Biofunctional Interfaces for Sustainable Emulsions: Insights from Microalgae-Copepod Nutrition and SCFA-Starch Pickering Systems

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Abstract. Sustainable emulsions rely on interfacial materials that are efficient, suitable for food applications, and environmentally friendly. This review connects two distinct but complementary areas: (1) the trophic interaction between microalgae and copepods in aquaculture live-feed systems, and (2) the use of short-chain fatty acid (SCFA)–modified starch particles as Pickering stabilisers. This study investigates the influence of molecular and colloidal factors, including adsorption, viscoelastic film formation, wettability, and digestion-triggered disassembly, on emulsion stability and functionality. In microalgae–copepod systems, cell-wall polysaccharides, membrane glycolipids, phospholipids, proteins, and extracellular polymers provide amphiphilic motifs and steric–electrostatic barriers that function as bioemulsifiers. In SCFA–starch systems, esterification and inclusion complexation modify particle hydrophobicity and contact angle, resulting in recyclable interfacial armour that provides additional nutritional benefits via SCFA release. This study examines the relationships between structure and function, methods for interfacial characterisation, stability during processing and digestion, and sustainability metrics, including circular bioeconomy approaches that enhance the value of algal residues and fermentation-derived short-chain fatty acids (SCFAs). We propose design rules for clean-label, digestion-responsive emulsions suitable for food applications, nutraceutical delivery, and aquaculture feed oils. The integration of these two platforms reveals opportunities for the development of scalable, low-impact biofunctional emulsions.

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1 Introduction

Emulsions are fundamental in the food, nutraceutical, cosmetic, agricultural, and life-science industries. Their stability depends on interfacial layers that absorb at oil-water boundaries, prevent droplet coalescence, and regulate digestion and release behaviour [1, 2]. Conventional surfactants exhibit effective performance; however, they present challenges regarding clean-label acceptance, environmental sustainability, and compatibility with complex matrices [3]. These concerns have stimulated interest in bio-based stabilisers through two complementary pathways.

The first strategy is based on biological systems. Microalgae contain high concentrations of proteins, polysaccharides, lipids, and pigments [4,5], whereas copepods accumulate long-chain omega-3 fatty acids and synthesise proteinaceous and mucopolysaccharide materials related to feeding and digestive processes [6, 7]. The microalgae–copepod trophic chain is well established in aquaculture [6, 7, 8] and this provides a new source of natural interfacial materials, facilitating the investigation of how nutrition influences surface-active biopolymers.

The second approach involves colloidal engineering via Pickering emulsions, in which solid particles stabilise the interface. Starch is easily accessible consumable, and cost-effective [9, 10] and its wettability of its granules or derived nanoparticles can be adjusted [11]. Short-chain fatty acids, including acetate, propionate, and butyrate, are metabolites derived from microbial activity that hold nutritional significance. When esterified or complexed with starch, they modify hydrophobicity, contact angle, and enhance nutritional functionality. The SCFA-starch particles generate stable Pickering shells and, in digestive environments, release SCFAs that promote gut health [12].

This review integrates biological and colloidal approaches within the framework of biofunctional interfaces. This study (i) outlines the physicochemical principles underlying interfacial stabilisation, (ii) examines insights from microalgae–copepod nutrition, (iii) delineates the design parameters of SCFA–starch Pickering systems, and (iv) suggests comprehensive design guidelines for sustainable, digestion-responsive emulsions applicable in food and aquaculture sectors.

2 Principles of bio-functional emulsion interfaces

Bio-functional emulsion interfaces utilise natural, food-grade components such as proteins, polysaccharides, phospholipids, biosurfactants, and colloidal particles to sustainably stabilise oil-water combinations. These amphiphilic biomolecules adsorb at the oil-water interface, diminishing interfacial tension and creating a protective coating that inhibits droplet coalescence [13, 14]. During adsorption, proteins undergo unfolding and reorientation of their hydrophobic and hydrophilic regions to align with the respective phases, resulting in cohesive interfacial layers. The rheological strength of these layers is contingent upon molecular flexibility and structure, globular proteins (e.g., whey) create thinner, more rigid films, while flexible caseins produce thicker, elastic coatings [15].

