was feasible, producing meatballs with good sensory acceptability.

Similarly, beef meatballs incorporated with OO emulsion had lower cholesterol content than beef meatballs made with lamb fat (control) (Abd-El-Aziz, 2020). The oxidative stability of meatballs was not affected despite having higher USFA content. In addition, the emulsion stability and cooking loss of meatballs improved with higher OO emulsion levels (75–100 %). Although meatballs with OO emulsion were softer than the control, their sensory evaluation scores were similar across all formulations, indicating that this substitution could effectively produce a healthier alternative without compromising quality.

However, substituting animal fat with oleogel gelled by CNW and made with SFO and black seed oil mixture in meatballs resulted in significant changes (Palamutoğlu, 2021). The effects on colour values, cooking parameters, lipid oxidation, and textural properties were evaluated. The type of oleogel significantly affected TBA values, with higher levels observed at the end of storage. Substitution rates also had a significant impact on the texture profile of meatball samples.

4.2. Bakery products

4.2.1. Cakes

Wax-structured oleogels were extensively studied for fat replacement in cakes (Table 3). SFW, BW, and RBW were evaluated as potential alternatives for fat in sponge cakes (Wettlaufer & Flöter, 2022). It was found that all tested waxes could create oleofoams. The sensory evaluation also confirmed satisfactory outcomes for the use of wax-based oleogels. Moreover, replacing shortening with oleogel (prepared using CNO and CNW) at 25 % had no significant effect on the specific gravity of cake batter and the volume of cake, while higher substitution levels negatively affected these parameters. However, the morphological parameters of cake crumbs and textural properties were similar to the control, whereas the hardness and chewiness of cakes increased when the oleogel level exceeded 50 % (Kim et al., 2017). Similar results were also observed when shortening was replaced with oleogels structured with BW, RBW or CDW (Malvano et al., 2022; Tanislav et al., 2022; Zhao et al., 2022). Cake crumbs were also lighter in colour when oleogels were added (Oh et al., 2017). Oleogels significantly increased the PUFA content and reduced the SFA content in cakes (Giacomozzi et al., 2022; Kim et al., 2017; Oh et al., 2017). And BW-based oleogel was the most suitable FR since it produced cake that was the closest to the control for most evaluated parameters (Oh et al., 2017).

Cakes with 50 % shortening replaced with SBO-based oleogels containing 6 % EC or a blend of 2 % EC and 4 % adipic acid exhibited lower L* and b* values but higher a* values than the control (Adili et al., 2020). Both oleogels yielded more springy cakes, but the cake was harder and chewier with increasing EC concentration. Thus, a higher EC content significantly impacted cake texture and reduced overall acceptability. These findings aligned with results from Aliasl Khiabani et al.(2020), who formulated SBO-based oleogels but used CNW instead of EC. Previous studies also reported that oleogel incorporation resulted in firmer cakes. Previously, it was reported that the incorporation of oleogel produced a harder cake (Kim et al., 2017; Oh et al., 2017). Oleogels that contained adipic acid gave softer cakes due to the close 3D network formed, which allowed more aerated cake batters (Aliasl Khiabani et al., 2020). These oleogels yielded cakes with similar sensory quality to the shortening cake and hence are prospective shortening replacers in bakery products (Adili et al., 2020; Aliasl Khiabani et al., 2020).

A complex oleogel system was also investigated for cake applications. Edible double-network oleogels were produced using hydroxypropyl methylcellulose (HPMC) and glyceryl monostearate (GMS) through the cryogel-templated method (Jiang et al., 2022). These oleogels were capable of substituting 50 % of commercial butter in cookies and cakes, offering the flexibility to adjust the texture of baked goods by optimizing the GMS crystal network's enhancing effect on the oleogels. In sponge cakes, a blend comprising whey protein, emulsifier E471, and BW was studied as a full replacement for butter (Malvano et al., 2022). The findings indicated that the optimal formulation consisted of 76.98 % OO-based oleogel, 7.28 % emulsifier, and 15.73 % whey protein. Plum cakes made with this formulation were stored at room temperature for three months. During this period, a reduction in water activity was observed, which resulted in increased hardness and decreased moisture content. However, despite these changes, the cakes maintained mold resistance, likely attributed to the effects of the emulsifier and whey proteins included in the dough.

