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Waychal SN
Ph.D., Scholar, Department of AHDS, PGI, MPKV Rahuri, Maharashtra, India

Patil BD
Deputy Director of Research, MPKV, Rahuri, Maharashtra, India

Lokhande AT
Assistant Professor, Department of AHDS, PGI, MPKV, Rahuri, Maharashtra, India

Kamble DK
Head of Department, Department of AHDS, PGI, MPKV, Rahuri, Maharashtra, India

Kadape BB
Ph.D., Scholar, Department of AHDS, PGI, MPKV Rahuri, Maharashtra, India

Corresponding Author:
Waychal SN
Ph.D., Scholar, Department of AHDS, PGI, MPKV Rahuri, Maharashtra, India

Advances in lipid structuring and health implication in dairy

Waychal SN, Patil BD, Lokhande AT, Kamble DK and Kadape BB

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Abstract
Milk fat is a vital component in dairy products, contributing to flavor, texture, and nutritional value. However, growing health awareness has prompted significant research into modifying the structure and composition of lipids to reduce saturated fat content and enhance functional benefits. Recent advances in lipid structuring technologies including enzymatic interesterification, oleogelation, fractionation, and nanoemulsion techniques have opened new avenues for designing healthier dairy products without compromising sensory quality. These approaches allow incorporation of bioactive lipids such as omega-3 fatty acids, conjugated linoleic acid (CLA), medium-chain triglycerides (MCTs), and phytosterols into traditional dairy products like milk, yogurt, butter, and cheese.
This review comprehensively explores the composition and characteristics of dairy lipids, various lipid structuring techniques applicable to dairy systems, and their implications for product development and human health. Particular emphasis is placed on technological feasibility, oxidative and sensory stability, regulatory challenges, and future perspectives involving clean-label trends, designer lipids, and sustainable lipid sources. By integrating food engineering, lipid chemistry, and nutritional science, structured lipid technology in dairy products represents a promising frontier for enhancing both functionality and health attributes. This review also identifies current research gaps and proposes directions for future innovations in dairy lipid design.

Keywords: Lipid structuring, dairy lipids, oleogel, functional dairy foods, omega-3 fatty acids, structured lipids, CLA, interesterification, nanoemulsion, phytosterols

1. Introduction
Milk fat plays an important role in determining the sensory characteristics, nutritional profile, and overall consumer acceptance of dairy products. It imparts richness, creaminess, and flavor, while also serving as a carrier for fat-soluble vitamins (A, D, E, and K) and bioactive compounds (German & Dillard, 2006) [25]. Although dairy fats are traditionally rich in saturated fatty acids (SFAs), their role in cardiovascular and metabolic diseases has been the subject of ongoing debate, with emerging research suggesting that the health impact of SFAs may depend on the specific food matrix and fatty acid profile. This has sparked growing consumer demand for healthier, functional dairy products with improved lipid profiles.
Concurrently, global food trends are shifting toward personalized nutrition, clean-label formulations, and functional foods that not only provide essential nutrients but also promote health and prevent disease. In this context, lipid modification or "structuring" technologies are gaining traction as innovative tools to tailor the functional, physical, and nutritional properties of dairy lipids. These methods enable the incorporation of health-promoting fatty acids (e.g., omega-3, CLA, MCTs), improve digestibility, and allow for better control over melting behavior, stability, and sensory attributes.
Recent advances in lipid structuring such as enzymatic interesterification, oleogelation, fractionation, and nanoemulsification have revolutionized the possibilities for designing dairy lipids with enhanced functionality. These techniques are particularly valuable for replacing saturated fats without compromising product quality or consumer satisfaction. This review aims to comprehensively explore the evolving landscape of lipid structuring technologies in the dairy sector. It focuses on the composition and physicochemical properties of dairy lipids, novel structuring methods and their technological applications,

incorporation of functional lipids to improve health outcomes and the current challenges and future directions in structured lipid development for dairy applications.

2. Composition and Properties of Dairy Lipids

Milk fat is a complex mixture of over 400 different fatty acids, making it one of the most intricate natural fats in terms of composition. The bulk of milk fat is in the form of triacylglycerols (TAGs), accounting for over 98% of the lipid fraction. In addition, milk contains minor lipid components such as diacylglycerols, free fatty acids, phospholipids (primarily in the milk fat globule membrane, MFGM), and sterols (Michalski *et al.*, 2006) [49].

2.1 Fatty Acid Composition

The fatty acid profile of bovine milk fat includes short-chain fatty acids (SCFA), medium-chain (MCFA), and long-chain fatty acids (LCFA), encompassing saturated (SFA), monounsaturated (MUFA), and polyunsaturated fatty acids (PUFA). The predominant fatty acids include palmitic acid (C16:0), oleic acid (C18:1), stearic acid (C18:0), and myristic acid (C14:0). Trace amounts of essential fatty acids like linoleic (C18:2) and alpha-linolenic acid (C18:3) are also present.

Table 1: Fatty Acid Composition of Bovine Milk Fat (Michalski *et al.*, 2006) [49].

Fatty Acid	Common Name	Percentage of Total Fatty Acids (%)
C4:0	Butyric Acid	3-4
C8:0	Caprylic Acid	1-2
C10:0	Capric Acid	2-3
C12:0	Lauric Acid	3-4
C14:0	Myristic Acid	11-12
C16:0	Palmitic Acid	26-32
C18:0	Stearic Acid	10-13
C18:1 (cis-9)	Oleic Acid	20-25
C18:2 (n-6)	Linoleic Acid	1.5-2.5
C18:3 (n-3)	α-Linolenic Acid	0.5-1.0

2.2 Structural and Physical Properties

The physical behavior of milk fat is governed by its complex crystalline and polymorphic nature. Milk fat can crystallize into multiple forms (α, β', and β), each with distinct melting points and textural impacts (Lopez *et al.*, 2005) [42]. The β' form is desirable for smoothness and spreadability, whereas β polymorphs are more rigid and waxy. Furthermore, milk fat exhibits broad melting behavior ranging from -40°C to 40°C due to the wide variety of TAG molecular species. Crystallization kinetics, polymorphism, and emulsification behavior influence the texture and sensory profile of products like butter, cheese, and ice cream. These properties also determine how well milk fat can be structured or modified for functional applications.