Protein–polysaccharide complexes augment interfacial resilience via covalent or electrostatic interactions, including Maillard-type conjugates or coacervates, hence enhancing emulsion stability under temperature or pH stress where individual components are inadequate [15]. Interfacial rheology assessed through dilatational and shear responses, quantifies mechanical stability; a dominance of elastic over viscous modulus ($G' > G''$) indicates robust interfacial networks that inhibit coalescence. Emulsions stabilised by Span 80 above its critical micelle concentration and those utilising PGPR (polyglycerol

polyricinoleate) exhibit elevated viscoelasticity and improved long-term stability in comparison to linear surfactants.

Biomolecular emulsifiers offer biodegradability and biocompatibility; nonetheless, their efficacy may fluctuate under different physicochemical conditions. Synthetic emulsifiers provide exact interfacial control and enhanced thermal stability, although they pose issues related to sustainability and regulatory approval. Incorporating bio-based stabilisers into structured systems, such as Pickering emulsions within hydrogels, presents a viable solution, balancing environmental sustainability with functional efficacy, exemplified by cellulose nanocrystal, soy protein emulsions integrated into alginate, chitosan matrices facilitating controlled intestinal release of thymoquinone [18].

In mixed systems, protein-polysaccharide interactions augment interface durability and efficacy. Covalent or electrostatic interaction such as Maillard-type conjugates or coacervate formations enhance emulsifying capacity, especially under adverse conditions where proteins alone exhibit instability [15].

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3 Microalgae-copepod nutrition as a source and model of interfaces

The interaction between microalgae and copepods functions as a natural resource and a model interface, demonstrating how sustainable biofunctional systems might be developed. Microalgae are a significant source of proteins, lipids, carbohydrates, and vitamins, with lipid content typically ranging from 20% to 50%, and are particularly rich in polyunsaturated fatty acids (PUFAs) like EPA and DHA. Amphiphilic lipids, including glycolipids and phospholipids, effectively adsorb at oil–water interfaces, reducing interfacial tension and enhancing emulsion stability [20]. Lipid-rich fractions from species like *Nannochloropsis salina* exhibit significant surface activity, whereas protein extracts create viscoelastic interfacial films that enhance structural integrity. The complementary mechanisms of rapid tension reduction by lipids and film formation by proteins reflect the desired balance between surfactant efficiency and mechanical resilience in emulsion design.

Microalgal biomolecules demonstrate comparable surface activity to synthetic emulsifiers, while exhibiting enhanced biodegradability, biocompatibility, and environmental safety. Nonetheless, the functional heterogeneity and complexity of extraction may impede consistency in large-scale applications. Integrating lipid- and protein-derived microalgal fractions into structured systems like SCFA–starch Pickering emulsions may enhance bioactivity while ensuring colloidal stability for sustainable formulations.

Copepods serve as trophic bio-converters, converting microalgal nutrients into enriched lipids and phospholipids with notable interfacial potential. Lipidomic analyses of *Labidocerca aestiva* demonstrate the presence of glycerophosphocholines and lysoglycerophosphocholines that are enriched with long-chain polyunsaturated fatty acids (PUFAs) such as EPA, DHA, DPA, and ARA. These compounds significantly decrease interfacial tension and improve emulsion stability. Trophic enrichment permeates the food web, as heterotrophic protists, such as *Oxyrrhis marina*, biosynthesise essential

polyunsaturated fatty acids (PUFAs) and sterols, which are then assimilated by copepods. This natural lipid upgrading demonstrates a biologically driven approach to producing high-performance, environmentally friendly emulsifiers sourced from marine systems.
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4 SCFA-starch Pickering systems

Starch, abundant and biodegradable, is a promising option for stabilising food-grade Pickering emulsions. The structure of starch consists of amylose (linear) and amylopectin (branched), with its particle characteristics varying based on its plant origin such as potato, corn, rice, wheat, maize, or cassava which subsequently affects its dispersibility and emulsification properties [9]. However, native starch is significantly hydrophilic and frequently displays substantial granule sizes (0.5μm to 100μm), constraining its capacity to effectively adhere to oil-water interfaces.

