

Review of advanced structural strategies for controlling lipid digestion in emulsion-based delivery systems

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Abstract. Structurally diverse emulsion systems play a pivotal role in improving the delivery, stability, and digestion of lipophilic nutrients in food and pharmaceutical applications. This review aims to compare the in vitro digestion behaviours and barrier mechanisms of various emulsion types, including surfactant-based, Pickering, gel-based, dried, and complex emulsions. A literature-based approach was adopted, emphasising findings from studies using standardized in vitro digestion models, particularly the INFOGEST protocol. Key parameters evaluated include lipid hydrolysis, bioaccessibility, and the structural features that influence enzyme access and digestion kinetics. Surfactant-based emulsions typically show rapid lipolysis, often reaching >70–90% free fatty acid (FFA) release, whereas Pickering and gel-based emulsions can reduce or delay digestion, with some systems limiting FFA release to ~30–60% depending on particle packing and gel matrix density. Dried emulsions exhibit variable behaviour depending on reconstitution efficiency, while complex emulsions offer tunable and sustained release profiles. These findings highlight the importance of interfacial engineering, matrix entrapment, and structural integrity in modulating digestive fate. In conclusion, selecting appropriate emulsion structures allows targeted control of nutrient release and bioavailability. Appropriate emulsion design enables controlled nutrient release and better bioavailability for next-generation functional emulsions.

1 Introduction

Emulsions are heterogeneous systems consisting of two immiscible liquids in which one phase (dispersed) is finely distributed as droplets within another (continuous) phase and

stabilised by surface-active molecules or particles [1, 2]. In functional foods and nutraceuticals, emulsion-based delivery systems (EDS) play a critical role in incorporating, protecting, and delivering lipophilic nutrients such as vitamins A, D, E, and K, omega-3 fatty acids, carotenoids, and hydrophobic phytochemicals [3]. By tuning droplet size, interfacial composition and continuous-phase rheology, formulators can manipulate sensory attributes such as creaminess and mouthfeel while simultaneously influencing the gastrointestinal fate of lipids. Lipid digestion involves the enzymatic hydrolysis of triglycerides into monoacylglycerols and free fatty acids (FFAs) by gastric and pancreatic lipases, followed by emulsification into mixed micelles by bile salts. The extent and rate of lipolysis are critical determinants of the bioaccessibility, defined as the fraction of nutrients solubilised in micelles, and ultimately the bioavailability of lipophilic compounds [4].

In vitro digestion models, particularly the INFOGEST static and semi-dynamic protocols, have become standardised approaches for examining the digestive fate of emulsion-based delivery systems (EDS). These models harmonise enzyme activities, bile salt concentrations and pH transitions across the oral, [3, 5] gastric, and intestinal phases, enabling clearer comparison of lipid hydrolysis kinetics, droplet restructuring and bioactive release among studies. However, the detailed description of these models is secondary to understanding that the emulsion system itself governs digestive outcomes. Previous reviews have primarily focused on introducing digestion protocols or outlining general lipid digestion pathways, with less emphasis on how specific structural features such as particle-stabilised interfaces, gelled matrices or multilayered interfacial coatings modulate lipolysis rates, micellisation efficiency and bioaccessibility [6, 7]. This synthesis is particularly relevant as controlled lipid digestion is increasingly linked to functional attributes such as satiety regulation, sustained nutrient release and targeted delivery. Brief consideration of emerging dynamic systems (e.g., DGM, TIM and gut-on-chip platforms) highlights their potential to provide more physiologically realistic insights, although their complexity limits routine application [8, 9].

The concept of digestion barriers has arisen from the recognition that structural and physicochemical features of emulsions can hinder or modulate enzyme and bile salt access to lipid cores. Such barriers may exist at multiple scales: interfacial films formed by surfactants, proteins or polysaccharides; particulate shells characteristic of Pickering emulsions; multilayer polyelectrolyte coatings or double interfaces in multi-compartment emulsions; matrix entrapment in emulsion-filled gels or oleogels; crystalline or solid fat domains; and surface layers generated during dehydration and rehydration [10-12]. These barriers can act through steric hindrance, electrostatic repulsion, hydrophobic exclusion or diffusion limitation, collectively delaying lipase adsorption, bile salt displacement and droplet coalescence. Understanding and intentionally designing such barriers allows targeted control of lipid digestion, enabling rapid release for immediate nutrient delivery, or conversely, retarded release to prolong satiety, protect sensitive compounds and modulate postprandial metabolism.

This review synthesises recent (2023–2025) literature on advanced structural strategies for controlling lipid digestion in emulsion-based delivery systems. It compares the digestion behaviours and barrier mechanisms of conventional surfactant-stabilised emulsions, Pickering emulsions stabilised by food-grade particles, gel-based emulsions such as

emulsion-filled gels and oleogels, dried and rehydrated emulsions, and more complex systems including multilayer, double and hybrid emulsions. For each class, we summarise key physicochemical characteristics, interfacial designs, droplet sizes, matrix rheologies and in vitro digestion outcomes, with a particular focus on standardised INFOGEST protocols. Finally, the review discusses applications including targeted nutrient delivery, satiety and weight management, oxidative protection, sustainability considerations and research directions for future development.