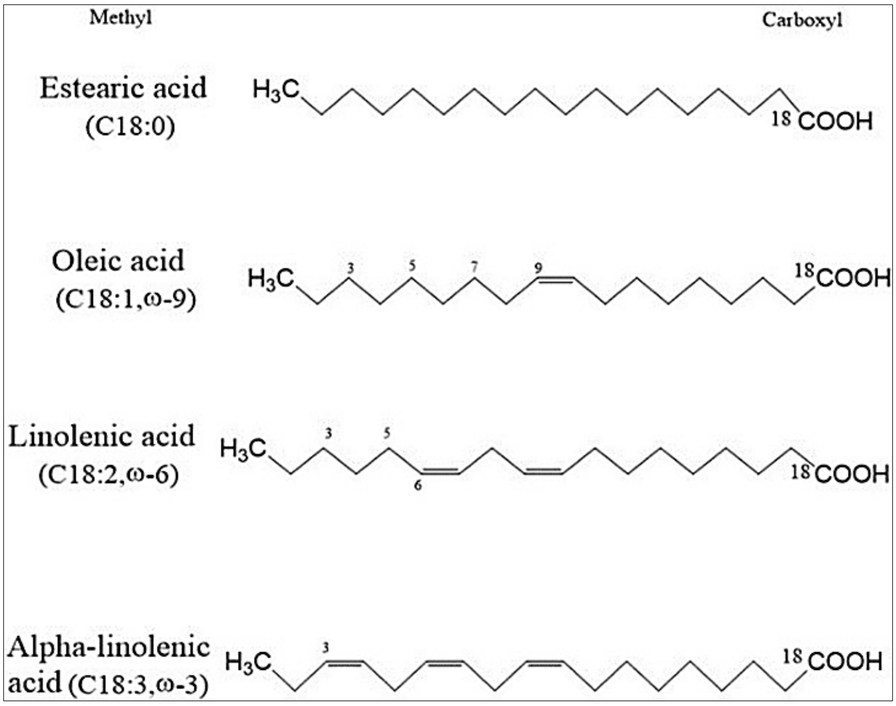

Fig 1: Chemical structures of α-linolenic acid, eicosapentaenoic acid, decoxaheptaenoic acid

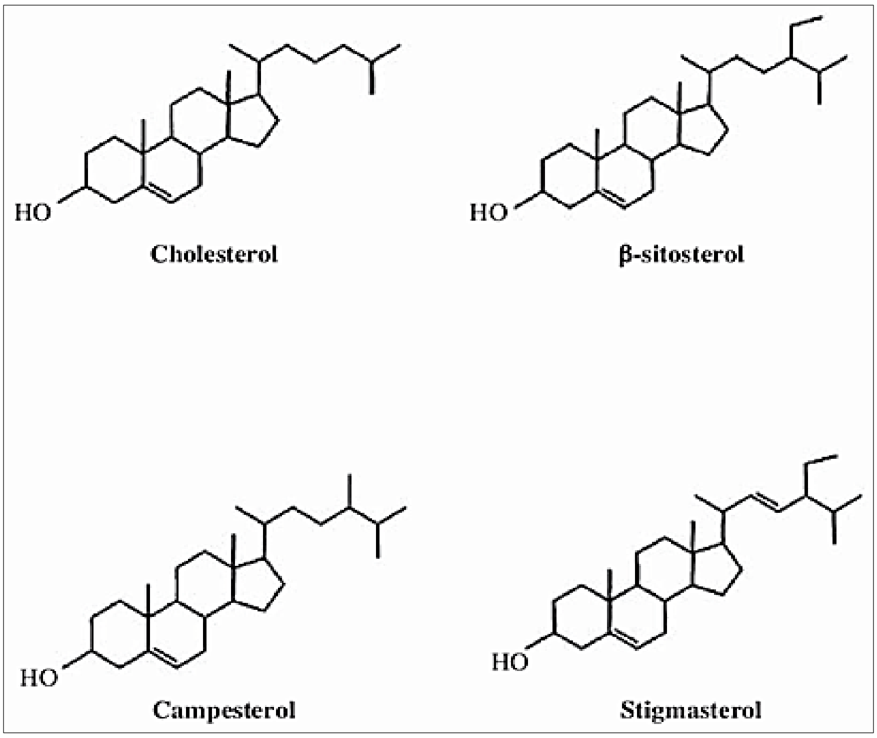

Fig 2: The chemical structures of cholesterol, sitosterol, sitostanol. campesterol and campestanol

2.3 Digestibility and Bioavailability

The structure of milk fat affects its digestibility and metabolic fate. TAG molecules with saturated fatty acids in the sn-1 and sn-3 positions are less efficiently hydrolyzed compared to those with unsaturated fatty acids or SN-2 palmitate (common in human milk fat). Additionally, milk fat globules enclosed in MFGM offer bioactive functions, such as antimicrobial and anti-inflammatory effects (Dewettinck *et al*., 2008) [20].

3.0 Lipid Structuring Techniques in Dairy

Advances in lipid structuring techniques have revolutionized the functional and nutritional design of dairy products. Lipid structuring refers to the physical and chemical modification of lipids to achieve desirable textural, thermal, and health-related characteristics. In the dairy sector, these approaches allow the reduction or replacement of saturated fats, incorporation of functional bioactives (e.g., omega-3 fatty acids, phytosterols, conjugated linoleic acid), and control over melting profiles and sensory properties. Key lipid structuring techniques applicable to dairy matrices include interesterification, oleogelation, fractionation, and emulsification/nanoemulsion technologies.