Hydrogenated fat in cakes was replaced with rice bran oil or its spreads containing 2 % or 5 % edible gelators (Shaik et al., 2017). All reformulated cakes had lower SFA and TFA contents, higher UFA content, and similar sensory quality to the control, despite having higher density. In addition, rice bran oil spread produced cake with a finer and smoother internal structure, and comparable to control based on the consumer evaluation study. Rice bran oil spread with 2 % gelators was concluded as the best FR that could formulate cakes with better FAC, texture and loaf volume without diminishing the cake quality. However, higher gelator concentrations negatively impacted overall acceptability.

All pound cake formulations with margarine replaced with oil mixtures, with or without 1 % gelatin, had lower firmness and L^* and b^* values than the control cake (Sánchez-Paz et al., 2020). Gelatinization temperature and protein coagulation remained unchanged during baking at a 70 % margarine replacement level. However, oil mixtures without gelatin reduced sensory quality, whereas pound cakes containing gelatin and 70 % oil mixtures had the highest preference scores and better fatty acid composition, particularly an improved n-6/n-3 ratio compared to the control. Thus, replacing margarine with a 70 % CNO and CO blend along with gelatin enhanced the nutritional quality of pound cakes with minimal impact on sensory characteristics.

However, other studies have shown that the replacement of shortening with as low as 10 % OO had adversely affected all evaluated sensory parameters, as well as physical (weight, height, volume) and textural (hardness, cohesiveness, chewiness) properties of muffins, and the increasing levels of OO further enhanced these effects. However, the partial replacement of shortening with up to 20 % OO in muffins would be appropriate since the FAC of the muffin was improved without significantly affecting its proximate composition and sensory and textural qualities (Punia et al., 2020).

Solid-like EG were also proposed as an effective alternative to traditional fats in cakes. For instance, water-in-oil (W/O) EGs were developed using water, peanut sprout oil (PSO), sorbitan monostearate (SMS), and CDW in different proportions (Jeong et al., 2023). These EGs were evaluated for their potential as shortening substitutes in muffins. Muffins prepared with these EGs exhibited a firmer texture and larger pore size compared to traditional muffins made with shortening. Sensory evaluation revealed that muffins containing a specific ratio of 25 % SMS and 75 % CW had a similar overall preference to shortening-based muffins, indicating the potential of W/O EGs to produce high-quality muffins without compromising taste or texture.

4.2.2. Biscuits and cookies

In a study, apeseed oil was thickened with microcrystalline wax crystals, forming an FR with uniformly distributed crystals that could mimic the general structure of the tested palm fat but consisted of larger and more loosely packed crystals (Schmid et al., 2020). Meanwhile, the emulsions stabilised by microcrystalline cellulose or rapeseed press cake were unable to mimic the microstructure of palm fat. All three FRs exhibited significantly lower viscosity than palm fat and produced darker shortbread biscuits that were fattier, firmer, and had a weaker aftertaste. Microcrystalline wax crystals reduced biscuit firmness, while emulsions resulted in less elastic biscuits, though these textural properties improved after storage. Biscuits with microcrystalline wax crystals showed higher sandiness due to their higher fat content compared to emulsion-type FRs. It was suggested that all FRs applied were prospective palm fat replacers in shortbread cookies.

Recently, Pang et al. (2023) observed similar outcomes with RBW (6 %) oleogel replacing 7:3 (oleogel:shortening) in cookies, exhibiting comparable hardness, crispness, colour, and sensory scores to those without shortening. Their study further explored the effects of different wax types, including BW, candle wax, and CNW, and identified BW and RBW oleogels as the most promising alternatives. Similarly, Li et al. (2022) further studied the effect of the structure and physical properties of wax oleogels on the quality of cookies. Their findings showed that cookies containing 5–9 % RBX and CDW had a soft texture, porous structure, and appealing spread and colour. Oleogels with lower solid fat content and higher β' crystal content resulted in cookies with hardness levels comparable to those made with shortening. Notably, the hardness of cookies prepared with wax oleogels was primarily influenced by crystal quantity rather than crystal size.

On the other hand, camellia oil was structured into oleogels using an emulsion template method, incorporating tea polyphenol ester particles

Table 3
Summary of the application of fat replacers in bakery products.