2 Methodologies for In Vitro Digestion Studies

2.1 Static and dynamic digestion models

Static in vitro digestion models are widely used due to their simplicity and reproducibility. They sequentially simulate the oral, gastric and intestinal phases in a single vessel or series of vessels with constant enzyme activities, bile salt concentrations and pH values. The consensus INFOGEST protocol is the most widely applied static method [13-15]; it uses simulated salivary fluid containing amylase for the oral phase, porcine pepsin for gastric digestion and pancreatin with bile salts for the intestinal phase. Reactions are performed at physiological temperature (37 °C) under agitation, and pH is maintained to mimic human gastrointestinal conditions as shown in Fig. 1. Standardised enzyme activities, bile salt levels and saliva flow rates allow direct comparison across studies. However, static models lack physiological feedback mechanisms such as dynamic secretion, peristalsis, gastric emptying and mucosal absorption [5].

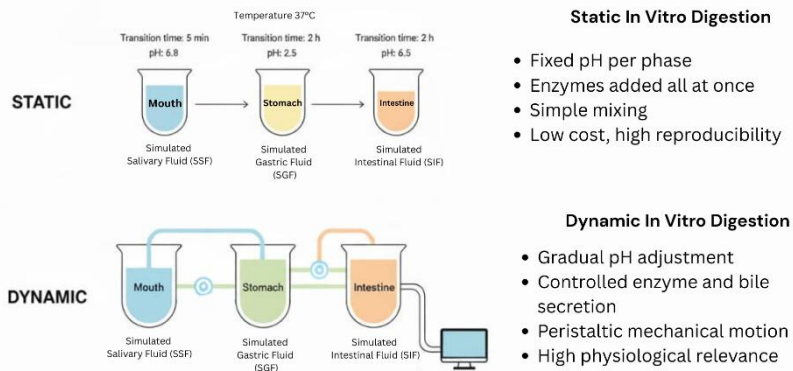


Fig 1. Comparison between static and dynamic in vitro digestion models.

On the other hand, dynamic digestion models attempt to address these limitations by replicating mechanical and physiological processes. The dynamic gastric model (DGM) simulates peristaltic motions and gastric emptying, while the TNO gastrointestinal model (TIM) replicates stomach and intestinal compartments with time-dependent secretion of enzymes and bile. More advanced microfluidic “gut-on-chip” devices integrate flowing

digestive fluids, intestinal cell layers and mucus, allowing continuous monitoring of nutrient breakdown and absorption. Meanwhile, organoid models derived from human stem cells create three-dimensional intestinal tissues that can be used to study absorption, metabolism and barrier properties in a controlled setting. Although these dynamic models provide more realistic digestion conditions than static systems, they are less widely adopted due to their high cost, technical complexity and limited experimental throughput [9].

2.2 Measurement of lipolysis, micellization and bioaccessibility

Lipolysis is typically quantified by measuring the release of free fatty acids (FFAs) as lipases hydrolyse triglycerides. In pH-stat titration, sodium hydroxide is automatically added to maintain constant pH during digestion; the cumulative amount of base correlates with the FFAs released. FFA profiles can also be determined by high-performance liquid chromatography (HPLC) or gas chromatography (GC) coupled with flame-ionisation or mass-spectrometric detection [5, 18, 19]. The formation of mixed micelles containing lipid digestion products and bile salts is essential for absorption; bioaccessibility is defined as the fraction of a bioactive compound solubilised in the micellar phase relative to the total amount present. To determine bioaccessibility, digesta are ultracentrifuged to separate the oil, micellar and pellet fractions. The concentration of lipophilic compounds in the micellar phase is quantified via HPLC or spectrophotometric methods [6, 12, 20].

Additionally, droplet size distributions are monitored using laser diffraction or dynamic light scattering. Changes in ζ -potential (electrostatic potential at the shear plane) indicate modifications of interfacial charge during digestion. Microstructural analyses employ optical, confocal or cryo-scanning electron microscopy to visualise droplet integrity and coalescence. Interfacial rheology (dilatational and shear) probes film elasticity and resistance to deformation [6, 17, 21]. Collectively, these metrics provide insight into how interfacial structures influence lipase adsorption, bile displacement and droplet stability.

Table 1. Summary of analytical techniques commonly used to characterise lipid digestion and bioaccessibility in emulsion systems.

Measurement	Technique	Measured Variables	Findings	References
Free fatty acid (FFA) release	pH-stat titration	Amount of NaOH added; FFA release rate and extent	Pickering interfaces slow lipase access, resulting in delayed and lower FFA release compared with surfactant-stabilised emulsions.	[8, 18]

Bioaccessibility of lipophilic compounds	Ultracentrifugation + HPLC / UV-Vis	Fraction of compound solubilised in micellar phase (%)	<ul style="list-style-type: none"> ▪ Particle-stabilised interfaces reduce micelle formation, leading to lower bioaccessibility of encapsulated compounds. ▪ Surfactants and bile salts interact synergistically, promoting micelle formation and resulting in higher bioaccessibility of lipophilic compounds. 	[22, 23]
Droplet size distribution	Laser diffraction / Dynamic light scattering (DLS)	Mean particle size	Tightly packed particle layers limit coalescence and reduce lipase binding efficiency during digestion.	[1, 19, 20]
Surface charge	ζ -potential (electrophoretic mobility)	ζ -potential (mV) over digestion time	<ul style="list-style-type: none"> ▪ Particle-stabilised droplets show less bile salt displacement, slowing initiation of lipolysis. <p>ζ-potential shifts markedly during digestion as bile salts displace emulsifiers.</p>	[3, 24, 25]
Microstructure	Optical microscopy / CLSM / Cryo-SEM	Droplet morphology, aggregation behaviour	Droplets remain intact or aggregated, confirming restricted	[26, 27]

			breakdown and slower digestion.	
Interfacial rheology	Dilational and shear interfacial rheometers	Interfacial elasticity and viscosity	Higher interfacial elasticity forms a barrier to enzyme penetration, delaying hydrolysis.	[7, 14]