3.1 Interesterification

Interesterification is a process wherein fatty acids are redistributed within or among triacylglycerol (TAG) molecules without altering their degree of saturation. This rearrangement can be achieved through chemical or enzymatic catalysis, resulting in modified melting behavior, plasticity, and digestibility of fats.

Chemical Interesterification-

Chemical interesterification typically uses sodium methoxide or sodium ethoxide as catalysts under high temperature and vacuum conditions. Although cost-effective and widely used in industrial settings, this method lacks positional specificity, potentially resulting in random rearrangement of fatty acids and loss of structured lipid benefits (Chakraborty *et al*., 2014) [13].

Enzymatic Interesterification

Enzymatic interesterification, often using lipases such as Lipozyme TL IM or Novozym 435, offers regioselective and stereospecific modifications, allowing targeted placement of beneficial fatty acids at the sn-2 position (e.g., SN-2 palmitate for infant formula applications) (Osborn & Akoh, 2003; Liu *et al*., 2006) [53, 41]. It is considered more suitable for food applications due to its mild reaction conditions and better control over product functionality.

In dairy product development, interesterification has been widely applied to produce low-saturated-fat butter analogs, which maintain desirable textural and spreadability characteristics while reducing the intake of saturated fats. This process also enables the formulation **of** customized spreadable fats with controlled melting points suited for specific climatic and culinary preferences. interesterification is crucial for creating fortified dairy lipids enriched with health-promoting compounds such as omega-3 fatty acids and conjugated linoleic acid (CLA). By strategically positioning these bioactive fatty acids especially at the sn-2 position on the glycerol backbone their digestibility and bioavailability can be significantly improved, enhancing their physiological efficacy (Maduko *et al*., 2005) [43].

3.2 Oleogelation

Oleogelators are agents that transform liquid oils into semi-solid structures through mechanisms like crystallization, hydrogen bonding, self-assembly, and emulsion stabilization, making them valuable in dairy fat structuring. Waxes form crystalline networks effective at low concentrations and are commonly used in trans-fat-free formulations. Fatty alcohols and fatty acids structure oils via hydrogen bonding but may require blending to optimize sensory qualities. Phytosterols and phytostanols selfassemble into fibrillar networks and offer added health benefits like cholesterol-lowering effects. Proteins and polysaccharides, used in emulsion-based gels, are especially suited for dairy systems such as probiotic yogurts and functional spreads due to their clean-label and food-grade status.

Table 2: Types of Oleogelators, Mechanisms, Applications

Oleogelator Type	Examples	Mechanism	Key Dairy Applications	References
Waxes	Beeswax, Rice bran wax, Candelilla	Crystallization, van der Waals forces	Butter analogs, low-sat-fat spreads	Dassanayake *et al*. (2009); Acevedo *et al*. (2012) [2]; Marangoni & Garti (2011) [44]
Fatty Alcohols/Acids	Stearyl alcohol, Stearic acid	Hydrogen bonding, lamellar networks	Texture modifiers, solid fat mimetics	Rogers *et al*. (2009); Pernetti *et al*. (2007); Davidovich-Pinhas & Barbut (2015) [19]
Phytosterols/Phytostanols	β-sitosterol, Stigmasterol	Fibrillar self-assembly	Functional yogurts, cholesterol-lowering dairy spreads	Co & Marangoni (2012) [16]; Barbut *et al*. (2016) ; Patel *et al*. (2014) [55].
Proteins & Polysaccharides	Gelatin, Xanthan gum, Pectin	Emulsion-based gelation	Probiotic dairy drinks, low-fat cheese, functional emulsions	Meng *et al*. (2018); Patel *et al*. (2015) [55]; Sarkar & Dickinson (2020) [21].

3.3 Fractionation

Fractionation is a widely used physical technique in lipid structuring that involves separating fats into distinct fractions based on their melting behavior and crystallization characteristics. This process enhances the functional utility of dairy fats by tailoring their physical and nutritional properties. There are two principal types of fractionation i.e dry fractionation and solvent-assisted fractionation. Dry fractionation involves controlled cooling of the fat followed by mechanical separation, typically through filtration or centrifugation. It is a solvent-free, energy-efficient method suitable for food-grade applications. In contrast, solvent fractionation utilizes solvents such as acetone or hexane to selectively solubilize certain fractions while inducing crystallization of others, offering finer control over the molecular composition of the resulting lipid fractions.

In dairy applications, fractionation facilitates the isolation of high-melting-point fractions rich in saturated fats, which can be used to enhance the texture and firmness of spreads, processed cheese, and table butter. Conversely, low-melting unsaturated fractions obtained through this method can be incorporated into functional lipid blends aimed at improving the nutritional profile of dairy products. Overall, fractionation provides a versatile means of enhancing the spreadability, plasticity, and thermal behavior of dairy fats, contributing to both consumer appeal and health-oriented reformulations.

3.4 Emulsification and Nanoemulsions

Emulsification is a foundational technique in food science, involving the dispersion of one immiscible liquid phase (such as oil) within another (such as water) with the aid of emulsifiers. In the dairy sector, this principle underlies the creation of stable systems like cream, flavored milk, and functional beverages. Recent advancements have led to the development of nanoemulsion technology, which produces emulsions with droplet sizes typically below 200 nm. These systems are particularly valuable for delivering lipophilic bioactive compounds such as omega-3 fatty acids, phytosterols, conjugated linoleic acid (CLA), and lipid-soluble vitamins within dairy matrices.

