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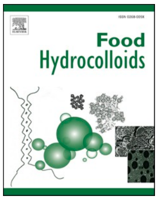

Microalgal exopolysaccharides as emerging food hydrocolloids: Structure–Rheology relationships, bioactivity, and industrial potential

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ABSTRACT

Microalgal exopolysaccharides (EPSs) are emerging as promising next-generation food hydrocolloids with distinctive structuring and biofunctional attributes. This review critically evaluates the taxonomic diversity, molecular architecture, and structure–rheology relationships of microalgal EPSs, highlighting how charge density, branching, and sulfation patterns translate into viscosity, gelation, and interfacial behaviours relevant to complex food matrices. Recent advances in cultivation strategies, bioreactor design, and downstream processing are summarized with an emphasis on yield, techno-functional quality, and integration into biorefinery concepts. Particular attention is given to solution and gel properties, emulsification and film-forming capacity, and synergistic interactions with established hydrocolloids and food biopolymers in applications such as dairy and plant-based analogues, beverages, and confectionery. The bioactive potential of microalgal EPSs, including antioxidant, prebiotic, immunomodulatory, and other health-related effects, is examined in the context of functional food design, safety assessment, and novel food regulatory pathways. By integrating physicochemical, technological, and regulatory perspectives, this review identifies key research gaps and outlines priority directions needed to position microalgal EPSs as sustainable, clean-label hydrocolloids for future food systems.

1. Introduction

1.1. *Food hydrocolloids: functional roles and emerging needs*

Hydrocolloids are large molecular weight exopolysaccharides (EPSs) and proteins that modify viscosity, stabilize emulsions, and form gels in food applications. Hydrocolloids such as pectin, alginate, carrageenan, and xanthan gum are widely used to control viscosity, gelation, and stability in food systems. However, supply limitations and increasing demand for sustainable and structurally versatile polymers have driven interest in alternative hydrocolloid sources, including microalgal exopolysaccharides. (Gao et al., 2024). Hydrocolloids were extracted industrially and characterized in the 19th to 20th centuries, after which they could be applied a large-scale foundation as a gelling agent and thickener (Liao et al., 2021).

A significant benchmark occurred when xanthan gum was obtained in the mid-20th century by the fermentation of *Xanthomonas* species, providing unique rheological properties as well as stability. Microbiological, algal, and plant-derived gums (e.g., agar, alginate, carrageenan, and pectin) are widely used as gelling and thickening agents in dairy, bakery, confectionery, and processed food products to improve texture, stability, and structural properties (Pirsa & Hafezi, 2023). Since the 1980s, advances in polymer science have enabled systematic investigation of structure–property–function relationships in hydrocolloids, allowing the design of polymers with tailored rheological and interfacial properties for specific food applications. These developments have expanded the role of hydrocolloids beyond texture modification to include fat replacement, viscosity control, satiety enhancement through

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modulation of gastric emptying, and controlled release of bioactive compounds and nutrients (McClements, 2021).

Recent and current research has looked into sustainable and novel sources (seed gums, underutilized crops, by-products, etc.), also health-related aspects such as dietary fibers and gut microbiota manipulation, and some clean-label options because of demand from consumers (Garcia-Vaquero, 2023). Hydrocolloids from seaweed are still at the forefront of both traditional uses and new types of applications such as edible films, encapsulation, and 3D food printing (Gao et al., 2024; Liao et al., 2021).

Hydrocolloids have undeniably moved beyond their traditional role as thickener to that of a multipurpose, health-oriented, sustainable food ingredient. The advances of hydrocolloids confirm the utility of hydrocolloids as both texturizers and bio functional components of food in modern food design.

1.2. Limitations of conventional hydrocolloid sources and market demands

There is an inherent dependency of using traditional hydrocolloids - locust bean gum, carrageenan, starch, and guar gum, and an attached risk to supply chain, risk of climate variability, and long lead times (e.g. locust bean gum and long timelines for tree maturation); risk of seaweed harvests from carrageenan and seaweed harvests can be lost on a whim (Supply issues: Supply Chain Issues Hit Hydrocolloids (2022)); there are functional constraints that are intrinsic to using a traditional hydrocolloids that can limit the versatility of the hydrocolloid due and the sensitivity it has to pH, temperature, or electrolyte conditions (Medina-López et al., 2022; Mahmood et al., 2017). Concurrently, society is demanding more-natural, clean label, plant-based, and product forms that allow individuals to personalize texture profiles especially in the older populations and ethical behaviours in eating (Medina-López et al., 2022). The combination of constrained supply and functional performance of traditional sources and shifting expectations and demands of the consumer marketplace suggests there is an urgent need to explore non-conventional and more creative hydrocolloid sources for next generation food formulation challenges.

1.3. Microalgae as a source of next generation food hydrocolloids

Recently microalgae have been identified as a useful and sustainable biomass in biorefinery systems, because of the potential for sustainable multi-use outputs from biofuels to high-value bioproducts, while having the potential to improve environmental parameters (Hamid Nour et al., 2024) discuss novel extraction methods that are connected to wastewater treatment, and how this type of biorefinery can further enhance eco-efficiency, while (Gupta et al., 2024) describe microalgae examples of phycoremediation illustrated with applied microalgae research examples that are utilizing wastewater to produce biomass for fuel, while discussing nutraceuticals. Despite these opportunities, generally, wastewater treatment cost is a hurdle; however (Dutta et al., 2025), provided an example of a self-sustaining and closed loop microalgal biorefinery, that would eliminate some sustainability issues associated with resource recovery and process efficiency, and provide economic sustainability through biofuel multi-use products. Overal these examples provide an encouraging start to account the potential of microalgae to make positive contributions to engaging in more circular bioeconomy initiatives while outlining remaining potential limitations in scale, cost, viability, and technological maturity.

1.4. Molecular architecture of microalgal EPSs relevant to hydrocolloid functionality

Microalgal EPSs are high molecular weight heteropolymers of varying sizes depend more on the type of microalga and growth environment than the demonstration of their value, either bound to the cell surface or released into the extracellular space are extracellular polysaccharides (EPS). Generally, EPS are very complex polysaccharides consisting of many different monosaccharides (glucose, galactose, xylose, fucose, rhamnose, uronic acids, etc). In addition to the diversity in the sugar components, there can be substitutions, for example, sulfates, acetyl, and/or pyruvate moieties. The EPS is a charged bioactive polymeric material (He et al., 2025). ECPS polymerizes into three-dimensional hydrated networks forming critical physical properties that mediate cell to surface adhesion and biofilm development, and carbon/energy storage reserves (Babiak & Krzemińska, 2021). EPS demonstrate unique physicochemical properties, notably pseudoplasticity, shear thinning behaviour, and high viscosity, which enable their use as thickening agents, gelling agents, bioflocculants, and functional ingredients in food, pharmaceutical, and biotechnology applications (Zhou et al., 2024; Babiak & Krzemińska, 2021).

1.5. Scope and objectives of the review

This review will provide an overview of microalgal EPSs as a new source of food hydrocolloids. It places more emphasis on their structural variability, rheological properties, and bioactive functions. Although there is still a large reliance on traditional hydrocolloids from plants and seaweeds, their low availability, sustainability issues, and inconsistent demand mean that alternative biopolymers sources must be developed. Microalgal EPSs may be uniquely well-suited as a biopolymer source, due to their unique monosaccharide, functional substituents, and diverse set of natural physicochemical properties that can be modified for various food uses.

In this review, we propose that microalgal exopolysaccharides should be understood not merely as biologically derived polysaccharides, but as an emerging class of food hydrocolloids distinguished by their tunable molecular architectures. Unlike many conventional hydrocolloids whose functional space is largely fixed by botanical origin, microalgal EPSs exhibit programmable variations in monosaccharide composition, sulfation pattern, charge density, branching degree, and molecular weight distribution. These structural parameters directly govern hydration behaviour, viscosity development, gelation mechanisms, interfacial adsorption, and synergistic interactions in complex food matrices. By explicitly linking molecular architecture to rheological performance and techno functional outcomes, this review establishes a structure–property–function framework that positions microalgal EPSs as designable hydrocolloids for next generation food systems.

2. Molecular architecture of microalgal EPSs and implications for hydrocolloid functionality

Microalgal exopolysaccharides (EPSs) exhibit substantial taxonomic diversity, however, from a food hydrocolloid perspective, their primary relevance lies in the structural parameters that govern physicochemical behaviour (Terpou et al., 2025). Rather than considering taxonomic distribution as an endpoint, it is more informative to interpret EPS diversity through the lens of molecular architecture, including monosaccharide composition, glycosidic linkage pattern, charge density, branching topology, substituent groups, and molecular weight distribution (Mouro et al., 2024). These architectural variables directly determine hydration dynamics, chain conformation, intermolecular association, and ultimately rheological performance in food matrices (Qian et al., 2026). This section therefore reframes taxonomic diversity in terms of structure–property implications and establishes the molecular basis for subsequent discussions on rheology and functionality.