Modifications are necessary to enhance interfacial activity and enable starch to function well as a Pickering stabiliser. Chemical treatments, such as esterification using octenyl succinic anhydride (OSA), lauroyl chloride, acetylation, or epichlorohydrin crosslinking, augment hydrophobicity, hence enhancing affinity for oil phases and facilitating successful emulsification. Physical techniques like acid hydrolysis, high-pressure processing, ultrasonication, ball milling, and nanoprecipitation can reduce starch granule size to the nanoscale, hence enhancing surface area and cohesiveness at oil-water interfaces [11].

The functionalisation of starch with short-chain fatty acids (SCFAs), specifically acetyl, propionyl, and butyryl groups, is typically achieved through esterification processes. The chemical modifications aim to enhance interfacial properties and stabilise emulsions. Rice and quinoa starch underwent esterification with various short-chain fatty acids of differing chain lengths in foundational research. The modified starches demonstrated significant changes in physicochemical properties, including decreased gelatinisation and pasting temperatures, reduced paste hardness, improved clarity, and a marked increase in resistant starch content. Furthermore, modifications employing longer short-chain fatty acids with high degrees of substitution (DS) resulted in emulsions that demonstrated improved stability metrics over a duration of 50 days.

The alterations of longer-chain SCFAs were associated with high emulsion indices and prolonged stability, particularly when quinoa starch was utilised. This indicated than chain length and degree of substitution considerably affect the emulsifying performance of SCFA-starch, making customisation a crucial benefit for functional emulsion systems. A significant method entails the synthesis of butyric acid-modified porous starch (BA-PS) through the esterification of enzymatically produced porous starch. Research indicated that augmenting the degree of substitution in BA-PS produced emulsions characterised by reduced droplet sizes, higher stability, and superior encapsulation effectiveness for hydrophobic chemicals such as paclitaxel. The improved release patterns and retentions rates highlighted the potential of SCFA-functionalized porous starch in controlled delivery systems.

Besides direct SCFA esterification, similar routes encompass esterification utilising derivatives such as octenyl succinic anhydride (OSA). Although not classified as SCFAs. OSA incorporates hydrophobic alkenyl succinate groups that markedly enhance the surface activity and emulsification properties of starch. Methods like lipase-coupled esterification, ultrasonic pretreatment, hydrothermal treatment, and high-shear processing have been employed to improve substitution efficiency, facilitate deeper penetration into granules, and minimise byproducts. These methodologies yield starches characterised by reduced gelatinisation temperatures, enhanced viscosity, and significant advancements in emulsion stabilisation.

While the SCFA-starch pathway provides significant engineering control over interfacial properties such as size, hydrophobicity, and substitution, the microalgal/biomass pathway presents notable advantages in sustainability and direct biotic integration. The engineered starch particles demonstrate superior performance in applications requiring precise specifications, such as delivery, stability, and customised droplet size. In contrast, microalgal-derived particles may be more compatible with circular bioeconomy principles, aquaculture feed-chain integration, and streamlined processing methods. In aquaculture, particularly in stabilising lipid-rich feeds for zooplankton or encapsulating sensitive nutrients, the selection of particle systems represents a trade-off between precision and performance, and sustainability and ecosystem compatibility. Combining the strengths of both systems, such as SCFA-modified starch blended with microalgal residue particles, represents a promising hybrid direction for future research.