3 Physicochemical and Structural Factors Influencing of Emulsion Digestion

3.1 Droplet size, surface charge and interfacial composition

The rate of lipolysis increases with decreasing droplet size because smaller droplets provide a larger specific surface area for lipase adsorption. Nanoemulsions with droplet diameters below 200 nm often exhibit rapid digestion, whereas coarse emulsions above 1 μm display slower lipolysis [3, 9, 18]. Droplet size distribution directly affects interfacial area and therefore influences FFA release profiles and micellization. Surface charge, represented by ζ -potential, further modulates electrostatic interactions between droplets and digestive components. For example, strongly negative droplets can repel negatively charged bile salts, delaying their adsorption and reducing digestion rates [4, 28]. Interfacial composition—whether comprised of small-molecule surfactants, proteins, phospholipids or polysaccharides—governs the thickness, elasticity and permeability of the interfacial film. Thick protein–polysaccharide layers hinder enzyme penetration through steric and electrostatic repulsion, whereas small surfactants are easily displaced by bile salts [6, 7, 29].

3.2 Microstructural and colloidal stability

Colloidal stability during digestion depends on interparticle forces, droplet concentration and continuous-phase properties. Flocculation and coalescence reduce interfacial area by forming larger droplets, thereby decreasing lipase access [3, 27, 30]. Highly concentrated emulsions may also experience limited mixing during digestion, leading to spatial heterogeneities in FFA release. Stability can be enhanced by electrostatic repulsion (high ζ -potentials), steric hindrance (polymer coatings) or network formation (Pickering shells or gel matrices). However, excessive stability may hinder digestion and lower bioaccessibility [20, 24, 31].

3.3 Emulsifier type and interfacial design

Emulsifiers range from low-molecular-weight surfactants (Tween, Span, lecithin) to proteins (whey, casein), phospholipids and polysaccharides (pectin, chitosan, gum arabic).

Surfactants adsorb rapidly at oil–water interfaces but form thin, fluid films that are easily displaced by bile salts and lipases, facilitating fast lipolysis [17, 18]. Proteins often form thick, viscoelastic films that can resist enzyme attack; however, they may undergo conformational changes or proteolysis in gastric conditions. Multilayer interfacial designs involve sequential adsorption of oppositely charged polymers, such as chitosan and pectin, creating thicker barriers that retard lipase binding and bile salt penetration [1, 19, 20]. Covalent crosslinking, enzymatic modification or Maillard conjugation can further enhance interfacial resilience [32, 33].

3.4 Influence of matrix viscosity and phase behaviour

The continuous phase of an emulsion affects digestion through viscosity and phase transitions. High-viscosity matrices hinder droplet mobility and enzyme diffusion, slowing lipolysis [7, 17, 34]. Hydrocolloids such as xanthan gum, guar gum or κ -carrageenan can increase viscosity or form gels that entrap droplets. For example, cold-set pea protein– κ -carrageenan emulsion gels showed that 0.25% κ -carrageenan promoted digestion, whereas higher concentrations delayed both lipid and protein hydrolysis. Emulsion gels based on plant proteins, such as camellia seed, encapsulating EGCG delayed its release from 81% to 27% and increased its bioaccessibility by 31% [17]. Phase separation phenomena such as creaming, sedimentation or gelation modify droplet spatial distribution and influence the local digestion environment [35-37].

4 Surfactant-Based Emulsions

4.1 Composition and interfacial dynamics

Surfactant-based emulsions are among the simplest and most widely used systems. Low-molecular-weight surfactants, such as Tweens (polyoxyethylene sorbitan esters), Spans (sorbitan esters), sodium dodecyl sulphate and lecithin, adsorb at oil–water interfaces within seconds. They reduce interfacial tension, facilitating droplet breakup during homogenisation. Surfactant molecules form monolayers that are flexible and fluid; their hydrophilic–lipophilic balance (HLB) determines their affinity for oil or water phases. Because of their small size, surfactants are easily displaced by bile salts during intestinal digestion, enabling rapid lipase access [28, 38, 39]. During digestion in the small intestine, bile salts can easily replace surfactants at the interface, allowing lipase to bind rapidly and begin lipid hydrolysis [4, 40]. As a result, surfactant-stabilised emulsions usually show a fast initial lipolysis rate and a high overall extent of digestion. For example, emulsions stabilised with Tween 80 were reported to reach >80% triglyceride hydrolysis within 30–40 minutes, while protein-stabilised emulsions required longer digestion times under the same conditions [40, 41]. Food-grade surfactants such as Tween 20, Tween 80 and lecithin are generally regarded as safe (GRAS) within established regulatory concentration limits; however, the use of synthetic surfactants

may be restricted in certain jurisdictions, and excessive inclusion levels can raise concerns related to gastrointestinal tolerance and off-flavour development [42].

4.2 Digestive behaviour and lipolysis profile

In INFOGEST digestion, surfactant-based emulsions often demonstrate steep FFA release curves. Within the first 30–60 minutes of the intestinal phase, more than 80% of FFAs may be liberated, depending on droplet size and oil volume fraction [5, 15, 17]. Surfactants do not provide significant steric barriers; thus, lipases can readily adsorb and hydrolyse triglycerides. However, differences in hydrophobic tail structure can modulate digestion: Tween surfactants with saturated fatty acid moieties increased FFA release percentages in alginate-based dispersions and capsules, whereas unsaturated moieties produced lower FFA release [10, 43]. This indicates that surfactant choice can influence lipolysis by altering interfacial fluidity or enzyme affinity.