2.1. Taxonomic distribution and diversity

While microalgal EPSs are produced across cyanobacteria, green microalgae, diatoms, and red microalgae, the functional significance of this diversity lies in the recurring structural motifs that differentiate these groups (Laroche, 2022). Cyanobacterial EPSs frequently exhibit high molecular weight heteropolymers with significant sulfation and uronic acid content, contributing to elevated charge density and shear thinning behaviour (Mota et al., 2022). Red microalgal EPSs, particularly from *Porphyridium*, are characterized by highly sulfated galactoxyloglycans with pronounced viscosity and strong hydration capacity (Laroche, 2022). Diatom derived EPSs often contain acidic sugars that promote gel formation and particle aggregation (Tiwari et al., 2025). These recurring compositional themes suggest that taxonomic classification is less important than the resulting macromolecular architecture, which dictates polymer conformation, intermolecular interactions, and structuring capacity in aqueous systems. Table 1 summarizes the major divisions, representative genera, and notable characteristics of EPSs in microalgae**.**

2.2. Chemical composition and structure–property relationships

Microalgal EPSs are predominantly heteropolysaccharides composed of variable ratios of neutral sugars, uronic acids, and sulfated residues (Laroche, 2022). The relative abundance and spatial distribution of these components dictate chain stiffness, electrostatic repulsion, hydration shell formation, and intermolecular association. High uronic acid content increases polyelectrolyte character and enhances water binding capacity, contributing to elevated intrinsic viscosity (Yang et al., 2023). Sulfation increases negative charge density, promoting chain expansion under low ionic strength conditions while enabling ionic cross linking in the presence of divalent cations (Peng et al., 2023). Branching architecture influences entanglement threshold concentration and gel network formation (Wang, Guo, et al., 2023). Molecular weight distribution further modulates rheological behaviour, with high molecular weight fractions contributing disproportionately to viscosity development and network formation (Meng et al., 2023). Polydispersity may influence shear sensitivity and viscoelastic balance in structured systems (Balyan et al., 2024). Fig. 1 below depicts conceptual schematic representation of the, major structural and functional properties discussed (Delattre et al., 2016; Hasan et al., 2024; Kiran et al., 2024; Wu et al., 2025).

2.3. Biosynthesis and physiological roles

The production of microbial EPSs begins with glycolysis, pentose phosphate pathway (PPP), and tricarboxylic acid (TCA) cycle which produce the essential sugar precursors. Fig. 2 shows specific biosynthetic pathways of nucleotide sugars which activate these carbohydrate structures, and EPSs specific polymerization/transport mechanisms which are categorized by Wzx/Wzy pathway, ABC transporter pathway, and Synthase (S) pathway. Each of these provide a coherent summary of the biochemical framework that links primary metabolism to EPSs assembly and export, which is necessary for biofilm establishment and microbial survival (Schmid et al., 2015) (Fig. 2). Current knowledge of environmental drivers is incredibly broad and generally taxon-specific, however we do know that light, nutrient ratios (C: N: P), salinity, temperature, pH, and trace metals strongly control the rates of production and chemical composition of EPSs produced-metanalytic work from cyanobacteria suggest that light and nitrogen are two of the most important factors while recent work on algae and bacteria indicates that inorganic N and P enrichment strongly increases bacterial EPSs in situ (Wu et al., 2025; Lipsman & Segev, 2025). EPSs perform several ecological functions, including defense against desiccation/UV/oxidation, facilitating adhesion and aggregation (i.e., marine snow and rhizosphere aggregates), sequestration of metals, and horizontal gene transfer in biofilms. The many functionalities of EPSs may contribute to their widespread presence in various ecological niches, and suggest possible uses of EPSs in applied biology/biotechnology. Finally, growth conditions (carbon source, aeration, and stress exposure) will not only affect yields, but also molecular weight, branching, and degree of acetylation, which are also significant in determining rheology, stability, and bioactivity; also, growth or genetic engineering can affect all these parameters, which is encouraging (Kong et al., 2022; Schmid et al., 2015).

Collectively, these architectural features establish the structural design space of microalgal EPSs. By modulating charge density, branching degree, and molecular weight through strain selection or cultivation conditions, it becomes possible to influence chain conformation, hydration behaviour, and intermolecular association. The following section therefore examines how these molecular attributes translate into measurable rheological properties and functional performance in food systems.

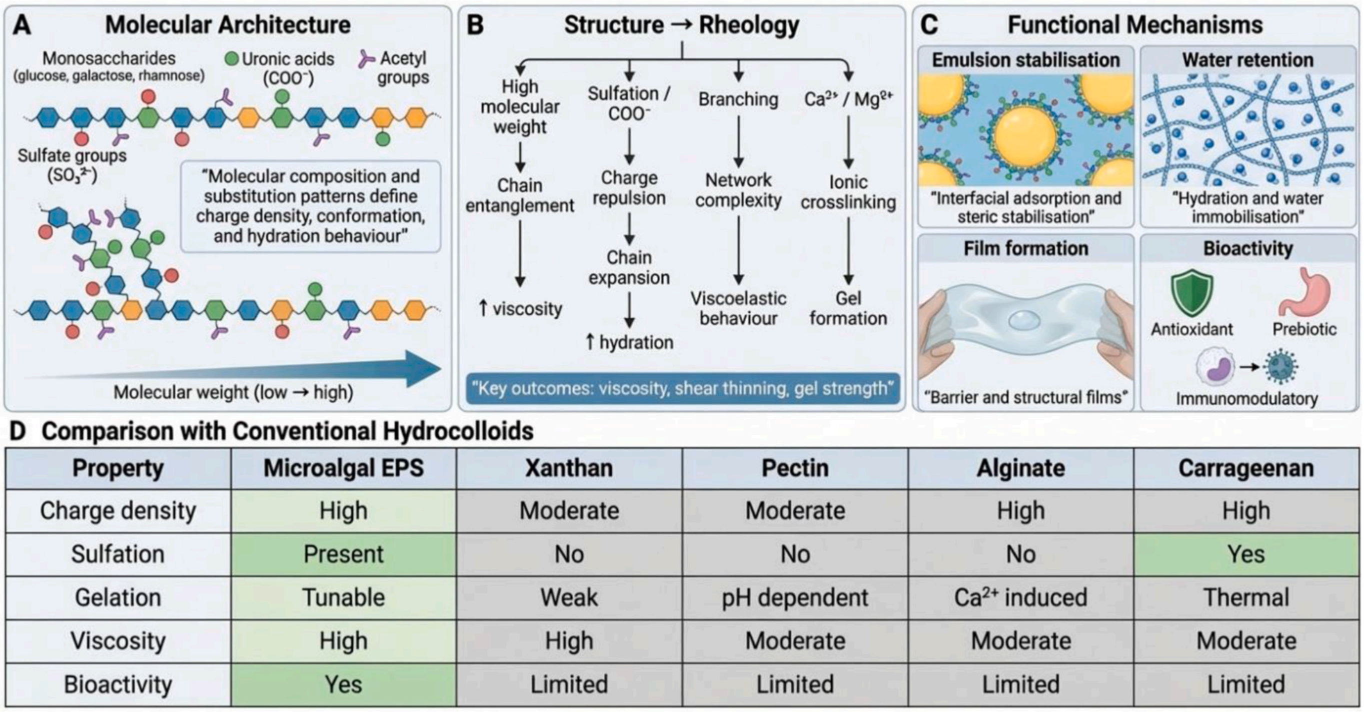
3. Production and processing technologies

3.1. Cultivation strategies for enhanced EPSs production

Since EPSs biosynthesis is closely related to cellular metabolism, the rationale for selection of proper trophic regime from the bioreactor design is a key leverage point in terms of yield gains. The phototrophic systems (i.e., light-based growth) are the most well understood for cyanobacteria and many microalgae, whereby light quality and light intensity directly determining both carbon fixation and EPSs production (Jung et al., 2022). Heterotrophic or mixotrophic strategies - where organic carbon (i.e., acetate, molasses) is given, or light is given and

Table 1
Taxonomic distribution of microalgal exopolysaccharides: major divisions, representative genera, characteristic EPS structural features, key functional properties, and indicative food/biotechnological applications.

Division/Class	Representative genera (examples)	EPSs hallmarks (composition/traits)	Noted functions & uses	Refernces
Cyanobacteria	*Arthrospira* (Spirulina), *Nostoc, Anabaena*	Heteropolysaccharides; often sulfated; high Molecular weight (Mw); Ca^{2+}-binding; shear-thinning	Antioxidant, antiviral, immunomodulatory; rheology modifiers and stabilizers	(Gal & Johnson, 2024; Ai et al., 2023; Laroche, 2022)
Chlorophyceae (green microalgae)	*Chlorella, Scenedesmus, Neochloris*	Neutral/weakly acidic heteropolysaccharides; may include uronic acids; stress-responsive secretion	Bioflocculation, emulsification/stabilization; emerging bioactive uses (e.g., anti-hyperglycemic)	(Guehaz et al., 2024; De Angelis et al., 2024; Zhang, Zhang, et al., 2024; Laroche, 2022)
Bacillariophyceae (diatoms)	*Phaeodactylum, Skeletonema, Navicula*	Abundant extracellular polymeric substances (EPSs)/Transparent Exopolymer Particles (TEP); acidic sugars; gel-forming; biofilm matrices	Adhesion/biofilm formation; particle aggregation; potential hydrocolloids	(Gasco et al., 2024; Laroche, 2022)
Rhodophyceae (red microalgae)	*Porphyridium, Rhodella*	Sulfated galactoxyloglycans; highly anionic; very high viscosity	Thickening, moisture retention; antiviral/anti-inflammatory; cosmetic and food hydrocolloids	(Liberti et al., 2023; Dulong et al., 2024; Antoniou et al., 2023; Laroche, 2022)
Haptophyceae (& related)	*Emiliania* (*E. huxleyi*), *Glossomastix*	EPSs/TEP rich in acidic sugars; can form weak/"fragile" gels; high Mw	Carbon export/aggregation in oceans; suspension stabilization; prospective food/cosmetic texturants	(Passow, 2002; Dulong et al., 2024)