Food products	Fat replacers	Plant oils	Gelators, emulsifiers, or stabilizers	Replacement levels (%)	Main findings	Refs.
Cakes	Oleogel	SBO	EC, adipic acid. CNW, adipic acid	50	Cakes had better sensory characteristics and more acceptable texture when oleogel was prepared with 2 % CNW or EC and 4 % adipic acid.	Adili et al. (2020), Aliasl Khiabani et al. (2020)
		SFO	BW, RBW	100	Cakes incorporated with oleogels had a healthier lipid profile. BW cake and CNW cake (with 25 % fat replacement) resembled the control cake the most in terms of volume and texture.	Kim et al. (2017), Oh et al. (2017)
		CNO	CDW. CNW	25, 50, 75, 100		
		High oleic SFO	MAG	100	The oleogel-based muffin scored higher in appearance and colour compared to the Control, while flavour and sponginess were similar.	Giacomozzi et al. (2022)
		CNO	SFW, BW, RBW		All waxes formed oleofoams, with crystal aggregate location affecting properties. In sponge cakes, oleogels improved oil-leaping and appearance compared to CNO.	Wettlaufer and Flöter (2022)
		OO	BW	100	Stored for 3 months at room temperature, the cake showed no significant changes in hardness, moistness, or mould growth.	Malvano et al. (2022)
		High oleic SBO	MAG, RBX	100	MAG oleogel delayed gelatinization in both bread and cracker doughs, while RBX oleogel showed similar dough properties to shortening.	Zhao et al. (2022)
		SFO	CNW, β-sitosterol, BW, lecithin, and glycerol monostearate	100	Dough with carnauba wax oleogel had the highest hardness. All oleogel-containing doughs showed solid-like behaviour.	Tanislav et al. (2022)
	Emulsion gel	Peanut sprout oil	Water, sorbitan monostearate, and CDW	100	Muffins made with emulsion gels exhibited increased hardness compared to those made with shortening, although sensory evaluations did not reveal a significant difference in perceived hardness.	Jeong et al. (2023)
		SBO	Zein, β-carotene	100	Cakes made with zein-based O/G emulgels as a substitute for margarine exhibited similar functionalities, including texture and sensory attributes, when compared to traditional cakes.	Chen et al. (2016)
	Emulsion	Rice bran oil	Edible gelators (hydrocolloids)	100	Rice bran oil spread with 2 % gelators gave the best cake with reduced fat content, improved FAC, and similar overall acceptability as the control.	Shaik et al. (2017)
	Liquid oil	Rice bran oil	-	100	Cakes had lower TFA and SFA contents and higher PUFA content. Overall acceptability was not affected, and perceived texture was better than the control.	
		CNO, chia oil	-	70, 90	At 70 % replacement level, cakes had healthier FA profiles, higher volume and uniform crumb texture.	Sánchez-Paz et al. (2020)
		OO	-	10, 20, 30, 40	Proximate composition was not affected. With up to 20 % OO incorporation, cakes were nutritionally better and had acceptable sensory properties.	Punia et al. (2020)
Biscuits and cookies	Oleogel	Camellia oil	Tea polyphenol esters, citrus pectin	25, 50, 75, 100	Up to 50 % inclusion of oleogels structured with tea polyphenol palmitate or stearate particles resulted in cookies with similar break strength, spread ratio and quality scores as the control.	Pan et al. (2020)
		High-oleic rapeseed oil	EC, RBW, CDW, BW, monoacylglycerol	100	Oleogels containing 5 % monoacylglycerol produced biscuits with the most comparable properties to the control. EC, monoacylglycerol, RBW, and CDW oleogels maintained the fat migration properties of biscuits.	Onacik-Gür and Żbikowska (2020)
		Corn oil	HPMC, MAG, SSL, RBW and BW	100	Texture, microstructure, and colour analyses revealed similar properties among MAG, RBW, and shortening-based cookies.	Li et al. (2021)
		Corn oil	MAG, SSL, PGE and SPAN	100	MAG and SPAN cookies showed similar hardness and colour to shortening cookies, with uniformly porous cross sections.	Li et al. (2022a)
		Rapeseed oil	sunflower wax, EC, MAG	100	Oleogel-based cookies have reduced saturated fats and increased polyunsaturated fats, though consumer acceptance is slightly lower compared to conventional cookies.	Schubert et al. (2022)
		RBO	Candle wax, CNW, BW, RBW	30, 50, 70, 100	BW and RBW oleogels showed greater potential for replacing shortening in cookies compared to CDW and CRW oleogels.	Pang et al. (2023)
		Rapeseed oil	Microcrystalline wax	100	Biscuits exhibited similar elasticity and firmness to the control after two days of storage.	Schmid et al. (2020)
	Particle stabilised emulsion	Rapeseed oil	Microcrystalline cellulose	100	Both structuring agents produced FRs with comparable effects and yielded biscuits with sensory properties near to that of the control.	Schmid et al. (2020)
	Palm-based shortening	SBO, palm fraction	Distilled monoglyceride	100	The thickness, width and spread ratio of cookies were unaffected. A lower liquid SBO content in shortening resulted in softer cookies.	Nur Illiyin et al. (2020)

Note: hydroxypropyl methylcellulose (HPMC), monoacylglycerol (MAG), sodium stearyl lactate (SSL), sorbitan monostearate (SPAN), and Glyceryl monostearate (GMS).