4.3 Barrier mechanisms during digestion

Although surfactant layers are thin, they can still transiently resist enzyme penetration when densely packed. High surfactant concentrations produce more ordered monolayers that may slow the initial rate of lipolysis. Competitive displacement by bile salts is a critical step; bile salts, being amphiphilic, insert into the interface, displace surfactants and provide co-lipase for pancreatic lipase activation. The efficiency of this displacement influences the onset of lipolysis [7, 10, 44]. Some surfactants may interact with lipases or alter interfacial curvature, modulating catalytic activity. Proteins as co-surfactants can stabilise interfaces and affect enzyme binding.

4.4 Nutrient release and bioaccessibility outcomes

Surfactant-stabilised emulsions generally yield high bioaccessibility of lipophilic nutrients because rapid digestion quickly solubilises the lipids into mixed micelles [45–47]. They are suitable for applications requiring immediate nutrient delivery, such as infant formula or rapid-release nutraceuticals. However, their lack of structural barriers limits protection of acid-labile or oxidation-prone bioactives, and they may not promote satiety because fast lipid absorption leads to brief postprandial signals. To address these limitations, researchers combine surfactants with other structures, such as multilayer coatings or gel matrices, to provide additional control over digestion [38, 48].

5 Pickering Emulsions

5.1 Types of stabilising particles

Pickering emulsions are stabilised by solid particles that adsorb irreversibly at the oil–water interface. These particles create a rigid or semi-rigid shell around droplets, preventing

coalescence and reducing interfacial permeability. Food-grade particles include inorganic materials (silica, calcium carbonate), biopolymers (cellulose nanocrystals, lignin-containing cellulose nanofibrils, starch granules), proteins (zein, whey protein microgels), polysaccharides (chitin nanocrystals, chitin nanofibers) and composite particles (protein–polysaccharide complexes)[3, 19, 30] as shown in Table 2. Particle wettability (contact angle), size, shape and surface charge determine the energy of adsorption and interfacial coverage. Hydrophobic modifications or pH/ionic environment adjustments can tune particle wettability for O/W or W/O emulsions. Pickering emulsions have gained attention as surfactant-free, highly stable delivery systems in foods [1, 31, 49].

Table 2. Relationship between particle type, interfacial mechanism and digestion behaviour in Pickering emulsions.

Particle Type (Example Materials)	Interfacial Mechanism	Digestion Effect	Findings	References
Cellulose nanofibrils (CNF) / nanocrystals	Dense, rigid particle shell; formation of droplet network structures	Strong reduction in lipase and bile salt access; delayed and lower FFA release	Final FFA release \approx 26% in CNF-stabilised emulsions compared >90% in surfactant emulsions	[18, 20]
Starch granules (native or OSA-modified)	Granular packing creates a semi-permeable barrier; wettability is tunable by modification	Moderate digestion delay depending on hydrophobicity and granule swelling	OSA-modified starch reduces lipolysis more than native starch	[3, 50]
Protein microgels	Soft, deformable interfacial layer that swells during gastric digestion	Partial delay in lipase penetration; less resistance than rigid polysaccharides	Microgel interfaces gradually become more permeable during digestion	[51, 52]
Chitin nanocrystals / nanofibers	Thick steric barrier plus electrostatic repulsion (especially when negatively charged)	Sustained suppression of lipolysis due to reduced bile salt displacement	Slower hydrolysis kinetics reported in chitin-stabilised systems	[19, 53]
Protein–polysaccharide	Composite interfacial network combining steric,	Robust digestion resistance across	Droplet structure and interfacial integrity	[54, 55]

composite particles	electrostatic and hydration-layer effects	gastric and intestinal phases	maintained during digestion	
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5.2 Interfacial assembly and barrier effects on digestion fate

The high desorption energy of particles in Pickering emulsions hinders displacement by bile salts, leading to enhanced stability under gastric and intestinal conditions. Cellulose nanofibril stabilisers can form network structures bridging droplets. For instance, corn-oil-in-water Pickering emulsions stabilised with lignin-containing cellulose nanofibrils exhibited a final FFA release of only 26.3% under INFOGEST conditions, compared with $\approx 100\%$ for conventional surfactant-based emulsions [5, 16, 18]. The low FFA release was attributed to the physical barrier of the particle shell and the network structure among droplets. In general, Pickering emulsions show delayed lipolysis because lipases and bile salts have difficulty penetrating the particle shell and accessing the oil core. Particles may also reduce lipid droplet coalescence during digestion, maintaining smaller droplets and decreasing surface area available for enzymes. Similar reductions in lipolysis have been reported using cellulose nanocrystal Pickering stabilisers combined with biopolymers [18, 20, 24].

The main mechanisms by which Pickering emulsions slow lipid digestion include steric hindrance, diffusion limitation, and electrostatic repulsion. The dense particle layer surrounding oil droplets acts as a steric barrier that physically prevents lipases from reaching triglycerides. In addition, the thickness of the particle shell limits the diffusion of bile salts and enzymes toward the oil core, delaying interfacial displacement and lipid hydrolysis. Negatively charged particles such as cellulose nanocrystals can also repel bile salts, which are anionic, further delaying their adsorption. Particle shells may also create local microenvironments that alter interfacial pH, ionic strength or hydration, indirectly reducing enzyme activity. Beyond single-droplet effects, particle-stabilised droplets often form interconnected networks in the continuous phase, which further impede droplet mobility and mixing during digestion.