Property	Microalgal EPS	Xanthan	Pectin	Alginate	Carrageenan
Charge density	High	Moderate	Moderate	High	High
Sulfation	Present	No	No	No	Yes
Gelation	Tunable	Weak	pH dependent	Ca^{2+} induced	Thermal
Viscosity	High	High	Moderate	Moderate	Moderate
Bioactivity	Yes	Limited	Limited	Limited	Limited

Fig. 1. Structure–function relationships of microalgal exopolysaccharides (EPSs) in food systems. Key molecular features, including sulfation, uronic acids, branching, and molecular weight, influence polymer conformation, hydration, and charge interactions, thereby governing viscosity, gelation, and interfacial behaviour. Distinct functional roles such as emulsion stabilization, water retention, film formation, and bioactivity are illustrated, with comparison to conventional hydrocolloids.

organics - are frequently used to produce cell densities and volumetric EPSs titres, and, under certain conditions can also modify the composition of EPSs (Kiran et al., 2024). Modifying nutrient stoichiometry (i.e., which nutrients are in excess, limiting, or in the sweet spot) and exerting some controlled abiotic (not biotic) stress (i.e., nitrogen limitation, salinity transitions or shocks, light stress, trace-metal increases) systematically shifts the carbon flux to EPSs as protection/overflow product, but these responses were dependent on both strain and genus and need to be partially developed empirically (Hasan et al., 2024; Wu et al., 2025). For industrial efficiency, process mode (fed-batch vs. controlled feeding), and the scale-up attributes of controlled agitation/oxygen transfer, and cheap carbon sources (e.g., agroindustrial molasses) have enabled enormous efficiencies in volumetric EPSs production while also decreasing costs (Ferreira Filho et al., 2025). Cultivation conditions influence not only EPS yield but also molecular architecture and functional reproducibility. Factors such as nutrient limitation, salinity, and growth phase can alter molecular weight distribution, sulfation degree, and monosaccharide composition, which directly affect intrinsic viscosity, gelation capacity, and interfacial stabilization behaviour (Duceac et al., 2022). Variability in these parameters may lead to batch dependent differences in rheological performance, posing challenges for consistent food formulation. Therefore, controlled cultivation and standardized processing are essential to ensure molecular consistency and predictable techno functional performance required for commercial food hydrocolloid applications (Kumar et al., 2023). In conclusion, integrated tactics that incorporate a considered trophic mode, light nutrient limitation or mild abiotic stress, and feeding/operations conditions amenable to scale (modern approaches to [potentially more efficient] industrial strategies) would seem to be the most optimal method for achieving increased yields in EPSs production and/or modify polymer characteristics for future/end use (Ferreira Filho et al., 2025; Hasan et al., 2024; Jung et al., 2022; Kiran et al., 2024; Wu et al., 2025) (Fig. 3).

3.2. *Extraction and purification effects on hydrocolloid structure and performance*

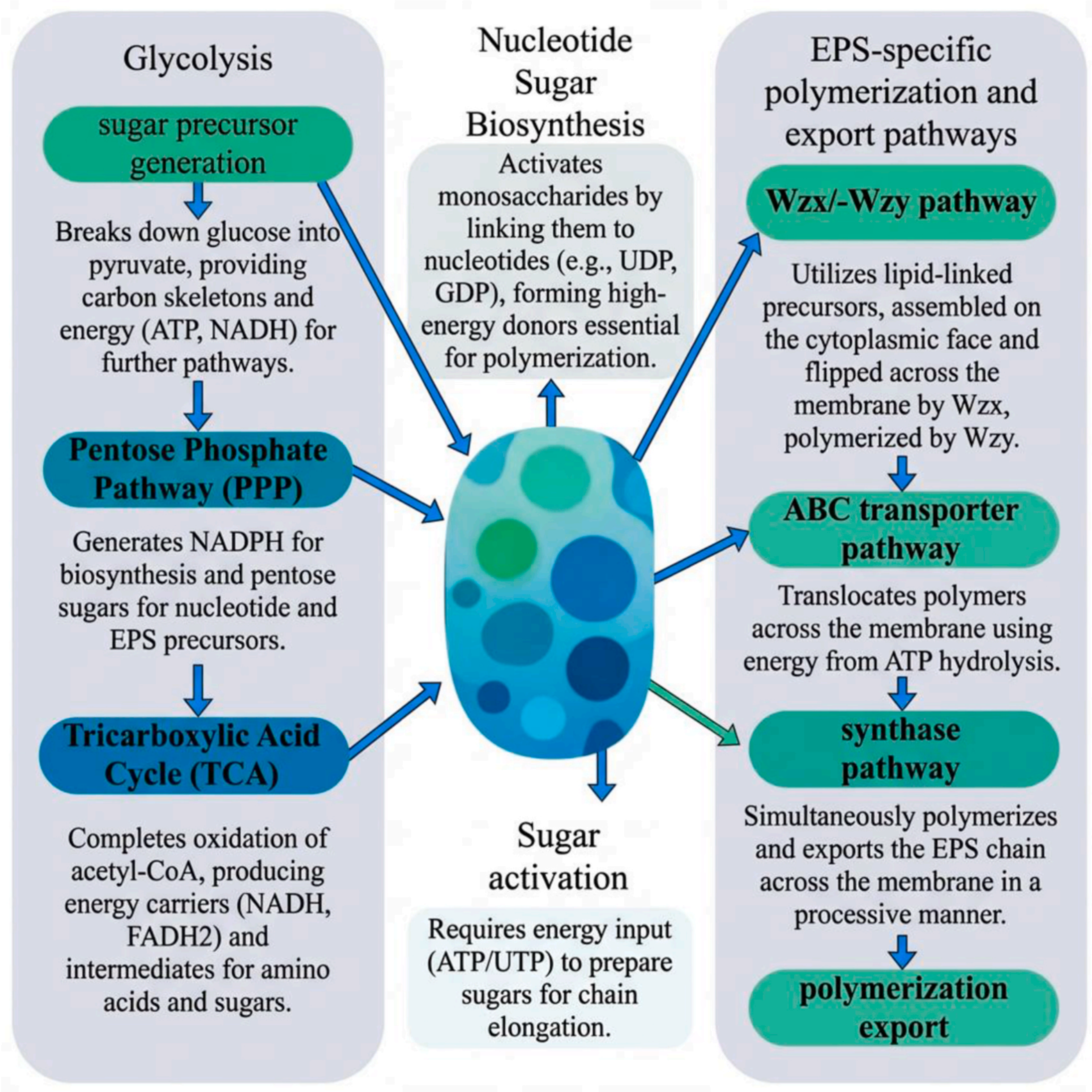
Downstream processing also plays a critical role in determining hydrocolloid functionality. Extraction severity, precipitation conditions, and drying methods can influence polymer integrity, molecular weight, and hydration behaviour (Li, Chen, et al., 2022). Excessive mechanical or chemical treatment may cause depolymerization, reducing viscosity and gel forming ability, while insufficient purification may introduce impurities that alter interfacial performance or regulatory compliance (Atmakuri et al., 2024). Consequently, downstream processing must be optimized not only for yield but also to preserve functional and structural consistency required for food grade hydrocolloids. The diagram provides an overview of different steps including biomass harvesting, cell disruption, centrifugation, precipitation, membrane filtration, and chromatography for the production and purification of EPSs from microalgae. Each of these steps is critical for the harvesting of functional EPSs with appropriate high purity for future food and industrial applications (Fig. 4).

3.3. *Process optimization and yield enhancement*

To realize an enhanced yield of microalgal EPSs, we will need a collaborative optimization framework that integrates biological, engineering, and economic metrics of yield pricing from an overarching scale. Various approaches have been suggested/assessed to improve yield, and also the techno-functional quality of EPSs to use them in industry (Fig. 5).

3.3.1. *Genetic and metabolic engineering*

Genetic and metabolic engineering can modify EPS molecular weight, sulfation degree, and branching, thereby enabling targeted tuning of viscosity, gelation, and interfacial functionality. in efforts to improve either rheological or bioactive properties. Clustered Regularly



Breaks down glucose into pyruvate, providing carbon skeletons and energy (ATP, NADH) for further pathways.

Generates NADPH for biosynthesis and pentose sugars for nucleotide and EPS precursors.

Completes oxidation of acetyl-CoA, producing energy carriers (NADH, FADH2) and intermediates for amino acids and sugars.

Activates monosaccharides by linking them to nucleotides (e.g., UDP, GDP), forming high-energy donors essential for polymerization.

Requires energy input (ATP/UTP) to prepare sugars for chain elongation.

Utilizes lipid-linked precursors, assembled on the cytoplasmic face and flipped across the membrane by Wzx, polymerized by Wzy.