5 Controlled delivery of bioactives

In the microalgae-copepod interaction, microalgal cells function as digestible nutrition sources, providing vital bioactives substances including polyunsaturated fatty acids (PUFAs), pigments, and vitamins to copepods. Their inflexible cells walls and internal structure govern the release of nutrients during digestion, so ensuring that bioactive compounds such as EPA, DHA, or carotenoids become accessible when required. Conversely. SCFA-modified starch Pickering emulsions exemplify a meticulously designed approach for the precise encapsulation and regulated release of bioactive compounds. In these systems, starch particles altered with short chain fatty acids stabilize emulsions and encapsulate hydrophobic substances such as curcumin, carotenoids, or nutrients within oil droplet.

Research indicates that these emulsions offer improved stability and tailored release, with curcumin encapsulation effectiveness significantly increasing. They facilitate stimulus-responsive release, remaining resilient under stomach conditions while releasing bioactives during the intestinal phase [10]. The current exploration's novelty resides in the integration of the structural resilience of natural biointerfaces, specifically microalgae cell walls, with the chemical tunability of designed biofunctional systems, such as SCFA-starch, to advance next-generation hybrid delivery platforms. Below is Table 1 of comparison of natural (microalgae–copepod) vs. designed (SCFA-starch pickering) biofunctional interfaces for emulsion stability and controlled bioactive delivery.

Table 1. Comparison of natural (microalgae–copepod) vs. designed (SCFA-starch pickering) biofunctional interfaces for emulsion stability and controlled bioactive delivery.

Aspect	Microalgae-copepod nutrition (natural biointerfaces)	SCFA-starch Pickering systems (designed particulate interfaces)	References
Structure function	Cellular surface and exudates regulate capture and digestion. The composition of microalgal cell walls (polysaccharides, glycoproteins, mucus/exudates) and	Hydrophobicity and particle size are the driving factors. Properties of Pickering adsorption and barrier. Esterification of short-chain fatty acids (SCFA) enhances surface hydrophobicity; longer acyl chains often augment	[6, 10]

	surface lipids/sterols influences adherence to copepod feeding appendage, digestibility, and nutrition transfer. Morphology influences ingesting efficiency and trophic transmission.	oil-wetting and interfacial anchoring, reduce droplet size and enhance emulsion stability. Particle shape, crystallinity, and degree of substitution govern interfacial packing and mechanical strength.	
Analytical approaches for interfacial characterizaton	Microscopy and biochemical tests. Confocal microscopy and SEM/cryo-SEM elucidate cell shape, mucilage, and feeding contacts; lipid staining (Nile Red, BODIPY) and biochemical studies measure lipids and carbohydrates available to copepods. Feeding assays and growth/reproduction measures establish a link between interface and function.	Interfacial physics toolkit. Dynamic tensiometry (pendant drop/spinning drop) for adsorption kinetics; interfacial shear and dilatational rheology to assess elastic/viscous interfacial films; QCM-D and ellipsometry for mass/viscoelastic layer characterisation; CLSM and cryo-SEM for microstructural analysis; particle sizing (DLS, laser diffraction) and zeta potential for colloidal state evaluation. The integration of rheology and microscopy connects the mechanics of interfacial films to the stability of emulsions on a macroscopic scale.	[6]
Stability under processing (heat, shear, ionic strength) & gastrointestinal (GI) conditions	Variable – frequently susceptible to processing yet suited for digesting. Intact algal cells or colonies exhibit resistance to mechanical shear based on wall composition; certain species retain lipids more effectively throughout gut passage, influencing nutrition delivery. Enzymatic and acidic stomach environments will	Exhibits robust resilience to shear and ionic fluctuations; gastrointestinal destiny is adjustable. Short-chain fatty acid starch Pickering emulsions frequently exhibit significant physical stability against coalescence and variations in ionic strength or moderate shear due to the formation of a solid-like interfacial layer by particles. Thermal processing and extreme pH or digestive enzymes can	[10]