Nanoemulsions offer several advantages in structured lipid delivery. First, the small droplet size significantly enhances the bioavailability of lipophilic nutrients, facilitating better absorption and systemic efficacy. Second, nanoemulsions provide oxidative protection by minimizing the surface area exposed to oxygen, thereby stabilizing unsaturated lipids such as EPA and DHA. Third, they improve the sensory profile of dairy products by integrating seamlessly without altering mouthfeel or appearance. Methods used to generate nanoemulsions include high-energy techniques such as high-pressure homogenization and ultrasonication, as well as low-energy approaches like spontaneous emulsification (Solans & Sole, 2012) [64].

The integration of nanoemulsions into dairy products has been explored for several applications. For instance, omega-3 fortified milk and yogurt utilizing nanoemulsified fish or algal oil have demonstrated improved oxidative stability and sensory acceptability (Patel *et al*., 2014) [55]. Similarly, nanoemulsions are used in flavored milk products to deliver lipid-soluble vitamins such as A, D, and E without compromising taste or clarity. Functional dairy spreads and cheeses have also been enriched with nanoencapsulated bioactives like CLA or coenzyme Q10, offering added health benefits while maintaining product integrity (McClements, 2015) [45-47]. These technologies collectively represent an innovative strategy for designing next-generation functional dairy foods.

4.0 Application in Dairy Product Development

The application of structured lipids in dairy product development represents a significant advancement in improving the nutritional, technological, and sensory profiles of dairy foods. Owing to their colloidal nature and consumer familiarity with high-fat content, dairy matrices offer a suitable medium for the incorporation of various structured lipids such as oleogels, nanoemulsions, interesterified fats, and phytosterol-based systems. The ability to manipulate lipid composition and structure within these products allows developers to achieve specific health targets such as lowering saturated fat, enhancing functional lipid intake, or improving lipid bioavailability without compromising the sensory appeal of the final product.

4.1 Milk and Cream

Milk and cream are widely consumed dairy products that serve as practical vehicles for delivering structured lipids. Their inherent emulsified nature facilitates the integration of bioactive lipids, though challenges such as oxidative degradation and off-flavors remain prevalent. Nanoemulsion-based systems have been successfully employed to deliver omega-3 fatty acids in milk, offering improved oxidative stability and minimal sensory disruption (McClements, 2015) [45-47]. Similarly, phytosterols and medium-chain triglycerides (MCTs) have been incorporated into fluid milk using emulsification techniques, contributing to cardiovascular and cognitive health benefits (Rao *et al*., 2016) [58]. For reduced-fat cream formulations, structured emulsions and oleogels have been utilized to replicate the rheological properties of full-fat products while decreasing saturated fat content (Davidovich-Pinhas *et al*., 2016).

4.2 Yogurt and Fermented Milk

Yogurt and other fermented milk products present a semi-solid, protein-rich matrix conducive to the inclusion of structured lipids. The fermentation process, characterized by a low pH environment, offers protection to sensitive lipid molecules and can also enhance bioavailability. Lipid structuring in yogurt has enabled the successful replacement of saturated fat using oleogels composed of rice bran wax and monoglycerides, without sacrificing creaminess or consumer acceptance (Zárate-Ramírez *et al*., 2021). Furthermore, nanoemulsified omega-3s have been incorporated into yogurt products, providing oxidative protection and avoiding undesirable fishy flavors (Patel *et al*., 2014) [55]. Functional lipids such as CLA and phytosterols can also be incorporated into fermented dairy systems, contributing to improved metabolic health (Lin & Meijer, 2006) [39].

4.3 Cheese

Cheese, being a highly structured and fat-rich dairy product, presents unique challenges for lipid restructuring due to its defined meltability, stretchability, and flavor. Nevertheless, enzymatic interesterification of cheese fats has allowed manufacturers to modify melting profiles, resulting in enhanced functional properties such as sliceability and stretch in processed cheese varieties (Gunstone, 2011) [28]. Oleogel incorporation into cheese matrices has also shown promise in lowering saturated fat content while maintaining desirable texture and sensory characteristics (Davidovich-Pinhas & Marangoni, 2015). Additionally, nanoemulsified bioactives such as coenzyme Q10 and omega-3 fatty acids have been effectively delivered through cheese spreads, expanding the functional appeal of these products (McClements, 2015) [45-47].

4.4 Butter and Dairy Spreads Butter and margarine-type spreads, traditionally high in saturated fats, are well-suited for lipid structuring approaches aimed at health improvement. Interesterification has been employed to modulate the melting properties of butterfat, enabling the production of healthier spreads with reduced solid fat content and improved nutritional profiles (Chakraborty *et al*., 2014) [13]. The integration of oleogels formulated with phytosterols and omega-3s has facilitated the development of cholesterol-lowering spreads that retain the plasticity, flavor, and spreadability of conventional butter (Barbut *et al*., 2020) [7]. These innovations support the delivery of functional lipids in formats that align with both health trends and traditional sensory expectations.

4.5 Ice Cream and Frozen Dairy Desserts: The structural complexity of ice cream, involving a balance of solid and liquid fats, air incorporation, and thermal stability, demands precise fat structuring. Fractionation of milk fat has been utilized to control melting behavior and texture, contributing to smoother and more consistent frozen products (Rousseau, 2007) [60]. Moreover, the inclusion of oleogels derived from unsaturated oils provides a strategy for reducing saturated fat while maintaining creaminess and desirable mouthfeel (Zárate-Ramírez *et al*., 2021). Nanoemulsified delivery systems have also proven effective in incorporating omega-3 fatty acids and CLA into ice cream and frozen desserts, achieving functional fortification without causing oxidation or adverse flavor development (McClements, 2015) [45-47].