Translocates polymers across the membrane using energy from ATP hydrolysis.

Simultaneously polymerizes and exports the EPS chain across the membrane in a processive manner.

Fig. 2. Simplified metabolic pathways underpinning microalgal EPS biosynthesis, illustrating precursor sugar formation (glycolysis, pentose phosphate pathway, TCA cycle), nucleotide sugar activation, and representative polymerization/transport routes (Wzx/Wzy-dependent, ABC transporter, and synthase pathways).

Interspaced Short Palindromic Repeats (CRISPR-Cas) systems and transformation programs, while still in their infancy relative to bacteria, facilitate and encourage metabolic rewiring in microalgae (Hasan et al., 2024).

3.3.2. *Bioreactor design*

The design of cultivation systems has a significant impact on EPSs yield. In photoautotrophic cultivation systems, light and hydrodynamics are the most relevant limiting factors. Innovations in flat-panel and tubular photobioreactor designs have allowed better light penetration, mixing, and CO_2 mass transfer and a higher combined productivity of EPSs. Finally, closed photobioreactor systems are less likely to be infected than open ponds, and thus allow for more stable EPSs yields (Jung et al., 2022).

3.3.3. *Harvest timing*

EPSs secretion in microalgae often can be shown to increase at the stationary phase of growth or during times of adverse nutrient stress. When producing EPSs from microalgae, it is important to choose the right time to harvest to maximize EPSs while using the least amount of energy. Harvesting too conservatively could put the producer at risk of lower EPSs production, while delaying harvesting much longer raises risks of contamination or EPSs degradation. Process monitoring devices are being improved to include the capability of monitoring live exiting microalgal EPSs (Wu et al. 2025) along with rheological or optical sensors that can document when the peak or state of highest secretion occurs.

3.3.4. *Economic feasibility*

Cost-effective cultivation systems will be important for the commercial viability of microalgal EPSs production issues at higher scales. Improvements in operational efficiency and sustained productivity over longer cultivation times can be managed using fed-batch or semi-continuous cultivation modes, which could limit downtime from continuous mode, and can help to increase volumetric productivity overall. The utilization of low-cost or waste feedstocks such as molasses, glycerol, or wastewater streams will further bring down open costs associated with the production of EPSs, while including a circular economy aspect. In combination with the feasibility of using waste valorization, low-cost solutions improve the overall economic feasibility, environmental sustainability, and increase another aspect of the circular economy (Ferreira Filho et al., 2025). Thus, using genetic tool improvements, bioreactor engineering or design, harvesting optimization, and low-cost cultivation strategies, makes a perfect package to

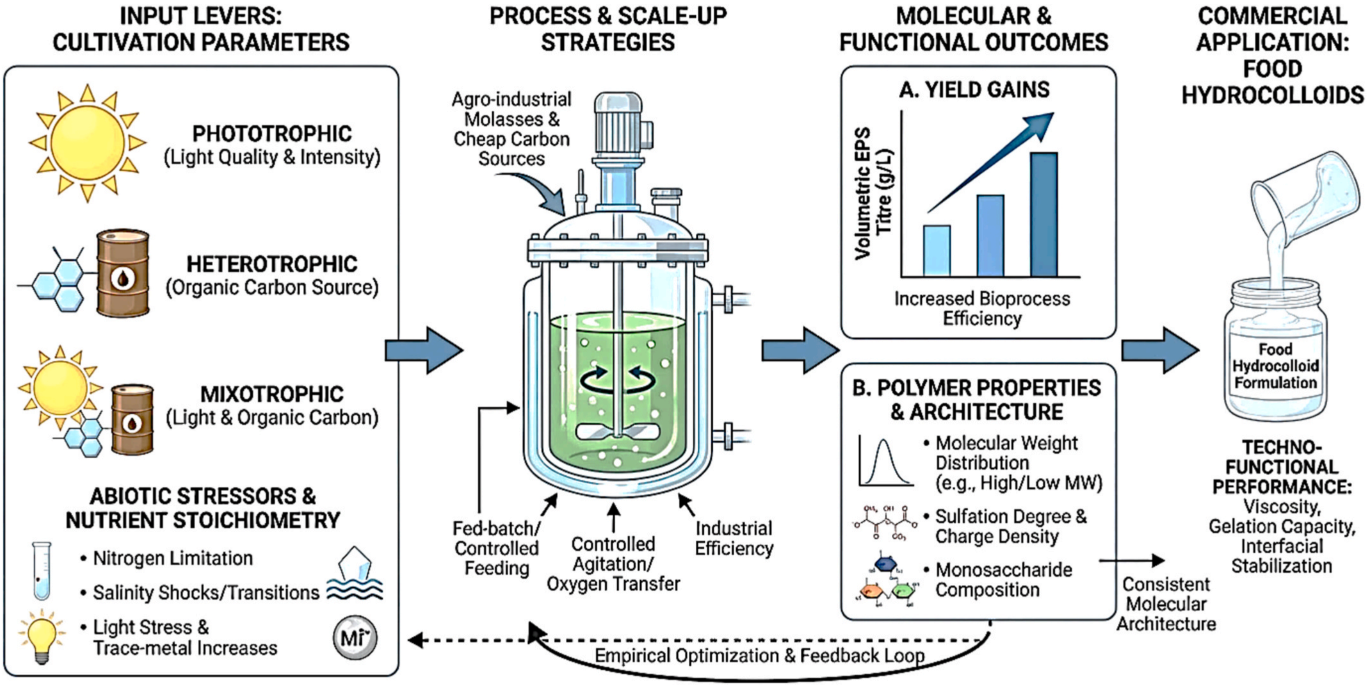


Fig. 3. Process–structure–function framework of microalgal EPSs. Cultivation conditions determine EPS composition and molecular architecture, while downstream processing influences polymer integrity. These combined factors govern hydrocolloid functionality, including viscosity, gelation, emulsification, and film-forming properties in food systems.

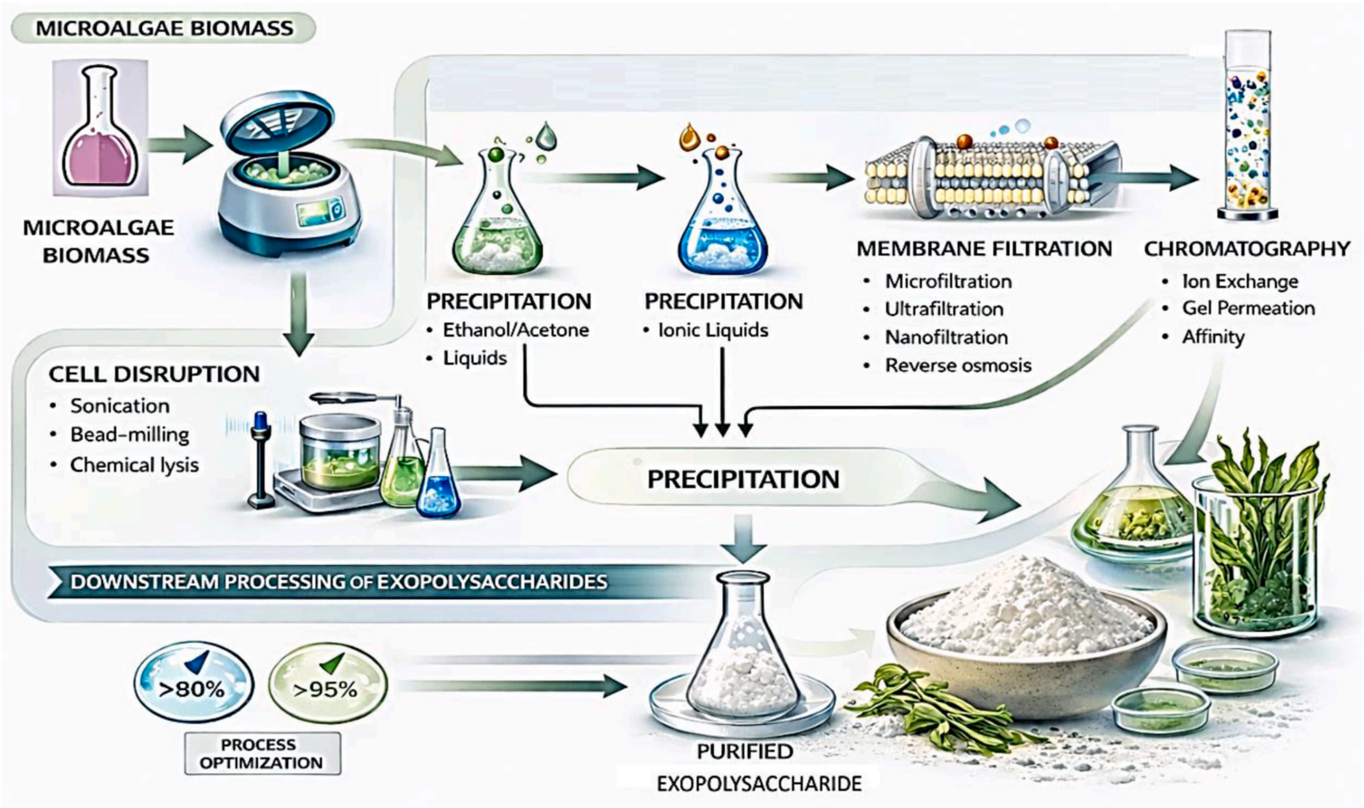


Fig. 4. Downstream processing and purification workflow for microalgal exopolysaccharides (EPSs) and its influence on hydrocolloid functionality.

improve EPSs yield and ultimately make microalgal EPSs a more viable option, as a food hydrocolloid.