	lyse vulnerable species, releasing nutrients; protective cell walls diminish immediate bioaccessibility but may facilitate distal digestion. Research highlights species-specific results in simulated gastrointestinal and aquaculture environments.	destabilise particle films (gelatinised or enzymatically degraded starch) or induce release. Gastrointestinal simulation studies indicate that particle-stabilized emulsions can safeguard encapsulated actives during the gastric phase and subsequently release them in the intestinal phase, contingent upon particle chemistry.	
Key limitations & knowledge gaps	Variability among species, scaling of algal mass culture for uniform interface characteristics; correlating cell surface chemistry with anticipated digestion release; ecological and energy life cycle assessment data for feed vs biochemical valorisation pathways.	Requirement for standardised measurements for degree of substitution against interfacial performance; environmentally friendly modification chemistries (enzyme-assisted acylation); scalability and regulatory evaluation for food-grade modified starch generated from waste-based short-chain fatty acids. A more thorough life cycle assessment comparing direct algal feeding to the conversion of biomass into particle emulsifiers is required.	[10]

6 Application landscapes and practical design rules for clean-label, digestion-responsive emulsions

6.1 Food and beverage

Short-chain fatty acid starch Pickering emulsions are notably advantageous as structurally robust and functional components in applications like salads, sauces, and non-dairy creams. These emulsions provide a dual benefit creating strong interfacial shells that improve texture and stability while supplying short-chain fatty acids (SCFAs) that promote gut health and regulate satiety. Research indicates that SCFA-starch emulsions with longer-chain modifications, such as propionylated and butyrylated quinoa starch attain high emulsion

indices (>71%) and preserve stability for prolonged storage durations of up to 50 days. Furthermore, starch-based Pickering emulsions exhibit remarkable resistance to oral and gastric digestion, making them ideal carriers for lipophilic bioactives, facilitating regulated lipid release and improved delivery efficacy.

Microalgal bioemulsifiers enhance these systems by providing natural pigments such as such as chlorophylls, carotenoids (β-carotene, lutein, astaxanthin), and phycobiliproteins that function as colourants and possess antioxidant and health promoting attributes. These pigments such as β-carotene, facilitate vision and immunological function, while astaxanthin serves as a powerful antioxidant both augment the sensory and functional attributes of dietary goods. Nevertheless, many pigments particularly chlorophyll and carotenoids exhibit sensitivity to light, pH, and temperature. Encapsulation in food-compatible carriers can enhance colour retention and antioxidant effectiveness, hence increasing their utility in processed food systems.

In comparison, SCFA-starch emulsions provide higher structural stability and digestibility regulation, while microalgal bioemulsifiers add multifunctionality through bioactivity and aesthetic improvement. Nonetheless, starch-based systems may be devoid of inherent bioactivity, while microalgal pigments encounter stability limitations under processing conditions. Integrating both elements could thus achieve a balance between robustness and usefulness, resulting in hybrid emulsions with synergistic nutritional and technological advantages.

6.2 Nutraceutical and pharmaceutical delivery

Short-chain fatty acid starch Pickering systems provide substantial protection for delicate bioactives, including omega-3 oils. Their particle-stabilized surfaces serve as robust physical and barrier layers, diminishing oxidation and facilitating sustained release, essential for prolonging shelf life and maintaining efficacy in nutraceutical and pharmaceutical formulations [11]. Encapsulating curcumin in starch particle-stabilized emulsions enhances its chemical stability and bio-accessibility under simulated gastrointestinal conditions.

Microalgal components such as astaxanthin, phycocyanin, polyunsaturated fatty acids (PUFAs), and sulphated polysaccharides exhibit significant pharmacological properties, including antioxidant, anti-inflammatory, and neuroprotective actions [5]. Their bioavailability is frequently constrained by inadequate solubility, breakdown by gastrointestinal conditions, or robust cell wall. Encapsulation technologies, including nano/microemulsions, liposomes, and hydrogels, improve protection, solubility, controlled release, and concealment of off-flavours, essential for the successful administration of microalgal actives in functional health products [5]. Furthermore, methods such as ultrasonication, high-pressure homogenisation, and enzymatic treatments improve cell wall disintegration, hence augmenting nutrient release and bio-accessibility.