5.0 Health Implications of Structured Lipids in Dairy

The strategic restructuring of lipids in dairy products goes beyond functional enhancement—it plays a important role in addressing modern health challenges, particularly those linked to cardiovascular disease, obesity, metabolic syndrome, and neurodegenerative disorders. The incorporation of bioactive lipids such as omega-3 fatty acids, conjugated linoleic acid (CLA), medium-chain triglycerides (MCTs), phytosterols, and structured triacylglycerols (TAGs) into dairy matrices has demonstrated promising health effects when appropriately stabilized and delivered. This section explores the physiological benefits and scientific rationale for integrating such structured lipids into dairy systems.

Table 3: Recent Applications of Lipid Structuring in Dairy Products: Techniques, Health Implications

Dairy Product	Lipid Structuring Technique	Health Implication	References
Fortified Milk	Nanoemulsified Omega-3s	Improved cardiovascular health, reduced inflammation, enhanced bioavailability	McClements (2015) [45-47]; Shahidi & Ambigaipalan (2018) [62]; Swanson *et al.* (2012) [66]
Yogurt	Oleogelation with phytosterol waxes	LDL cholesterol reduction, texture enhancement	Patel *et al.* (2014) [55]; Lin *et al.* (2009) [40]; AbuMweis *et al.* (2008) [1]
Infant Formula	Enzymatically structured SN-2 lipids	Better fat absorption, softer stools, enhanced calcium uptake	Innis (2011) [31]; Kennedy *et al.* (2005) [34]; Carnielli *et al.* (1996) [12]
Cheese Analogs	Interesterified milk fat blends	Improved meltability, reduced saturated fat, controlled lipid profile	Rousseau (2007) [60]; Osborn & Akoh (2003) [53]; Akoh (2017) [3]
Dairy Spreads	Oleogels using beeswax/candelilla	Replacement of trans fats, improved oxidative stability	Acevedo *et al.* (2012) [2]; Marangoni & Garti (2011) [44]; Ghosh & Rousseau (2011) [26]
Probiotic Yogurt	Omega-3 nanoemulsions + CLA blends	Gut microbiome modulation, metabolic and immune support	Zárate-Ramírez *et al.* (2021); Lin & Meijer (2006) [39]; Benjamin & Spener (2009) [8]
Ice Cream	MCT-structured emulsions	Quick energy release, improved overrun and reduced fat content	St-Onge & Jones (2002) [65]; Ghosh & Rousseau (2011) [26]; Bach & Babayan (1982) [6]
Low-fat Creams	Oleogels with plant wax and starch	Creamy texture with reduced saturated fats	Patel *et al.* (2014) [55]; Aschemann-Witzel *et al.* (2019) [5]; van der Goot *et al.* (2021) [68].
Functional Beverages	Encapsulated designer lipids	Targeted delivery of bioactives, personalized health effects	Akoh (2017) [3]; Silva *et al.* (2022) [63]; Wishart (2021) [70]

5.1 Omega-3 Fatty Acid Fortification

Omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are essential polyunsaturated fats with well-documented anti-inflammatory, cardioprotective, and neuroprotective properties. Dairy products represent a practical vehicle for delivering these lipids to a broad population. Fortification is commonly achieved using fish oil, algal oil, or flaxseed oil (Shahidi & Ambigaipalan, 2018) [62]. To prevent oxidation and enhance absorption, technologies such as microencapsulation and nanoemulsion systems are employed in milk, yogurt, and dairy spreads (Patel *et al*., 2014; McClements, 2015) [55, 45-47]. Omega-3 fortified dairy has been shown to reduce triglyceride levels, lower blood pressure, support neurodevelopment in infants, and help prevent age-related macular degeneration.

Table 4: Omega-3 Fortification in Dairy Products

Product Type	Fortificant Source	Added Amount (g/100g)	Final Omega-3 Content (g/100g)	Reference	Remarks
Yogurt, Cream (liquid)	Fish oil	0.1-0.5	N/A	Kolanowski & Weißbrodt (2007) [35]	Liquid products tolerate low addition levels
Processed Cheese, Butter, Spreads (semi-solid)	Fish oil	2-6	N/A	Kolanowski & Weißbrodt (2007) [35]	Semi-solids accommodate higher fortification levels
Yogurt	Flaxseed oil	0.3	0.7	Dal Bello *et al*. (2015) [17]	Plant-based source with good retention
Yogurt	Camelina oil	0.5	0.2	Dal Bello *et al*. (2015) [17]	Low conversion efficiency
Yogurt	Raspberry oil	0.7	0.2	Dal Bello *et al*. (2015) [17]	Low conversion efficiency
Yogurt	Black currant oil	1.4	0.4	Dal Bello *et al*. (2015) [17]	Low efficiency despite high addition
Yogurt	Echium oil	0.6	0.6	Dal Bello *et al*. (2015) [17]	High efficiency, stable retention
Queso fresco	Fish oil	1.0	0.8	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Marine source shows higher retention
Queso fresco	Flaxseed oil	1.0	0.2	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Lower omega-3 content than fish oil
Cheddar cheese	Fish oil	1.0	0.9	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Good retention from marine source
Cheddar cheese	Flaxseed oil	1.0	0.5	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Moderate retention
Mozzarella	Fish oil	1.0	0.3	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Some loss, but still higher than plant oil
Mozzarella	Flaxseed oil	1.0	0.08	Bermúdez-Aguirre & Barbosa-Cánovas (2011) [10]	Very low retention
Yogurt	Flaxseed oil	0.2	N/A	Almasi *et al*. (2021) [4]	Successfully incorporated with sensory acceptability

5.2 Conjugated Linoleic Acid (CLA) Enrichment

Conjugated linoleic acid (CLA), especially the cis-9, trans-11 isomer, is a naturally occurring fatty acid found in ruminant dairy fat. CLA has been associated with multiple health benefits including anti-carcinogenic effects via modulation of apoptosis and angiogenesis, reduction of body fat, enhancement of lean mass, and improvement in insulin sensitivity and glucose metabolism (Jiang *et al*., 2014; Lin & Meijer, 2006) [32, 40]. Enrichment strategies include dietary manipulation of dairy cattle, fermentation using CLA-producing probiotics, and fortification with CLA-rich oils or encapsulated formulations, particularly in yogurts, cheeses, and fermented milk products.