4. Rheological properties and functional behaviours

To facilitate mechanistic understanding, the functional behaviour of microalgal EPS hydrocolloids is discussed under four major property

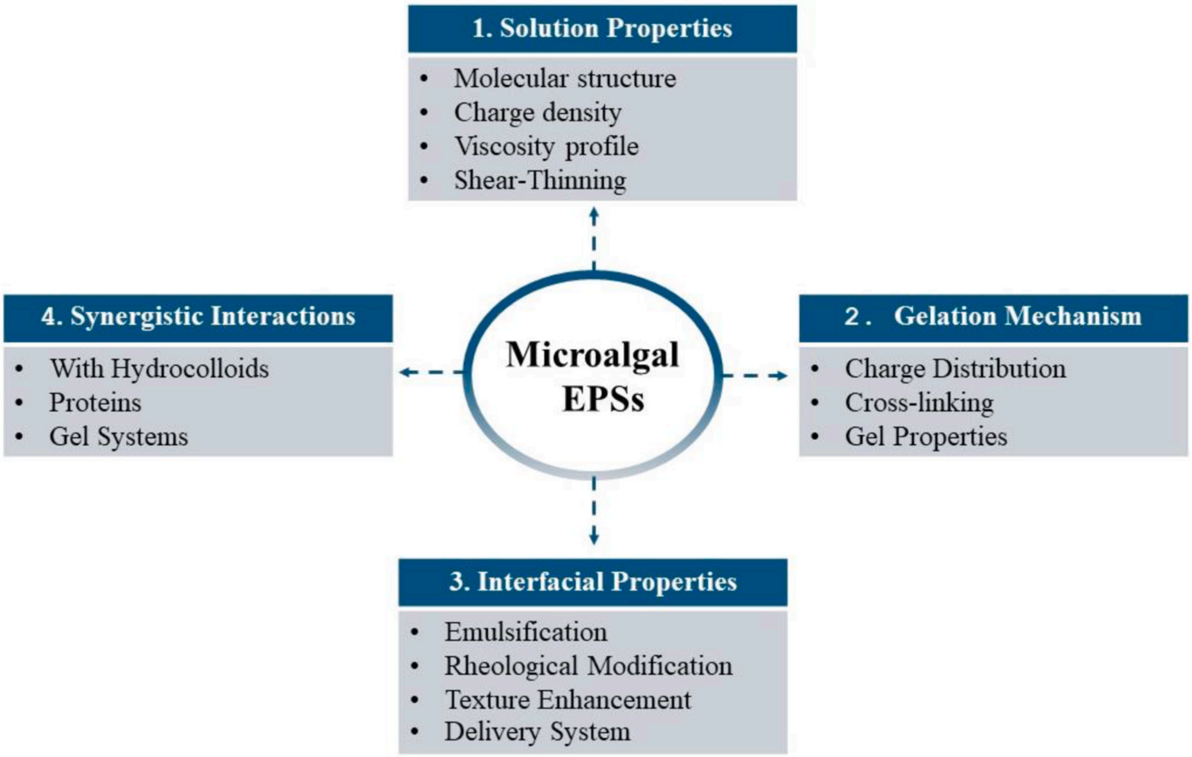


Fig. 5. Summary of rheological and functional behaviours of microalgal EPSs in food systems, organized by solution properties, gelation behaviour, interfacial functions (emulsions and foams), and synergistic interactions with other food biopolymers.

categories: solution properties, gelation mechanisms and gel properties, interfacial properties, and synergistic interactions with other food biopolymers.

4.1. *Solution properties*

The solution properties of microalgal EPSs depend on their molecular structure, charge density, and flexibility of conformation. Intrinsic viscosity gives an indication of polymer chain dimensions and conformation in solution and generally had higher emipirical viscosities for EPSs from *Porphyridium* and *Arthrospira* (which are high molecular weight branched EPSs) when compared to many plant-based hydrocolloids (Jung et al. 2022). Microalgal EPSs generally displayed similar solution properties as a function of concentration as lower concentrations displayed consistent Newtonian behaviour; yet, once the EPSs exhibited critical overlap concentration, viscosities increased substantially due to chain entanglements (Dulong et al. 2024). Several microalgal EPSs exhibited shear-thinning and thixotropic behaviour, which are both ideal for use in food formulation, as they are easier to mix but maintain viscosity over time (Kiran et al. 2024). Microalgal EPSs exhibit viscosity behaviour that is sensitive to temperature, pH, and ionic conditions, reflecting the influence of charged functional groups on polymer conformation and intermolecular interactions. Sulfate groups introduce negative charges along the polymer backbone, increasing electrostatic repulsion and chain expansion, which can enhance solution viscosity and influence gelation behaviour, as demonstrated in sulfated polysaccharides such as agar and carrageenan (Nishinari & Fang, 2017). Similarly, uronic acid residues contribute carboxyl functional groups that promote intermolecular associations and network formation through hydrogen bonding and ion mediated interactions, analogous to pectin systems. These structural features highlight that microalgal EPSs are structurally tunable hydrocolloids whose rheological and gel forming properties can be modulated through molecular composition and environmental conditions.

4.2. *Gelation mechanisms and gel properties*

The gelation behaviour of microalgal EPSs is governed by molecular architecture, including charge distribution, branching, and the presence of functional substituents such as sulfate and uronic acid groups. These charged and polar groups influence intermolecular interactions, enabling polymer chains to self-associate through hydrogen bonding, ionic interactions, and other non-covalent forces, leading to the formation of three dimensional gel networks. Microalgal EPSs and other structurally similar polysaccharides form gel matrices through these physicochemical mechanisms under appropriate environmental conditions (Terpou et al., 2025). Reported thermal gelation of EPSs gelling is comparatively less evident than observed in proteins, however porphyridium-derived EPSs exhibited gel strength upon cooling addition somewhat resembling carrageenan type transitions (Maulina et al. 2026).

Molecular weight and ionic environment can account for differences in gelling strength and stabilizing effects. Sulfated EPSs have been shown to promote stronger gel structuring in EPSs gel matrices with addition of divalent cation ions (Ca^{2+}, Mg^{2+}). Polymers consisting of relatively high contents of uronic acids promote hydration, while reducing syneresis (water expulsion) somewhat synergistically albeit to a lesser extent. Additionally, TPA of EPSs gels have shown hardness, cohesiveness, and elasticity to be in a range comparable to traditional hydrocolloids including xanthan and carrageenan (Jung et al., 2022; Wu et al., 2025) which fortifies the exploratory applications for product formulations in dairy, desserts, plant-based meat alternatives.

4.3. *Interfacial properties*

Microalgal EPSs exhibit specific interfacial properties enabling their use not only to alter viscosity in food systems, but for other functions as well. For instance, the ability of EPSs to emulsify can be attributed to their amphiphilic regions and charge groups to stabilize oil-in-water emulsions. EPSs from *Porphyridium cruentum* and *Arthrospira*, for example, formed more stable emulsions (reduced droplet coalescence) than a variety of traditional hydrocolloids (Maulina et al., 2026).

EPSs may also play a role in foam activity (formation and stabilization) based on their ability to lower surface tension and form viscoelastic interfacial films - and may be equally meaningful to the constituents of aerated food products (i.e. whipped toppings, bakery foams) (Hu & Meng, 2024). The film forming ability of EPSs and their barrier properties were linked to hydrogen bonding and their ability to form networks and free sulfated EPSs have been described to form edible films with moisture and oxygen barriers - which makes them desirable.

EPSs will also interact with lipids and/or surfactants within the formulation in a somewhat synergistic manner and will alter the shape of micelles and further aid in the stabilization of the emulsified food system. The interactions of EPSs with lipids and surfactants, depending on charge density, pH, and ionic strength, could add additional stabilization to more complex food systems (Jung et al., 2022). All of these interfacial properties work together to enhance the possibility of their multifunctionality as food hydrocolloids.

Collectively, available evidence indicates that sulfation degree and uronic acid content primarily modulate charge density and hydration behaviour, thereby influencing intrinsic viscosity, gelation kinetics, and interfacial stabilization. Molecular weight distribution and branching topology determine entanglement threshold concentration and viscoelastic balance, while chain flexibility and substitution pattern govern enzymatic accessibility, fermentability, and bioactive interactions. Framing microalgal EPSs through these causal linkages enables predictive understanding of food system performance rather than descriptive characterization alone.

4.4. Synergistic interactions

Microalgal EPSs have distinctive and specific properties in their capacity to solidify alongside other food biopolymers in an additive manner. These interactions are frequent and in conjunction with hydrocolloids that are already established (e.g., xanthan gum, carrageenan, and guar gum), often inducing modified viscosity and gelation properties, but of particular interest, creates a food matrix that provides stability and elasticity and remains unaffected by a singular hydrocolloid (Delattre et al., 2016). Microalgal EPSs aslo create complexes with proteins-polysaccharides and show a preference at lower pH's when interactions generate coacervative pathways of opposite charge groups. The protein EPSs complexes particularly further stabilize emulsions during food.