5.3 Hydrolysis and nutrient delivery outcomes

The slower digestion of Pickering emulsions can be advantageous for applications requiring sustained lipid release and prolonged satiety. For example, particle-stabilised emulsions have been shown to reduce postprandial glycaemic response by slowing lipid hydrolysis and moderating hormone secretion linked to satiety. From a nutrient delivery perspective, delayed digestion may protect sensitive bioactives during gastric transit, allowing targeted release in the intestine. Chitin nanocrystal- and silica-stabilised Pickering double emulsions demonstrated sustained release of chlorogenic acid, with intestinal bioaccessibility reaching $\sim 60\%$, comparable to conventional emulsions, while maintaining gastric protection [14, 18]. Similarly, pH-responsive Pickering emulsions made with glycosylated zein and ferulic acid improved the bioaccessibility of coenzyme Q10 under INFOGEST conditions [59, 60]. These

findings highlight the potential of Pickering systems to provide both structural stability and tunable release profiles.

6 Gel-Based Emulsions

6.1 Hydrogel and oleogel structures

Gel-based emulsions combine dispersed oil droplets with a three-dimensional gel matrix. Hydrogels are formed by proteins (e.g., gelatin, whey, soy, pea) or polysaccharides (e.g., carrageenan, alginate, pectin) that crosslink to immobilise water and trap oil droplets within the network. Oleogels, in contrast, structure liquid oils into semi-solid matrices using organogelators such as waxes, monoglycerides, or ethyl cellulose. The structural properties of gels including pore size, elasticity and water-holding capacity to control droplet mobility and the accessibility of lipases to triglycerides. Emulsion-filled gels are versatile systems that can be tailored to deliver lipids, bioactives and flavour compounds in a controlled manner [10].

6.2 Digestive behaviour

The digestion of gel-based emulsions is strongly influenced by gel density, network structure and breakdown under gastrointestinal conditions. Hydrogels typically swell in gastric fluid and gradually release embedded droplets for digestion. In pea protein- κ -carrageenan gels, low κ -carrageenan concentrations (0.25%) accelerated lipid digestion by loosening the network, whereas higher concentrations restricted both lipid and protein hydrolysis due to excessive rigidity [9]. Similarly, in camellia seed protein emulsion gels containing EGCG, the gel matrix slowed digestion, reducing EGCG release from 81% in solution to 27% in gel form, while enhancing bioaccessibility by 31% [10]. Oleogels, such as ethyl cellulose-based systems, release FFAs more slowly than liquid oils (40–55% vs ~64%), reflecting the limited accessibility of lipases to entrapped triglycerides. These examples highlight how gelation can either accelerate or retard digestion depending on formulation.

6.3 Barrier mechanisms

Gel-based emulsions employ multiple barrier mechanisms. Physical entrapment of droplets within the gel matrix restricts droplet mobility and limits coalescence, reducing available surface area for lipase binding [10, 11]. The dense polymer networks act as diffusion barriers, slowing the transport of enzymes and bile salts. Electrostatic interactions between proteins and polysaccharides in mixed gels further modulate enzyme adsorption. For instance, negatively charged polysaccharides may repel bile salts, delaying displacement of interfacial proteins. Phenolic compounds such as EGCG can crosslink proteins, increasing gel stiffness and enhancing resistance to digestion [11]. In oleogels, crystalline organogelators form solid networks around lipid droplets, reducing interfacial fluidity and impeding enzymatic access

[10]. Collectively, these mechanisms explain the slower digestion profiles of many gel-based systems.

6.4 Controlled release and satiety

One of the main applications of gel-based emulsions is controlled release of lipids and bioactives for satiety and metabolic regulation. High-viscosity gels prolong gastric retention, stimulating satiety hormones such as cholecystokinin and glucagon-like peptide-1 [10]. By moderating postprandial lipaemia, emulsion gels can reduce cardiovascular risk factors. Emulsion-filled hydrogels have been proposed for weight management by slowing digestion and prolonging nutrient delivery. Oleogels structured with waxes or ethyl cellulose also delay lipolysis and may reduce caloric bioavailability. Importantly, gel-based systems allow targeted release profiles: rapid release in the intestine for nutrient absorption or delayed release for colonic delivery of functional lipids. Thus, they represent promising tools for precision nutrition and functional food development [10, 11].

However, the structural rigidity of gel matrices can introduce textural challenges in food applications. High gel strength may produce a firm or rubbery mouthfeel, as reported for alginate–protein gel emulsions where increased crosslinking improved digestion resistance but significantly reduced sensory acceptability scores. Conversely, weaker gels may show syneresis or fracture during storage, leading to oiling-off and loss of emulsion stability. Therefore, the level of structuring must balance controlled digestion with acceptable texture, particularly when targeting products such as yoghurts, spreads or plant-based creams.

7 Dried and Rehydrated Emulsions

7.1 Methods of preparation

Dried emulsions are produced by spray drying, freeze drying or vacuum drying of liquid emulsions into powders for extended storage stability. Wall materials such as maltodextrin, gum arabic, whey protein isolate and modified starches encapsulate lipid droplets during drying. Upon rehydration, these powders ideally redisperse into emulsions resembling their original state. However, the drying process alters interfacial structures and droplet aggregation, often resulting in incomplete redispersion and modified digestion behaviours.