Short-chain fatty acid starch systems present significant potential for enhancing emulsion stability, protecting bioactives, and enabling controlled release, thereby rendering them especially appropriate for nutraceutical and functional food applications. Nonetheless, their performance is constrained by the complexity of the formulation and their sensitivity to processing conditions. Microalgal bioactives offer significant nutritional and pharmacological advantages; however, they encounter substantial challenges concerning bioavailability and stability. Encapsulation and cell disruption technologies address these challenges; however, they introduce cost and scalability limitations, necessitating process optimisation for commercial viability.

6.3 Aquaculture feeds and live-feed enrichment

In aquaculture, microalgae serve as a validated, sustainable source of vital nutrients such as proteins, polyunsaturated fatty acids (PUFAs), and pigments, crucial for larval growth, immunological development, and pigmentation in cultivated species. Copepods are outstanding as live feeds due to their high HUFA content especially DHA and EPA and their superior survival and growth results compared to traditional feeds like rotifers or *Artemia*.

While study on SCFA-starch emulsions in aquafeeds is limited, parallels from food systems indicate considerable potential. Starch-based Pickering emulsions can efficiently transport oil-rich nutrients in feed, minimising leaching into raising water, enhancing feed efficiency, and decreasing environmental impact. Incorporating microalgal colours and lipids into these emulsions can improve bioavailability and appeal, potentially enhancing larval performance and health, The release of SCFAs from particles may also influence the gut or aquatic microbiota. Nonetheless, this area remains an intriguing frontier yet to be thoroughly investigated in aquaculture research.

Microalgae and SCFA-starch emulsions offer complementary advantages in aquafeeds. Microalgae serve as natural sources of essential fatty acids, pigments, and bioactives vital for larval nutrition and health; however, issues related to digestibility, stability, and nutrient loss during feeding remain significant challenges. In contrast, SCFA-starch Pickering emulsions provide a delivery system that improves nutrient protection and facilitates targeted release, potentially addressing these limitations. However, their practical application in aquatic systems is still insufficiently investigated, necessitating additional validation regarding stability, digestibility, and microbiome effects in aquaculture settings.

7 Conclusion

This review integrates not only innovative methodologies for developing environmentally sustainable, but fundamentally proposes a new high-performance emulsion technology, the symbiotic coupling of rigid, food-grade particle stabilizers with dynamic, nutrient-rich biointerfaces. SCFA-functionalized starches, specifically quinoa or rice starch modified with propionyl and butyryl groups, exhibit remarkable promise as food-grade Pickering emulsifiers. The modified starch particles create strong interfaces, attaining emulsion indices more than 71% and maintaining stability for over 50 days, while simultaneously increasing resistant starch content and lowering the temperature parameters of the starch matrix. This integration advances emulsion science by moving beyond simple structural stability to achieve pre-programmed bio-functionality. The complementation of the starch-based Pickering scaffold with components derived from microalgae and copepods introduces a dynamic layer of amphiphilic lipids, proteins, and pigments, which are biodegradable and impart antioxidative and high-value nutritional efficacy (like unique essential fatty acids). This dual-layer approach a rigid, functionalized core stabilized by a soft, nutraceutical shell, represents a critical synthesis, enabling the creation of systems that are simultaneously highly stable and highly bioactive. To fully realize the potential of these sustainable and multifunctional systems, future research must focus on two critical directions. First, investigations must optimize the synergistic ratio between the SCFA-starch Pickering particles and the microalgal/copepod biointerfaces to maximize stability while minimizing raw material usage. Second, a deeper understanding is required regarding the stability and controlled release kinetics of these emulsions under in vitro and in vivo gastrointestinal tract (GIT) conditions, which will be essential for validating their efficacy as advanced nutraceutical and food delivery vehicles.

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