Microalgal EPSs can also manipulate mixed gels (e.g. carrageenan or gelatin) with organisms such as *Porphyridium* or *Arthrospira* which can alter the phase behaviour of those gels and reduce syneresis. These interactions can also be altered with respect texture, water activity or shelf-life in edible substances such as baked goods and candy (Kiran et al., 2024). Likewise, in even more intricate food systems, co-acting EPSs function all at once to serve various purposes to enhance rheological, mouthfeel, and stability functionalities of the food system, all the while avoiding synthetic food additive. These multi-functional interactions illustrate the possibilities for clean-label, natural food alternatives in innovative food formulation (Jung et al., 2022)

The preceding sections demonstrate that the functional behaviour of microalgal EPSs is not incidental but arises directly from definable molecular architecture parameters. Sulfation degree and uronic acid content modulate charge density and electrostatic interactions, influencing chain expansion, ionic crosslinking capacity, and viscoelastic moduli in aqueous systems. Molecular weight distribution and branching topology determine overlap concentration, entanglement threshold, and shear thinning behaviour, thereby governing viscosity development and yield stress. Chain flexibility and substitution patterns influence hydration dynamics, interfacial adsorption, and enzymatic accessibility, linking rheological performance to digestibility and bioactivity.

When interpreted within this unified framework, microalgal EPSs can be understood as structurally programmable hydrocolloids whose molecular motifs translate into measurable techno functional outcomes in food relevant systems.

5. Bioactive properties relevant to functional foods

Microalgal EPSs exhibit antioxidant activity through free radical scavenging, metal chelation, and lipid oxidation inhibition. Their prebiotic potential supports gut microbiota fermentation and short chain fatty acid production. EPSs also demonstrate immunomodulatory, anti inflammatory, anti adhesive, and mineral binding properties, contributing to improved nutritional and functional performance in food systems.

5.1. Antioxidant activities

Recent studies have indicated that microalgal EPSs behave as active antioxidant substances, which is leading to considerations for them to become functional food. The free radical scavenging activity was determined 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity and through an 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) based model methods for evaluating antioxidant activity. EPSs, which are typical EPSs and sulfated (or have uronic acid) have increased electron donating groups and also increased scavenging activity (Chi et al., 2022). EPSs were also found to be metals chelators having strong chelation ability towards metals ions that can generate free radicals and limit Fe^{2+} activity in the Fenton reaction in the presence of metals (Hasan et al., 2024). The EPSs discussed showed that the chelation ability it had was selective to Fe^{2+} and Cu^{2+} metal ions which allowed the limiting of Fe^{2+} to be involved with the Fenton reaction and free radical generation (Hasan et al., 2024). In addition, due to the unique properties of EPSs, also in respect to protecting food lipids oxidation when they contain a hydrophilic area; EPSs act as a natural protector by increasing emulsion stability (Kiran et al., 2024). Additionally, EPSs can selectively protect food lipids from oxidative degradation by acting as antioxidant agents and metal chelators, thereby improving lipid stability in food systems. Of particular importance, the degree of substitution (DS), molecular weight, and monosaccharide composition contribute to structure–activity relationships that influence the antioxidant capacity of microalgal EPSs. EPSs originating from strains of *Porphyridium spp* exhibited greater antioxidant activity processes than neutral EPSs, since the former were found to have more sulfonate substitutions (Maulina et al. 2026). EPSs originating from microalgae have shown in previous literature can control rheology features, as well as provide naturally occurring antioxidant properties that functions with beneficial properties for functional food.

5.2. Prebiotic potential

There has been considerable interest recently in the potential prebiotic effects of microalgal EPSs. While EPSs are partially digestible, like other polysaccharides, they are likely to reach the colon mostly intact and undigested following digestive and gastric acid influences (Zhang et al., 2024). Once in the gastrointestinal tract, EPSs can be fermented by beneficial gut bacteria (such as *Bifobacterium* and *Lactobacillus spp*.) and stimulate their growth and activity (Kiran et al., 2024). The fermentation of EPSs can lead to products, including short-chain fatty acids (e.g., acetate, propionate, and butyrate) that can provide health benefits, including reducing gut-tract pH, acting as bacteriostatic agents against pathogenic bacteria, and influencing metabolic responses (Hasan et al., 2024). EPSs are thought to provide a growth supportive base for beneficial bacteria while also being growth limiting for pathogenic bacteria, and may instigate changes in gut microbiome community structure diversity. Structure–function studies indicate that monosaccharide composition, molecular weight, and degree of substitution influence polysaccharide fermentability and microbial selectivity by affecting enzymatic accessibility and polymer conformation (Flint et al., 2012). These structural parameters contribute to the prebiotic potential of microalgal EPSs.

5.3. Immunomodulatory and anti-inflammatory effects

The EPSs from microalgae have the potential for immunomodulatory and anti-inflammatory properties, and therefore increase the opportunities to serve as functional food constituents. These polymers may adhere to receptors on immune cells that influence the innate immune system and adaptive immune system. Sulfated EPSs from *Porphyridium* or EPSs from *cyanobacteria* had positive effects such as stimulating cytokine production, enhancing immune defense, or maintaining homeostasis (Maulina et al., 2026). Many EPSs are also provided to decrease inflammation by down regulating pro inflammatory mediators (TNF-α, IL-6, or reactive nitrogen species) (Kiran et al., 2024). Furthermore, several EPSs have polyanionic character and other structural motifs which can remove nitric oxide and reactive oxygen species and as a result, down regulate the activation of inflammation related signalling pathways. Most studies suggest that many of the microalgal EPSs offer a low risk of allergy response, it would be necessary to perform a safety evaluation to utilize in food safety systems (Hasan et al., 2024). The multifunctionality of EPSs is further compounded by the reality that EPSs are antioxidant and possess immunodulatory activity (Wu et al., 2025).

5.4. Other bioactivities with relevance to food applications

In addition to their antioxidant, prebiotic, and immunomodulatory actions, microalgal EPSs also possess other biorelevant activities of significance to food science. To illustrate, one area of distinction is that some EPSs demonstrate anti-adhesive activity, which indicates the EPSs were capable of inhibiting microbial adherence to epithelial surfaces, thereby reducing the chances of infection in the gastrointestinal tract (Mougin et al., 2024). EPSs can also enhance the bioavailability of nutrients through chelation resulting in improved absorption of minerals, for example calcium, iron and magnesium (Hasan et al., 2024). Some EPSs have been noted to alter glucose and lipid levels to metabolic health; this is possibly due to viscosity and fermentability attributes which may slow digestion and glycemic response of food ingested. Particularly with regard to metabolic syndrome and diabetes, this would be advantageous for using EPSs as component of food design (Kiran et al., 2024).Studies conducted in the area of structure-function relationships have led scientists to argue that EPSs have bioactive properties based on some functional properties (e.g., sulfate groups, molecular weight, and branching), which suggests multi-functional bioactive properties of EPSs for food (Wu et al., 2025).In conclusion, relevant multipotent bioactivities indicate that there may, or may not, be functional properties of microbial EPSs that would behave similar to functional foods, that could not only behave as a hydrocolloid modifier to affect food product texture, but also contain potential health-promoting bioactive properties.

6. Food applications and case studies

Functional performance in food systems is governed not only by intrinsic polymer properties but also by processing induced structural changes and interactions with other matrix components (Yiasmin et al., 2026). Unlike dilute model systems, real foods contain proteins, salts, lipids, and small molecules that alter polymer conformation through charge screening, competitive hydration, and interfacial competition. Increased ionic strength compresses electrostatic double layers and reduces chain expansion in polyelectrolytes such as sulfated EPSs, lowering intrinsic viscosity and modifying gelation behaviour (Yong et al., 2025). Thermal processing may induce depolymerization or alter intermolecular association kinetics, while high shear mixing and homogenization can reduce effective molecular weight and modify viscoelastic balance (Jicsinszky et al., 2023). Consequently, hydrocolloid functionality must be interpreted within the context of processing history and formulation environment rather than intrinsic composition alone.

While numerous studies report promising techno functional properties of microalgal EPSs in simplified aqueous or model gel systems, translation into complex food matrices requires careful evaluation (Terpou et al., 2025). Real food systems are multiphase, multicomponent environments in which ionic strength, pH, thermal processing, mechanical shear, and competitive biopolymer interactions can substantially alter polymer conformation and functionality (Yiasmin et al., 2026). Therefore, performance observed under controlled laboratory conditions may not directly predict behaviour in dairy products, plant based analogues, beverages, or processed foods. The following sections critically examine these contextual variables and distinguish between model system observations and validated food applications.

6.1. Dairy and plant-based dairy alternatives

Compared with established hydrocolloids such as xanthan gum and carrageenan, microalgal EPSs exhibit both similarities and important distinctions. Like xanthan, many microalgal EPSs demonstrate shear thinning behaviour and high viscosity at low concentrations due to extended chain conformation and intermolecular entanglement (Laroche, 2022). However, their higher structural heterogeneity and variable charge density may result in less predictable rheological responses under changing ionic conditions (Yang et al., 2022). In contrast to carrageenan, which exhibits well defined ion mediated gelation transitions, gelation mechanisms in microalgal EPSs are often weaker or more dependent on specific compositional features such as sulfation level or uronic acid content (Guo et al., 2024). These differences suggest that microalgal EPSs may be particularly suited to viscosity modification and interfacial stabilization applications, while their use as primary gelling agents may require targeted structural optimization.