7.2 Reconstitution and digestion kinetics

When dried emulsions are rehydrated, the droplet size distribution often shifts towards larger diameters due to partial aggregation during drying. This reduces the available interfacial area for lipase adsorption, thereby slowing lipolysis. Incomplete redispersion leads to heterogeneous droplet populations, with some droplets remaining embedded in wall materials or aggregated clusters. Consequently, digestion kinetics are altered: FFA release

tends to be slower and less complete compared to freshly prepared emulsions. Freeze-dried systems often preserve interfacial proteins more effectively than spray-dried ones, but both show delayed digestion due to structural rearrangements upon drying and rehydration.

7.3 Barrier mechanisms

Several barrier mechanisms explain the reduced digestibility of dried emulsions. The formation of dense carbohydrate–protein matrices during spray drying encapsulates lipid droplets, making them less accessible to lipases and bile salts. Maillard reactions between proteins and reducing sugars during drying can further crosslink wall materials, increasing rigidity and lowering enzymatic permeability. Aggregated or crust-like structures around droplets act as physical barriers, reducing interfacial exposure. Additionally, rehydrated powders often display high viscosity, which can slow enzyme diffusion and bile salt transport.

7.4 Shelf stability versus digestibility trade-offs

The main advantage of dried emulsions is their improved storage stability. Spray- and freeze-dried powders protect encapsulated lipids from oxidation, light degradation and microbial spoilage, extending shelf life significantly compared to liquid emulsions. However, this increased stability comes at the cost of reduced digestibility, as incomplete redispersion and dense protective shells slow lipolysis and bioaccessibility. To address this trade-off, researchers design wall materials and drying conditions that balance oxidative protection with efficient redispersion. For example, blends of maltodextrin and whey protein provide good redispersion and higher digestion rates than carbohydrate-only carriers. The goal is to create powders that combine the convenience and stability of dried products with favourable digestion kinetics upon rehydration. Industrial scalability is an important consideration for gel-based and dried emulsion systems. Although spray-dried or freeze-dried emulsions can be rehydrated, they typically recover only part of the original droplet size distribution, as partial protein denaturation and flocculation during drying can lead to larger, more polydisperse droplets after reconstitution. For example, mean droplet sizes have been reported to increase from $\sim 0.5 \mu\text{m}$ to $1\text{--}3 \mu\text{m}$ after rehydration [67, 70]. As a result, commercial applications commonly use formulations with strong interfacial stabilisers to maintain dispersion efficiency, as seen in infant formula emulsions and encapsulated flavour oil powders.

8 Complex Emulsion Systems

8.1 Multilayer emulsions

Multilayer emulsions are created by sequential adsorption of oppositely charged biopolymers onto droplet surfaces. For example, a primary emulsion stabilised by whey protein can be coated with chitosan and further layered with pectin or alginate. Each additional layer

increases interfacial thickness, elasticity and charge density, producing a robust interfacial barrier that restricts lipase and bile salt access [16, 18, 30]. The polyelectrolyte multilayer structure enhances resistance to pH changes, ionic strength variations and gastrointestinal enzymes. As a result, multilayer emulsions often show delayed FFA release and prolonged protection of encapsulated bioactives. For instance, chitosan–pectin multilayers reduced lipolysis rates compared with single-layer emulsions under INFOGEST digestion.

8.2 Double emulsions and hybrid systems

Double emulsions (W/O/W or O/W/O) contain two immiscible aqueous or oil phases separated by an intermediate oil or water layer. They provide multi-compartment structures that allow co-encapsulation of hydrophilic and lipophilic compounds. Conventional surfactant-stabilised double emulsions often suffer from instability due to osmotic pressure differences and coalescence. However, particle-stabilised double emulsions (PDEs) demonstrate greater structural integrity. For example, chitin nanocrystal/silica-stabilised W/O/W emulsions maintained droplet integrity during simulated digestion and released chlorogenic acid (CA) in a controlled manner. During oral and gastric phases, CA release was limited (11–19% oral; ~74% gastric), while intestinal digestion enabled sustained release with bioaccessibility reaching ~60%, similar to conventional emulsions. This highlights the potential of PDEs to provide both structural stability and effective delivery of bioactives.

Recent advances combine multiple structural strategies to design hybrid emulsions with synergistic properties. Examples include multilayer-stabilised Pickering emulsions, in which particle shells are coated with biopolymers to improve stability and digestion control. Hybrid emulsion gels embed double emulsions within gel matrices, providing multi-level barriers that regulate both droplet release and digestion rates. For instance, combining Pickering stabilisation with gelation allowed dual control: particle shells restricted lipase access, while the gel matrix slowed droplet mobility, resulting in sustained lipid release. Another emerging design involves stimuli-responsive emulsions that release bioactives in response to intestinal pH, redox conditions or enzymatic triggers. These systems mimic physiological cues to achieve site-specific delivery of lipids and nutraceuticals. Advanced fabrication techniques, including microfluidics, 3D printing and complex coacervation, are increasingly being applied to create precision-structured emulsions for targeted nutrition [1].

Unlike basic emulsions that only hold oil droplets stable, complex emulsions are designed to respond to pH, enzymes, or salts in the digestive system. This means they can control how fast and when lipids are released, providing more precise delivery of nutrients or bioactives.