Table 4
Summary of the application of fat replacers in dairy products.

Food products	Fat replacers	Plant oils	Gelators, emulsifiers, or stabilizers	Replacement levels (%)	Main findings	Refs.
Ice milk	Liquid oil	Red palm oil	-	25, 50, 75, 100	Successful incorporation of up to 50 % with increased carotenoid and vitamin E contents, decreased SFA, and good sensory quality as the control. Acidity and pH were also unaffected.	Abd-ElGhany et al. (2020)
Ice cream	Liquid oil	Red palm olein	-	100	The viscosity of ice creams was not affected. Ice creams had a similar hardness and melting rate as the control when added with 0.3–0.4 % stabilizers. Xanthan gum provided better sensory attributes.	Ismail et al. (2020)
	W/O/W double emulsion	SFO	PGPR-lecithin blend, guar gum, gum tragacanth, calcium chloride	100	Double emulsion and the combined use of gums successfully yielded low-fat ice cream that had better overrun and melting rate and similar overall acceptability as the regular fat ice cream.	Tekin et al. (2017)
	Emulsion gel	Sunflower seed oil	Bacterial cellulose nanofibers/Soy protein isolate complex colloidal particles	30, 60, 90	Ice cream with low-oil Pickering emulsion gels as fat replacers had a similar appearance and texture to traditional ice cream and a slower melting rate when fat replacement reached 90 %.	Gao et al. (2023)
	Oleogel	SBO, peanut oil	CNW	50, 100	Replacing the traditional lipid phase with oleogel reduced the melting rate of ice creams but adversely affected the ice cream overrun.	Airoldi et al. (2022)
		Camelia oil	BW	100	Oleogel ice cream outperformed both butter and camellia oil ice cream in overall quality.	Jing et al. (2022)
Cheese products	Oleogel	SBO	RBW, SFW	100	The proximate composition and meltability of processed cheese products were not altered, and the SFA content was lowered. Oleogel with 10 % RBW yielded samples with similar hardness as the control.	Huang et al. (2018)
		SBO	RBW	100	During the 14-day storage period, there were no significant differences observed in the total tocopherol content between the oleogel-cream-cheese and ungelled cream-cheese samples.	Park et al. (2018)
	Emulsion gel	OO	Dry-fractionated pea protein, inulin	10, 13, 15	The plant-based cheese analogues were characterized by high protein content and low-fat content. While their spreadability index was comparable to that of dairy cheese, they exhibited lower hardness and higher elasticity due to their reduced fat content.	Mefleh et al. (2022)
	Liquid oil	Palm oil	-	100	The rheological properties of cheese were not affected at the end of the ripening process (week 16)	Myhan et al. (2020)

(Pan et al., 2020). Cookie dough made with oleogels or camellia oil exhibited elastic behaviour similar to butter dough, but when oleogel content exceeded 50 %, the dough became harder, leading to cookies with higher breaking strength and hardness. Compared to oleogel cookies, camellia oil cookies had similar technological properties but exhibited a larger spread, lower height, and the lowest overall quality score. The study concluded that oleogels formulated with tea polyphenol ester particles containing 16–18 carbon FAs at a 25–50 % level yielded the best cookies, with sensory scores, spread ratio, break strength, and storage stability comparable to the control.

Lard in cookies was replaced with palm-based shortenings made from blends of palm fraction and SBO in two different ratios. Palm-based shortening produced cookie dough that had higher L^*, a^* and b^*, but was comparable to lard-containing dough in terms of thickness, width and spread ratio, indicating that both doughs had similar solid-like structures. However, shortening with a higher palm fraction led to doughs with the highest hardness and compressibility. Meanwhile, shortening with a higher SBO content led to harder biscuits (Nur Illiyin et al., 2020). This was due to the lower solid fat content of the shortening, which fastened the melting of the shortening and, hence, promoted gluten reaction (Du et al., 2024; Noor Raihana et al., 2017). These findings indicate that palm-based shortening, with an appropriate balance of liquid oil, could serve as a viable lard substitute in cookies.