6.1.1. Texture modification and stabilization

The alteration and stabilization of texture is an important aspect of formulating dairy and non -dairy alternatives. Hydrocolloids, polysaccharides, and proteins are commonly used as texturizing agents to help increase viscosity, stabilize emulsions, and minimize phase separation. In dairy systems, such as yogurt and cheese, the textural properties are mainly reliant on the interaction between milk proteins and the stabilizers, which can create a gel-like strength and ability to hold water (Lucey, 1998). For plant-based dairy alternatives, hydrocolloids like guar gum, xanthan gum, and pectin, which increase viscosity and create stable gel networks, can be used to replicate the creamy/thick textural mouthfeel observed in dairy products (Saha & Bhattacharya, 2010).

Stabilization can also include the prevention of syneresis, or the leaking of whey, which is a common defect seen with fermented dairy products. Also, the addition of protein-polysaccharide complexes, like caseinate-pectin and whey protein-carrageenan, are a known way to improve stability and structural integrity (Schmitt et al., 2009). Lastly, stabilization can also be achieved using thermal and mechanical processing. This can be done by inducing controlled denaturation and aggregation of milk proteins, mimicking the effect of mechanical rotational stress on texture stability (Mizuno and Lucey, 1998).

In practical dairy and plant based systems, the functional contribution of EPSs depends strongly on matrix conditions (Zang et al., 2025). Elevated ionic strength can screen electrostatic repulsion in sulfated EPSs, reducing chain expansion and viscosity. Divalent cations may either strengthen gel networks through ionic crosslinking or promote aggregation depending on concentration. pH shifts near protein isoelectric points influence protein–polysaccharide complexation, potentially enhancing gel firmness or inducing phase separation (Bou-Sarkis et al., 2024). Thermal treatments such as pasteurization or retorting may modify molecular weight distribution or alter hydration kinetics, while high shear homogenization can reduce effective chain length and decrease viscosity (Suryawanshi, 2022). These factors highlight the importance of evaluating EPS performance under realistic formulation and processing regimes.

6.1.2. Synergistic interactions with milk proteins

The interaction of milk proteins with hydrocolloids or biopolymers and other dairy proteins is particularly important to the texture and rheological properties of dairy matrices. Casein proteins and whey proteins can electrically and hydrophobically interact with polysaccharides like carrageenan and pectin, which carry a negative charge, to form coacervates that enhance firmness and stability of gels (Schmitt et al., 2009).

As these interactions were described in yogurt systems, they affect the microstructure and water holding capacity (WHC) with a yogurt system, while in cheese, they inform a basis whereby organized protein networks could be created that would develop an even chew or elasticity (Horne, 2003). In more recent considerations, the combination of polysaccharides with proteins would provide a stability of flavour and nutrients for sensory perception of flavours and nutrients in yogurt.

6.1.3. Mouthfeel enhancement

The mouthfeel, or the sensory perception of the texture in the mouth, is a critical factor in consumer acceptability for both dairy and non-dairy beverages. Hydrocolloids, such as xanthan gum, guar gum, or locust bean gum, can modify the viscosity of low-fat drinks while providing smoothness and creaminess (Rastegarpour et al., 2025). The presence of saliva and food colloids simultaneously lubricates for the perception of creaminess because of the soluble proteins and biopolymers, which may provide enhanced oral coating or smooth flow (De Wijk et al., 2006).

Conversely, the absence of casein micelles and milk fat globule membranes can make it more difficult to simulate a dairy-like mouthfeel in plant-based products. Structured emulsions, microgels, and polysaccharide-protein conjugates have received significant attention in dairy-like mouthfeel design (Dickinson, 2015). Hence, engineering rheological responses utilizing fat mimetics and biopolymers will always be a focal point for dairy and dairy-alternative products mouthfeel optimization.

Table 2
Summary of chemical composition and structural attributes of selected microalgal EPSs (monosaccharide profiles, charge characteristics, substituents, and molecular weight ranges) and their implications for hydrocolloid functionality.

Food system	Case study (short title)	Objective/innovation	Methods (brief)	Key findings/takeaways	Citation
Yogurt (dairy)	New synbiotic yogurt with *Lactobacillus plantarum/L. pentosus*	Design a yogurt product that is synbiotic (probiotic + prebiotic) enriched with probiotics and improved viability and sensory qualities.	Formulated yoghurt incorporating selected lactic acid bacteria (LAB) strains and prebiotic ingredients, shelf-life and sensory evaluation, microbial counts, physicochemical evaluation.	Probiotic survival during storage improved, acceptable sensory profile, prospective functional benefits (antioxidant capacity/ microbalance).	(He et al. 2024).
Yogurt (dairy + fruit)	Synbiotic mango yogurt optimized by RSM	Produce a fruit-flavoured synbiotic yogurt product with favourable texture and probiotic viability.	Experiment to optimize concentrations (fruit, cultures, stabilizers) using Response Surface Methodology (RSM); microbiological and sensory panels.	RSM enabled optimization of taste and texture while keeping probiotic counts, illustrating product development utilizing design statistics.	(Minj & Vij, 2025).
Yogurt (novel prebiotics)	Fucoidan-enriched synbiotic yogurt - in vitro prebiotic evaluation	Consider fucoidan derived from seaweeds, as a prebiotic ingredient in fermented dairy	Conduct in vitro prebiotic assays and formulation trials to assess growth promotion of proposed beneficial LAB and product stability.	Fucoidan exhibited in vitro prebiotic potential and compatibility with yogurt cultures; promising for added-functional yogurt claims.	Ricós-Muñoz et al. (2025).
Cheese (traditional)	Mapping microbiome of Grana-Padano/ Parmigiano and ripening dynamics	Characterize the microbial drivers of flavour and ripening composition in aged hard cheeses	Utilize amplicon or metagenomic sequencing across ripening stages, and chemical profiling (lipolysis or proteolysis).	The microbial succession during ripening is strongly predictive of and correlates with the biochemical markers of flavour; points to community level contributors to aroma and texture.	Valentino et al. (2025).
Cheese (review)	Universal drivers of cheese microbiomes — community ecology perspective	Summarize how the milk, starter culture, and environmental conditions shape the cheese microbiome and how all these factors influence cheese quality.	Make a review and then comparative analysis of sequencing studies across cheese types.	Highlight three common determinants (raw milk microbiota, starter culture, ripening conditions), and recommend various techniques for microbiome-informed process controls to achieve the final cheese quality.	(Reuben, Langer, Eisenhauer, & Jurburg, 2023).
Plant-based cheese (fermented nut-based)	Fermented cashew 'cheese' supplemented with seaweeds (Chondrus/Porphyra)	Improve the nutritional, textural, and sensory attributes of cashew-based, dairy alternative products using fermentation and addition of seaweed.	Fermentation utilizing LAB, addition of either red or green seaweed powders, textural analysis, assessment of proximate composition, sensory testing.	Fermentation improved flavour and texture while addition of seaweed influenced minerals/umami flavour, and structure was enhanced demonstrating utility for nut-based cheeses.	Campos et al. (2024).
Plant-based cheese (safety)	Listeria contamination in plant-based cheese analogue	Illustrated processing/safety concerns in PBCs manufacturing (ex: Listeria and Salmonella risk factors).	An incident was reported, providing evidence of experimental behaviour of pathogens as a result of sharing work spaces in preparation, and prior utilization of regulatory recall document.	PBCs are not low-risk, as it was determined that Listeria was linked to digestible beverages PBCs; strict process controls relative to HACCP/ thermal administrations/control must be taken.	Louvau et al. (2024).
Plant-based/ precision fermentation (industry)	Precision fermentation for microbial dairy proteins	Produce dairy proteins appropriate to animals, using microbes, as a means to replicate dairy chemistry and structure to a cheese type.	Utilize precision fermentation as a means to express casein or whey proteins in a pilot study through manufacturing, and grant submission, and consumer acceptance.	Demonstrate promise for delving in to the void control for texturizing plant-based cheese types, but also legal and liability issues around PBCs in reference to consumer risk-based trust.	Pereira et al. (2025)

6.1.4. *Case studies of yogurt, cheese, and plant-based alternatives*

Table 2 summarizes contemporary research studies illustrating changes in the innovative production of fermented products from dairy and plant-based food. The column describes improvements in microbial lactobacilli strain or their added fermentation process, while also enhancing the products during the growth process and post-fermentation as well. In advancing food products, these studies represent a trend of integration of biotechnologies with novel systems of sustainability in the fermentation science field.

6.2. *Bakery and confectionery applications*

The diagram illustrates the multifunctionality of hydrocolloids for bakery and confectionery applications condensed into four umbrella functions: (i) water holding/shelf-life prolongation (shelf-stability), (ii) texture improvement, particularly in gluten-free products, (iii) fat replacement, and iv) freeze-thaw stability (see Fig. 6). There are additional overlapping layers that illustrate combined functions of these roles to aid in delivering a range of quality attributes like moisture holding, improved texture, and stability at the same time. This overview is intended to illustrate the utility and relevance of hydrocolloids in developing high quality bakery and confectionery products (Fig. 7).