9 Comparative Analysis of Emulsion Systems

Comparing the different emulsion structures highlights distinct advantages and limitations. Surfactant-based emulsions offer simplicity, reproducibility and rapid nutrient release but

provide little protection against gastric degradation as shown in Table 3 [11]. Pickering emulsions deliver superior stability and slower lipolysis, making them ideal for satiety enhancement and sustained release, though they may reduce total bioaccessibility of lipids [11, 12]. Gel-based emulsions allow fine-tuned control via matrix density, providing delayed digestion and enhanced satiety but may be challenging to optimise for bioactive release. Dried emulsions extend shelf life and protect bioactives during storage, but their digestion rates are generally reduced due to incomplete rehydration and structural changes. Complex systems such as multilayer, double and hybrid emulsions provide programmable release and multi-compartment delivery but often require sophisticated fabrication and may face scalability challenges [19].

Table 3. Digestive Behavior of Emulsion and Gel Systems with Respect to Stabilizing Materials.

System Type	Material Used	Oral Phase (SSF)	Gastric Phase (SGF)	Intestinal Phase (SIF)
Classic O/W Emulsion	Small-molecule surfactants or food proteins (e.g., Tween 20, whey protein isolate, lecithin)	Surfactant remains at droplet interface; little structural change.	Rapid coalescence and flocculation due to protein displacement at low pH.	Bile salts replace emulsifier → fast lipolysis and high FFA release.
Pickering Emulsion	Solid particles such as starch granules, cellulose nanocrystals, chitin/chitosan nanoparticles, whey protein aggregates	Rigid particle shell forms at interface → highly stable droplets.	Particle shell remains adsorbed → excellent gastric stability.	Particle barrier slows lipase binding → controlled FFA release.
Pickering Emulsion Gel	Biopolymer gel matrix (e.g., gelatin, alginate, pectin) + Pickering particles stabilizing droplets	Droplets immobilized within gel matrix, restricting mobility.	Gel swells and softens but droplets remain partly trapped.	Gel degrades, releasing droplets gradually → delayed digestion.
Classic Hydrogel (No Emulsion)	Polymer network only (e.g., alginate, carrageenan, agar, protein gels)	Gel structure largely unchanged; minimal breakdown in oral stage.	Gel may shrink or swell depending on pH/ions.	Matrix erosion rate controls release → slow nutrient diffusion.
Complex Emulsion (e.g., W/O/W, multilayer)	Layered stabilizers: proteins + polysaccharides (e.g., WPI-pectin;	Outer interface stable; internal droplets	Internal compartment delays lipid release and	Sequential release of encapsulated droplets →

	casein–gum Arabic), or phospholipids	protected from saliva.	protects sensitive actives.	sustained digestion.
Dried Emulsion (Reconstituted)	Spray-drying wall materials: maltodextrin, gum Arabic, modified starch, whey protein	Partial droplet rehydration; interfacial layer reform depends on matrix composition.	Rehydrated droplets may aggregate if emulsifier is insufficient.	Digestion depends on degree of structural recovery → may reduce bioaccessibility.

Together, these comparisons suggest that the choice of emulsion system should be application-specific. For example, surfactant-based emulsions may be suited for infant nutrition where rapid lipid release is required, while Pickering or gel-based emulsions may be more suitable for weight management or chronic disease prevention where slower digestion is beneficial. Hybrid and complex systems show promise for multifunctional delivery in precision nutrition but will require advances in cost-effective, scalable processing before widespread application [3, 12]. Looking forward, emerging research is moving toward hybrid and adaptive emulsions that can respond to pH, enzymes or ionic conditions in vivo, offering opportunities for precision nutrition and targeted gastrointestinal release.

9 Applications of Emulsion-Based Delivery Systems

Emulsion-based delivery systems have diverse applications across the food, pharmaceutical and nutraceutical industries. Their ability to control lipid digestion and bioactive release allows tailored solutions for health promotion, disease management and food innovation.

10.1 Functional foods and nutraceuticals

Emulsion systems are increasingly incorporated into functional foods to enhance the delivery of lipophilic nutrients such as omega-3 fatty acids, carotenoids and fat-soluble vitamins (A, D, E and K). Surfactant-based nanoemulsions provide rapid bioaccessibility, making them suitable for fortified beverages and supplements [3, 15]. Pickering emulsions, with their slower digestion rates, are employed to design satiety-enhancing products or foods aimed at weight management [5, 8]. Gel-based emulsions serve as carriers for antioxidants such as EGCG and coenzyme Q10, protecting these compounds from degradation during gastric passage while improving intestinal absorption [12]. Such targeted release enhances efficacy and consumer compliance in nutraceutical formulations.

10.2 Pharmaceutical and medical nutrition

In pharmaceuticals, emulsions are used for oral and parenteral drug delivery. Complex emulsion systems allow co-delivery of hydrophilic and lipophilic drugs, offering controlled release profiles. For instance, PDEs have demonstrated effective encapsulation of polyphenols and improved intestinal bioaccessibility [15]. In medical nutrition, lipid-based

emulsions are vital for enteral and parenteral feeding, where controlled digestion profiles ensure steady energy release and minimise metabolic complications. Gel-based systems are explored for delivery of poorly soluble drugs, offering protection and targeted release within the gastrointestinal tract [1, 11].

10.3 Plant-based and sustainable food systems

The rise of plant-based diets has increased the demand for emulsions formulated with sustainable, food-grade stabilisers. Plant proteins from legumes (e.g., pea, faba bean), cereals (e.g., oat, rice) and oilseeds (e.g., soy, canola) are increasingly being used to replace dairy proteins as emulsion stabilisers, while polysaccharides and protein–polysaccharide complexes provide naturally derived alternatives to synthetic surfactants. Pickering stabilisers derived from starches, cellulose, or chitin nanofibrils align with clean-label demands [19, 49]. Moreover, emulsions facilitate the design of plant-based dairy alternatives, meat analogues and functional beverages with improved texture, flavour delivery and nutrient bioavailability.