Various high-oleic rapeseed oil oleogels (structured with EC, RBW, CDW, BW, or monoacylglycerol) were used to replace palm oil in biscuits (Onacik-Gür & Żbikowska, 2020). The structuring agent significantly influenced dough and biscuit properties, including texture, density, and oil migration. All biscuits added with oleogels were darker and had denser structures. In addition, most oleogel-incorporated biscuits were harder but easier to break than the control sample. Results showed that CDW-structured oleogels most closely resembled palm oil, while oleogels with monoacylglycerol produced cookies with properties most comparable to the control.

4.3. Dairy products

4.3.1. Ice cream and ice milk

Red palm olein and stabilizers were used to replace milk fat in ice creams (Ismail et al., 2020) (Table 4). The reformulated ice creams exhibited viscosity levels comparable to commercial products, but only those with 0.3–0.4 % stabilizer achieved hardness similar to commercial counterparts. Reformulated samples had higher a^* and b^* values due to stabilizers showing strong effects on colour enhancement, which may have affected consumer preferences. Meanwhile, although red palm olein incorporation increased the melting rate, the addition of gums helped improve both the melting resistance and overrun of the ice cream, with xanthan gum performing better than guar gum. Sensory analysis indicated that ice creams made with xanthan gum had better attributes than those made with guar gum. However, commercial ice creams remained the preferred choice due to their yellowish colour, slightly harder texture, and the absence of desirable flavours in the reformulated versions. Similarly, milk fat replacement at 50 % with SFO did not affect both *in-vitro* and in-mouth release of safranal, an aroma compound of saffron, from saffron ice cream, though overall aroma release was weaker than 100 % milk fat ice cream (Feyzi et al., 2020). In addition, green and herbal odours were perceived from the fat-replaced ice cream.

Red palm oil was also incorporated into ice milk, resulting in lower viscosity, lower overrun, and a higher melting rate compared to the control (100 % milk fat) (Abd-ElGhany et al., 2020). Increasing concentration of oil induced higher carotenoid and vitamin E contents in ice milk and, hence, a darker and greater intensity of redness and yellowness. Nevertheless, the reformulated ice milk had lower SFA content and higher PUFA and MUFA contents than the control. No significant changes were observed in the pH and acidity values of the reformulated ice milk. Only ice milk with 25 % or 50 % red palm oil had comparable sensory characteristics to the control.

Furthermore, a W/O/W double emulsion was successfully used as a milk fat replacer, formulating a low-fat ice cream with over 70 % fat reduction without compromising quality (Tekin et al., 2017). Polyglycerol polyricinoleate-lecithin blends were used as emulsifiers, while guar gum or guar gum-gum tragacanth blends functioned as stabilizers. The double emulsion ice cream (0 % milk fat) demonstrated higher overrun values and greater meltdown resistance than regular ice cream (12 % milk fat). In addition, double emulsion ice cream achieved better mouth-coating and overall acceptability than conventional low-fat ice cream (2.8 % milk fat). Notably, the incorporation of guar gum-gum tragacanth blends in double emulsion formulations led to a 6 % increase in overrun, a 13 % reduction in melting rate, and a 20 % improvement in overall sensory acceptability compared to formulations stabilized with guar gum alone.

Recently, Gao et al. (2023) developed food-grade pickering EG stabilized by bacterial cellulose nanofibers/soy protein isolate complex colloidal particles through a one-step method. These gels, with a 5 % oil phase fraction, were utilized as fat replacers in ice cream formulations. The results indicated that ice cream containing low-oil pickering EG as fat replacers exhibited a similar appearance and texture to conventional ice cream, with a significantly reduced melting rate (21.08 %) when fat replacement reached 90 %. This suggests that low-oil pickering EG are promising fat replacers with potential applications in low-calorie food production.