5.3 Medium-Chain Triglycerides (MCTs) for Rapid Energy and Metabolic Support

MCTs consist of fatty acids with chain lengths of 6 to 12 carbon atoms, primarily caprylic (C8:0) and capric acid (C10:0). These lipids are rapidly digested and absorbed, making them valuable for ketogenic diets, epilepsy management, neurodegenerative disorders, and weight control. MCTs also enhance thermogenesis and fat oxidation and may aid in insulin regulation (Osborn & Akoh, 2003) [53]. In dairy applications, they are used in infant formulas, medical nutrition, and sports beverages. Enzymatic interesterification allows for their integration into structured TAGs to deliver functional benefits in milk and yogurt.

5.4 Phytosterol Integration for Cardiovascular Health

Phytosterols are plant-derived sterols structurally similar to cholesterol, known for their ability to competitively inhibit intestinal cholesterol absorption. This action leads to a 30-40% reduction in cholesterol uptake, making phytosterols effective in lowering LDL cholesterol and reducing cardiovascular risk (Jones *et al*., 2000) [33]. Phytosterol-enriched dairy products, including milk and yogurt, are increasingly used as functional foods. Advanced structuring techniques such as emulsification and oleogelation improve their dispersion and bioavailability (Lin *et al*., 2009) [40]. Regulatory approvals for health claims on phytosterol-containing dairy further support their clinical utility and commercial potential.

Table 5: Fortification of phytosterols in dairy products

Sr. No.	Scientist Name	Product	Findings
1	Gilbert *et al*. (2005) [27]	Phytosterol-fortified foods	Phytosterols help decrease cholesterol levels in people with cardiovascular diseases.
2	Cantrill and Kawamura (2008) [11], Berger *et al*. (2004) [9], Kritchevsky and Chen (2005) [36]	Dairy products (yogurt, milk drinks, etc.)	Phytosterols are incorporated into various dairy products worldwide.
3	Berger *et al*. (2004) [9]	Phytosterols with fiber, healthy oils, soy protein, etc.	Phytosterols are combined with other functional ingredients in different countries.
4	Lees *et al*. (1977) [38]	Crystalline phytosterol powder	Large quantities were needed to significantly lower cholesterol due to poor solubility.
5	Salo and Wester (2005) [61]	Plant sterol and stanol esters	Esterification improves solubility, making them effective in dairy products.
6	Clifton (2009) [14]	Low-fat dairy products	Sterols in low-fat dairy lowered LDL-C by 6-14%.
7	Mensink *et al*. (2002) [48]	Low-fat yogurt with stanol esters	Cholesterol-lowering efficacy is independent of food matrix.
8	Gylling and Miettinen (1999) [29]	Butter with plant stanol esters	Stanol esterified with butter fatty acids effectively lowered LDL cholesterol.
9	Hyun *et al*. (2005) [30]	Low-fat yogurt with stanol ester	Effective in reducing cholesterol in a habitual diet.
10	Noakes *et al*. (2005) [52]	Milk, yogurt, bread, and cereal enriched with phytosterols	Phytosterol-enriched milk significantly lowered LDL-C levels (8.7-15.9%).
11	Richelle *et al*. (2004) [59]	Free and esterified sterols in low-fat milk	Both forms inhibited cholesterol absorption by about 60%.

5.5 Structured Lipids for Infant Nutrition

The formulation of infant nutrition products increasingly relies on the use of structured lipids to closely replicate the composition and functionality of human milk fat. One of the key structural features of human milk fat is the high proportion of palmitic acid (C16:0) esterified at the sn-2 position of triacylglycerols (TAGs), a configuration that promotes better absorption of fat and calcium, reduces the formation of calcium-fatty acid soaps in the intestine, and supports softer stool consistency. To emulate this structure, enzymatic interesterification techniques have been developed to selectively enrich milk fats with sn-2 palmitate, improving the physiological performance of infant formula fats (Innis, 2011) [31]. These tailored lipids are particularly valuable in specialized formulas designed for preterm infants or those experiencing fat malabsorption disorders. The use of structured lipids in such formulations has been associated with enhanced bone mineralization, improved development of gut microbiota, and more efficient absorption of dietary fat and calcium key outcomes for supporting optimal infant growth and health during early life stages.

Table 6: Summary of Health Benefits

Lipid Type	Primary Health Benefits	Typical Dairy Carriers	References
Omega-3 (EPA/DHA)	Cardiovascular protection, anti-inflammatory effects, brain development, eye health	Milk, yogurt, cheese, spreads	Shahidi & Ambigaipalan (2018) [62]; McClements (2015) [45-47]; Swanson *et al*. (2012) [66]
CLA	Anti-carcinogenic, body fat reduction, immune modulation, metabolic health	Yogurt, fermented milk, cheese	Lin & Meijer (2006) [39]; Jiang *et al*. (2014) [32]; Benjamin & Spener (2009) [8]
MCTs	Quick energy, fat oxidation, ketogenic benefits, improved insulin sensitivity	Dairy beverages, infant formula, milk	St-Onge & Jones (2002) [65]; Bach & Babayan (1982) [6]; Nagao & Yanagita (2010) [51].
Phytosterols	LDL cholesterol reduction, reduced risk of coronary heart disease	Milk, yogurt, spreads	Jones *et al*. (2000) [33]; Lin *et al*. (2009) [40]; AbuMweis *et al*. (2008) [1]
SN-2 Palmitate	Enhanced calcium absorption, better fat digestibility, improved stool consistency in infants	Infant formula, fortified milk	Innis (2011) [31]; Kennedy *et al*. (2005) [34]; Carnielli *et al*. (1996) [12]

6.0 Technological and Sensory Challenges

While lipid structuring techniques offer substantial promise for improving the nutritional and functional quality of dairy products, their successful translation into commercial applications requires overcoming several technological, sensory, and regulatory hurdles. These challenges encompass oxidative stability, rheological compatibility, sensory integrity, economic feasibility, and compliance with food labeling and safety standards. Each factor plays a critical role in the overall product performance and consumer acceptance.