Commercially, such emulsions contribute the texture and mouthfeel of plant-based milks (e.g., oat and soy beverages), plant-based yoghurts, coffee creamers, dressings and meat analogues, where controlled droplet size contributes to creaminess and flavour delivery. However, plant protein-based emulsions may exhibit challenges such as variable solubility, lower interfacial flexibility and off-flavours, requiring careful formulation adjustments (pH shifting, enzymatic modification, or blending) to achieve desired performance.

Beyond functionality, the adoption of plant-derived stabilisers offers sustainability benefits, including reduced greenhouse gas emissions, lower land and water use compared to dairy proteins, and valorisation of agricultural side-streams (e.g., pea protein residues or cereal by-products). Consequently, plant-based emulsions are positioned not only as nutritional alternatives but as part of broader strategies to reduce environmental impact in food manufacturing.

10.4 Weight management and metabolic health

Emulsion systems that slow lipid digestion are applied in weight management by prolonging satiety and moderating postprandial lipaemia. Pickering emulsions and gel-based systems are particularly suited for such purposes. By reducing rapid spikes in plasma triglycerides and glucose, these systems may reduce risks of metabolic syndrome and cardiovascular disease. Controlled digestion also provides opportunities for designing foods that support diabetic diets by moderating glycaemic response [7].

10.5 Food preservation and oxidative stability

Dried emulsions extend shelf life by reducing oxidative degradation of sensitive lipids, making them useful for powdered nutritional supplements and infant formula. Complex systems such as multilayer emulsions improve oxidative stability by providing thicker interfacial films that protect against oxygen and pro-oxidant penetration [7]. Such systems not only maintain bioactive efficacy but also enhance product quality during storage and transport.

10 Future Perspectives

The development of emulsion-based delivery systems is rapidly advancing, with new directions emphasising sustainability, personalisation and mechanistic understanding. Future systems will increasingly rely on sustainable, food-grade particles and biopolymers as stabilisers. Natural fibres such as starch nanocrystals, cellulose nanofibrils and chitin derivatives provide renewable alternatives to synthetic surfactants [5]. Valorisation of food processing by-products (e.g., lignin-containing particles from agricultural residues) as Pickering stabilisers further supports circular bioeconomy principles. Emulsion systems are poised to play a major role in precision nutrition, where release profiles are tailored to individual metabolic needs. Controlled lipid digestion can be adapted to populations with specific requirements, such as infants, older adults or patients with metabolic disorders. By incorporating biomarkers and gut microbiome data, AI-assisted formulation may optimise emulsion structures for personalised health outcomes [15]. Next-generation emulsions will incorporate smart interfaces that respond to gastrointestinal stimuli. Examples include pH-responsive coatings that release bioactives in the intestine, enzyme-sensitive particles that trigger release upon proteolysis, or redox-responsive layers that activate in the colon. Biomimetic designs inspired by natural structures, such as milk fat globules, offer promising blueprints for stable and digestible systems. A key challenge lies in translating laboratory-scale formulations into industrial production. While hybrid and complex systems show remarkable performance, they often involve intricate fabrication steps. Simplifying processes through scalable technologies such as high-pressure homogenisation, spray drying and 3D printing will be critical for commercialisation. Regulatory approval and consumer acceptance of novel stabilisers must also be addressed to enable widespread application.

Future advances in emulsion-based delivery systems will benefit from the development of new plant- and biopolymer-derived stabilizers, although considerations of regulatory approval, allergenicity, digestibility and long-term safety must be addressed before widespread adoption. Some emerging fibers and nanostructured biopolymers (e.g., cellulose nanofibrils, chitin nanocrystals) show excellent interfacial performance, but their metabolic fate and safe upper intake levels require further evaluation.

At the same time, AI- and machine learning-assisted formulation platforms offer exciting opportunities to accelerate emulsion design. For instance, predictive models that link ingredient structure, interfacial behavior and digestion outcomes have been used to optimize plant protein–polysaccharide emulsions with significantly reduced experimental screening effort [81]. Integrating such computational tools with green processing and clean-label

stabilizers may support the development of personalized and sustainable emulsion-based nutritional strategies in the coming years.

Conclusion

Emulsion-based delivery systems represent a versatile platform for modulating lipid digestion and enhancing the bioavailability of lipophilic nutrients. Surfactant-based systems offer rapid release, while Pickering and gel-based emulsions provide sustained digestion and targeted protection. Dried emulsions improve storage stability but may compromise digestion, whereas multilayer, double and hybrid systems offer programmable release with multifunctional applications. Comparative analyses reveal that each system presents trade-offs between stability, digestibility and scalability, necessitating application-specific design. This review provides a current synthesis of recent developments (2023–2025) framed within the INFOGEST standardized digestion model, allowing clearer comparison of how interfacial design strategies influence digestion kinetics. Applications extend across functional foods, clinical nutrition, weight management and plant-based systems. Looking ahead, progress in stimuli-responsive interfaces, biomimetic structuring, in vitro gut-simulation platforms, and AI-assisted formulation tools is expected to support the development of more tailored and sustainable emulsion-based delivery systems for precision nutrition.

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Conflict of interests

No potential conflict of interest was reported by the author(s).

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