Furthermore, research has explored the use of oleogels to reduce fat content in ice cream. Airoldi et al. (2022) investigated the physical and sensory effects of replacing 50 % and 100 % of milk fat with CNW soybean oil oleogel. While the fat replacement decreased the ice cream's melting rate, it adversely affected the ice cream overrun. However, substituting 50 % of the traditional lipid phase with CNW oleogel did not significantly alter sensory attributes, indicating the feasibility of using oleogel as a partial cream substitute in ice cream production. In another study, BW oleogel was tested as a substitute for milk fat in ice cream (Jing et al., 2022). The oleogel, comprising 7 % BW in camellia oil, was compared with an ice cream control made solely with camellia oil. The results indicated that the oleogel ice cream had moderate overrun, melting rate, and hardness, with a longer first dropping time than the camellia oil ice cream. However, sensory analysis revealed that the control ice cream was preferred by consumers, whereas the camellia oleogel ice cream received lower acceptance scores.

4.3.2. *Cheese products*

Palm oil insignificantly affected the chemical composition of Edam-type cheese when replaced milk fat fully but retarded the progression of the cheese ripening process (Myhan et al., 2020). The rheological properties of cheese made with palm oil were significantly affected at week 4 of ripening. However, the effect was not noteworthy since the cheese was at the beginning of the ripening process and was not ripened enough for consumption. Since textural and sensory analysis were absent in this study, the full potential of palm oil as a milk fat replacer in Edam-type cheese could not be determined.

Meanwhile, SBO oleogels were successfully used to produce processed cheese products with moisture and fat contents comparable to commercial counterparts but with lower saturated fat levels (Huang et al., 2018; Salama et al., 2024). The utilization of oleogels reduced the agglomeration of oil, demonstrating its ability to improve the oil-binding capacity of the product. Furthermore, oleogels improved the hardness and melting ability of processed cheese products, with RBW oleogel producing samples with similar hardness to the control. However, higher wax concentrations increased hardness due to the formation of denser lipid crystalline networks. Despite this, oleogels show promise as milk fat replacers in the production of processed cheese, enabling the development of lower-cost, reduced-milk-fat dairy products with favorable properties.

A spreadable plant-based cheese analogue was created by incorporating dry-fractionated pea protein and an emulsion-filled gel containing extra virgin OO and inulin as a FR (Mefleh et al., 2022). The developed products exhibited high protein content and low-fat content. Despite a similar spreadability index to dairy cheese, the plant-based analogues showed lower hardness and higher elasticity, attributed to their reduced fat content. These findings collectively highlight the potential of alternative fat replacers, including palm oil, oleogels, and emulsion-based formulations, in enhancing the development of cheese products at an industrial scale.

5. Conclusion and recommendations

Plant oil-based FRs (including liquid plant oils, hydrogenated and interesterified fats, oleogels, emulsion gels (EGs), and emulsions) offer viable alternatives to conventional animal fats, facilitating the modification of lipid profiles to achieve healthier and more sustainable formulations while maintaining desirable technological and sensory properties.

Each type of FR exhibits distinct physicochemical and functional characteristics, influencing its performance in different food matrices. Liquid plant oils, despite their high content of unsaturated fatty acids, often require structuring techniques such as hydrogenation, interesterification, or oleogelation to achieve the desired solid-like properties for specific applications. While hydrogenation and interesterification modify fat crystallization behavior and improve functional properties, concerns regarding trans fat formation and process complexity may limit their widespread use. Oleogels and EGs have gained increasing attention due to their ability to enhance oil-binding capacity, oxidative stability, and textural properties, offering promising alternatives to traditional solid fats. Additionally, emulsions have been explored as fat-reduction strategies, improving water retention and mouthfeel, though their long-term stability and interactions with other food components require further investigation.

Given the inherent complexity of food matrices, a universal fat replacer capable of fully replicating the functional and sensory properties of animal fats across all product categories remains elusive. Instead, tailored formulations are necessary to optimize technological functionality, sensory attributes, and nutritional benefits based on the specific requirements of each application. While many plant oil-based FRs have demonstrated the potential for improving the health profile of reformulated products, consumer acceptance remains a critical consideration, as differences in taste, texture, and oxidative stability may influence market viability. Future research should prioritize optimizing formulation strategies, improving stability, and enhancing consumer acceptance of plant oil-based FRs.

CRediT authorship contribution statement

Kok Jia-Wei: Writing – original draft, Data curation, Conceptualization. **Ming Fu:** Writing – original draft, Data curation. **Abu Bakar Asyrul-Izhar:** Writing – review & editing, Writing – original draft, Data curation. **Lilis Suryaningsih:** Writing – review & editing. **Dicky Tri Utama:** Writing – review & editing. **Kazem Alirezalu:** Writing – review & editing. **Mohammad Rashedi Ismail-Fitry:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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