6.1 Oxidative Stability of Structured Lipids

One of the foremost concerns in incorporating bioactive lipids such as omega-3 fatty acids and conjugated linoleic acid (CLA) into dairy products is their susceptibility to oxidation. Highly unsaturated lipids are prone to peroxidation, which leads to the formation of rancid off-flavors, degradation of nutritional value, and reduced shelf life. This issue becomes particularly critical in aerated dairy matrices like whipped creams and frozen desserts. To combat this, technological interventions such as microencapsulation and nanoemulsion techniques are widely employed to isolate lipids from oxidative environments and improve their stability (McClements, 2015) [45-47]. The inclusion of natural antioxidants such as tocopherols, rosemary extract, and polyphenolic compounds also helps to retard oxidation (Shahidi & Ambigaipalan, 2015) [62]. Furthermore, advances in packaging technology such as oxygen-impermeable films and modifiedatmosphere storage add an additional layer of protection during distribution and storage.

6.2 Sensory Attributes and Consumer Acceptance
Modifications in lipid structure or fatty acid composition can significantly alter the sensory characteristics of dairy products. Issues such as fishy or grassy off-flavors from omega-3-rich oils (e.g., fish or flaxseed oil), or a grainy and waxy texture resulting from the use of oleogels or interesterified fats, can negatively affect product acceptability. Additionally, deviations in meltability, spreadability, and creaminess compared to traditional milk fat may challenge consumer expectations. Addressing these issues involves the use of flavor-masking agents, as well as sourcing sensory-neutral lipid alternatives such as algal oil. Precision control over crystallization and fat polymorphism is essential to mimic the desired textural attributes of native dairy fats (Rousseau, 2007) [60]. Incorporating consumer preference studies and regional sensory profiling during product development also ensures alignment with target market expectations.

6.3 Functional and Rheological Compatibility
Structured lipids can interfere with the colloidal structure and mechanical properties of various dairy systems. For instance, modified lipids may reduce emulsion stability in milk and cream, resulting in phase separation. In cultured products like yogurt and soft cheese, altered crystallization behavior may influence syneresis and textural firmness. In aerated dairy systems such as frozen desserts or whipped toppings, these lipids can affect overrun, melting behavior, and foam stability. To manage these impacts, manufacturers often optimize emulsifier systems (e.g., using lecithin or mono- and diglycerides) and blend structured lipids with native milk fats. Additionally, careful adjustment of processing parameters, including homogenization pressure and cooling rates, can help maintain the desired functionality and consistency of the final product.

6.4 Scalability and Cost Considerations
Despite promising lab-scale results, scaling up lipid structuring technologies for commercial production introduces multiple challenges. These include the high cost of enzymatic interesterification, low yields and prolonged reaction times in oleogelation processes, and the complexity of downstream processing for nanoencapsulation or structured emulsions. Specialized equipment and tight control over temperature and humidity conditions further add to operational costs. Current research is focusing on process intensification, such as the use of immobilized enzymes, continuous flow systems, and modular bioreactor designs, to enhance the economic feasibility of structured lipid production (Acevedo *et al*., 2012) [2].

6.5 Regulatory and Labeling Challenges
The use of structured lipids in dairy foods must comply with food safety regulations established by governing bodies such as FSSAI (India), EFSA (Europe), FDA (USA), and Codex Alimentarius. Key regulatory aspects include the Generally Recognized As Safe (GRAS) status of added lipid components (e.g., phytosterols, MCTs, algal oil), permissible limits of enrichment, and mandatory labeling declarations. Functional claims such as "omega-3 enriched" or "supports cholesterol reduction" require substantiated scientific evidence and regulatory approval. Moreover, labeling must ensure transparency in composition and clearly indicate whether the product contains modified or engineered fats. As consumer perception plays a important role in product acceptance, clear and accurate labeling, supported by public education on the health benefits of structured lipids, is essential for market success.

Table 7: Technological and Sensory Challenges

Challenge Area	Problem	Solution/Strategy
Oxidative Stability	Oxidation of PUFAs and bioactives	Encapsulation, antioxidants, oxygen-barrier packaging
Sensory Attributes	Off-flavors, texture changes	Flavor masking, oleogel optimization, sensory trials
Rheological Performance	Phase separation, melt instability	Emulsifier selection, processing control, fat blends
Cost and Scalability	Expensive enzymes, slow processes	Enzyme immobilization, continuous systems, industrial optimization
Regulatory Compliance	Health claims, GRAS status, label confusion	Adherence to FSSAI/Codex/FDA, transparent labeling, consumer education

7.0 Emerging Trends and Innovations in Structured Lipids for Dairy
The evolution of lipid technology in the dairy industry is entering an exciting phase, marked by the convergence of nutrition science, food engineering, biotechnology, and digital technologies. While current advances in lipid structuring have demonstrated considerable promise, several emerging trends and innovative directions are set to reshape the future of functional and health-oriented dairy lipids.

7.1 Integration of Lipidomics and Precision Nutrition
Lipidomics, the comprehensive profiling of lipid species using advanced mass spectrometry and bioinformatics, is revolutionizing our understanding of lipids in dairy systems. This technique allows for the identification of bioactive lipid signatures, the exploration of lipid structural variations, and the investigation of processing-induced changes affecting lipid bioavailability and functionality (Quehenberger & Dennis, 2011; Wishart, 2021) [56, 70]. When integrated with precision nutrition an approach that personalizes dietary interventions based on genetic, metabolic, and microbiome data lipidomics offers a foundation for designing structured dairy lipids targeted to specific consumer needs, such as infants, elderly populations, or athletes (Galanakis, 2021; Shahidi & Ambigaipalan, 2018) [24, 62].

7.2 Designer Lipids for Targeted Health Outcomes
The field of designer lipids focuses on creating structured triacylglycerols (TAGs) with defined metabolic benefits. These lipids can be engineered to position long-chain polyunsaturated fatty acids (PUFAs) such as DHA and EPA at the sn-2 position to enhance absorption and exert anti-inflammatory or anti-obesity effects (Akoh, 2017; Silva *et al*., 2022) [3. 63]. Specific configurations like SN-2 palmitate have also been shown to support calcium absorption and mimic human milk fat in infant nutrition (Innis, 2011; Kennedy *et al*., 2005) [31, 34]. Enzymatic and microbial synthesis routes are increasingly favored due to their

selectivity and eco-friendly nature, with scalability and sustainability being critical areas of ongoing research (Osborn & Akoh, 2003; Ratledge, 2013) [53, 57].

7.3 Algal and Microbial Lipid Sources

The limitations of traditional animal- and plant-derived lipid sources have led to an increased focus on microbial and algal lipids, which can be engineered to produce high-value fatty acids like omega-3s, CLAs, and MCTs. Advances in metabolic engineering have enabled the cultivation of microalgae, yeast, and fungi in controlled bioreactors using CO_2 and agro-industrial waste as feedstock, aligning with circular bioeconomy principles (Ganuza & Izquierdo, 2020; Ratledge, 2013) [57]. These sources provide lipid profiles with fewer contaminants and greater consistency, and they appeal to plant-based, vegan, halal, and kosher food markets, expanding the utility of structured lipids in both dairy and dairy analogs (Swanson *et al*., 2012; Shahidi & Ambigaipalan, 2018) [66, 62].

7.4 Artificial Intelligence and Food Informatics

Artificial intelligence (AI) and machine learning are being increasingly utilized in the formulation and optimization of structured lipids. AI models can predict lipid-matrix interactions, sensory responses, and oxidative stability based on compositional data, aiding in the rational design of lipid systems (Misra *et al*., 2020; Galanakis, 2021) [50, 24]. Sensory modeling combined with lipidomics data enhances the ability to link consumer preferences to lipid structures. Moreover, AI-powered platforms and lipid databases are helping accelerate R&D timelines and enable precise customization of lipid-based dairy products (Wishart, 2021) [70].

7.5 Clean Label and Sustainable Structuring Approaches

In response to rising consumer demand for natural, clean-label products, structured lipid systems are increasingly being developed using natural oleogelators like waxes, proteins, and polysaccharides, while avoiding synthetic emulsifiers and chemical solvents (Barbut *et al*., 2020; Patel *et al*., 2015) [7, 55]. Techniques such as solvent-free enzymatic interesterification and minimal processing of oleogels contribute to cleaner formulations. Additionally, sustainability is being addressed through lifecycle analyses and carbon footprint reduction strategies in dairy lipid processing, aligning with international sustainability goals including the UN Sustainable Development Goals and Codex green labeling standards (Marangoni & Garti, 2011; FSSAI, 2020; Galanakis, 2021) [44, 23, 24].

8.0 Conclusion

Recent advances in lipid technology have significantly transformed the functional and nutritional profile of dairy products. The structuring of lipids—through techniques such as interesterification, oleogelation, emulsification, and nanoencapsulation—enables the creation of dairy products that are not only sensorially appealing but also tailored to promote health and wellbeing.

The incorporation of bioactive lipids, including omega-3 fatty acids, conjugated linoleic acid (CLA), medium-chain triglycerides (MCTs), phytosterols, and structured triacylglycerols, has expanded the potential of dairy as a vehicle for delivering essential and condition-specific nutrients. Such structured lipids offer therapeutic benefits ranging from cardiovascular support and weight management to neurological development and cholesterol reduction. Furthermore, the application of these technologies in dairy matrices such as milk, yogurt, cheese, spreads, and infant formula demonstrates the versatility of lipid modification strategies in addressing modern health needs.

However, the transition from concept to commercial application is not without challenges. Oxidative stability, sensory acceptability, rheological compatibility, production scalability, and regulatory compliance remain critical issues that demand integrated solutions. Innovations in encapsulation, flavor masking, process engineering, and emulsifier selection are helping to bridge these gaps. Additionally, growing interest in clean-label, sustainable, and plant-based lipid sources reflects evolving consumer expectations and global sustainability goals.

Looking ahead, the integration of lipidomics, artificial intelligence, microbial lipid production, and designer lipid synthesis will pave the way for the next generation of functional and precision-tailored dairy lipids. Multidisciplinary collaboration between dairy scientists, nutritionists, lipid chemists, and food technologists will be key to unlocking the full potential of lipid structuring in dairy systems.

Phytosterols are naturally found in all plant origin food products. Naturally available phytosterols have effects on cholesterol metabolism. People consume phytosterols through diet every day but in a small quantity which may not be effective for lowering LDL cholesterol levels, but if foods are enriched with plant sterols or their esters at a level of 2-3 g/day, they may help reduce the LDL cholesterol levels significantly.

In summary, structured lipid technology stands at the frontier of dairy innovation, offering the promise of products that meet both nutritional excellence and functional performance, while responding to the challenges of modern health, sustainability, and consumer demand.

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