6.3. *Beverages and drink systems*

6.3.1. *Suspension stabilization*

Particle stabilization in beverages deals with how we can minimize the tendency of dispersed particles (flavour oils, pulp, insoluble solids) to cream, sediment, or aggregate while stored and consumed. Stabilization approaches come from (a) causing dispersed phase droplet/particle size reduction (by means of homogenization or microfluidization), (b) causing interfacial adsorption by using emulsifiers or particle stabilizers, and (c) modification of the continuous phase using hydrocolloids to modify viscosity/yield stress (and slow down sedimentation) (McClements, 2004; Vilela et al., 2018). Protein-polysaccharide

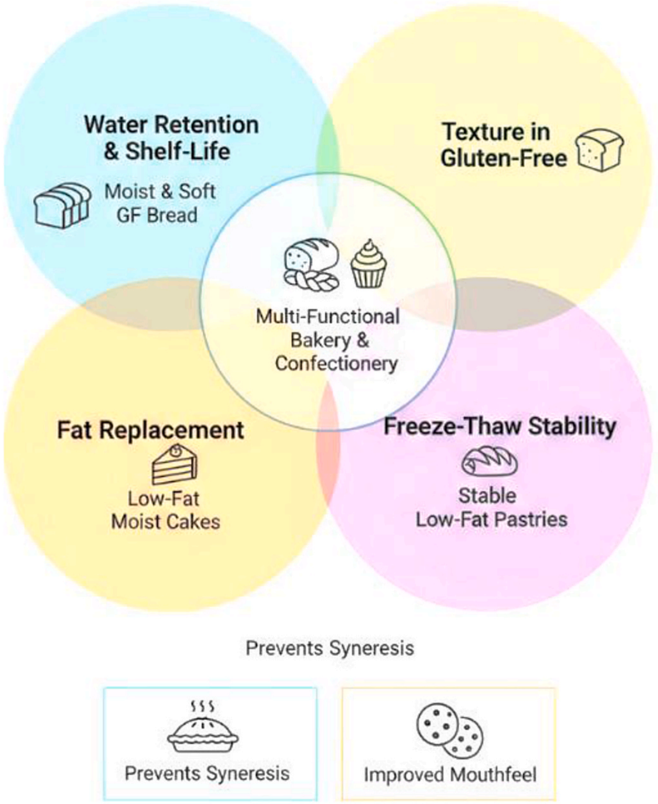


Fig. 7. Application landscape of microalgal EPSs in food products, highlighting their roles in dairy and plant-based alternatives, beverages, baked goods, confectionery, and encapsulation/film systems, with emphasis on texture, stability, and clean-label positioning.

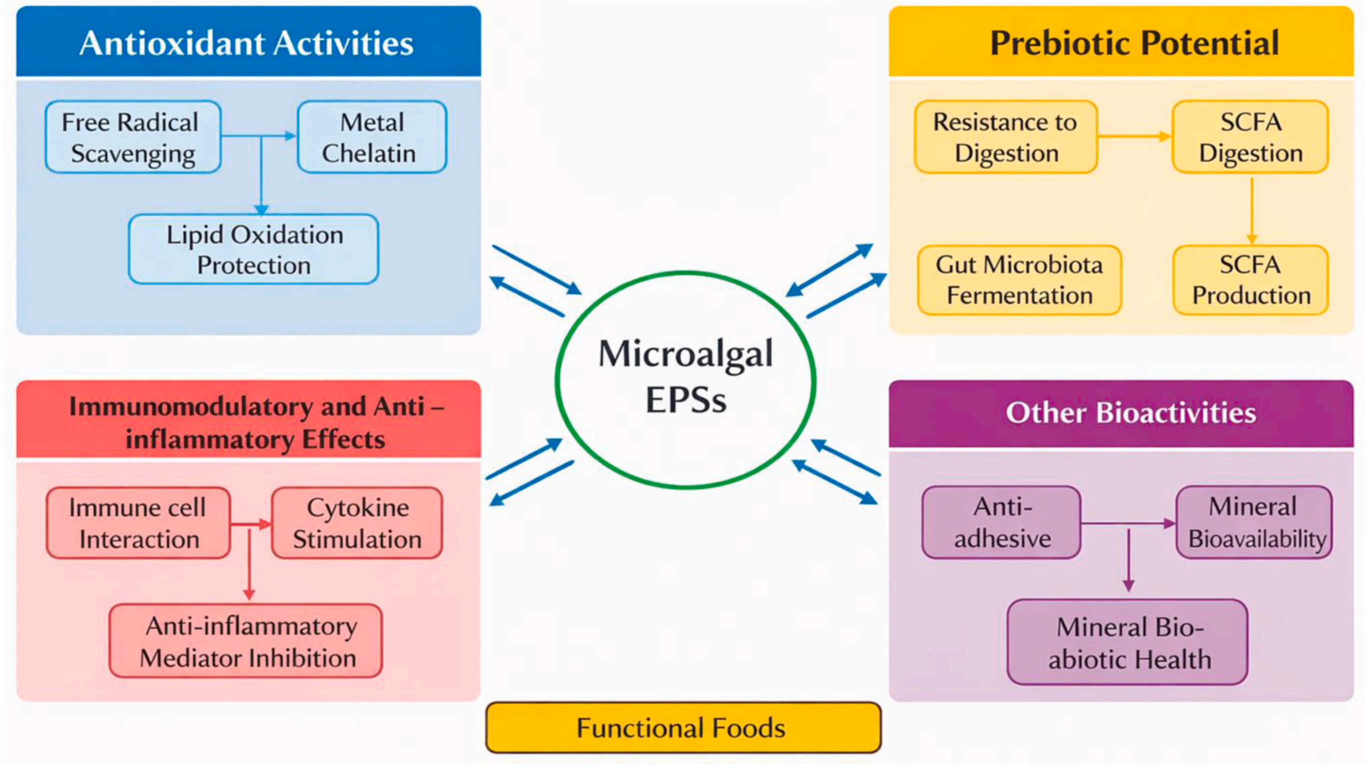


Fig. 6. Biofunctional properties of microalgal exopolysaccharides (EPSs) relevant to functional food applications.

complexes (such as whey protein-pectin) and modern Pickering stabilizers, which are food-grade particles (such as cellulose nanocrystals), both provide good kinetic stability with steric and/or electrostatic barriers to coalescence and flocculation (de Carvalho-Guimarães et al., 2022). Weighting agents (such esterified starches) are still used in beverages including citrus and flavoured beverages to better match the oil and aqueous densities and slow down creaming, but there has also been a focus on “natural” particle stabilization, and on interfacial proteins, in response to consumer demands for clean labels (McClements, 2004; Vilela et al., 2018).

In multiphase beverage systems, EPS behaviour is further influenced by competitive adsorption at oil–water interfaces and interactions with proteins, surfactants, and weighting agents (Korin et al., 2025). Under high shear conditions typical of industrial homogenization, polymer alignment and partial degradation may alter rheological responses compared to static laboratory measurements (Dulong et al., 2024). Furthermore, viscosity enhancement alone does not guarantee colloidal stability, as interfacial elasticity and steric stabilization play critical roles (Guo et al., 2024). Therefore, systematic rheological, interfacial, and microstructural characterization is necessary to validate functionality beyond model emulsions.

6.3.2. *Mouthfeel modification*

Mouthfeel in beverages is a sensory construct as multi-faceted (viscosity, thickness, astringency, lubrication, and thermal/aspiration), but has a significant effect on consumer acceptance (Wolinska-Kennard, Schönberger, Fenton, & Sahin, 2025). Advances in technology for modifying mouthfeel include (i) modifying viscosity using hydrocolloids (pectin, xanthan, CMC) to enhance perceived body; (ii) controlling microstructure by adding micro- and nano-sized particles (starch, proteins, fiber) to modify lubrication and particulate mouthfeel; and (iii) assessing flavour-texture interactions where thickeners modify flavour release and flavour perception temporal (Chakraborty et al., 2019; Gama et al., 2019). Hydrocolloid selection must balance the functional benefits against off-flavours or astringency (some gums can add sliminess or suppress flavour, for example). Sensory mapping and rheology (steady shear and tribology) can be used to aid linking formulation changes to mouthfeel perception (Wolinska-Kennard et al., 2025; Chakraborty et al., 2019).

6.3.3. *Cloud stability in fruit beverages*

The stability of cloud is substantial for the appearance and perceived freshness of cloudy fruit juices (e.g., orange, apple). Cloud is a complex of insoluble pulp particles, cell wall remnants and pectin; destabilization is due to enzymatic (pectin methylesterase) or physicochemical (calcium-mediated pectin cross-linking, aggregation) systems that lead to clarification or sedimentation. Methods to maintain cloud include inactivation of native enzymes (either by thermal or high-pressure processing), modification of pectin (using specific pectin fractions or adding low-methoxyl pectin in order to help suspend pulp particles), modification of particles (adsorbed to pectin or proteins), and control of ionic strength and concentration of calcium in order to avoid precipitation due to calcium (Yu et al., 2021; Zhang et al., 2023). New technologies (high-pressure processing, hydrodynamic cavitation, targeted fractionation) may improve cloud stability, while better preserving fresh flavour than harsh heat treatments (Lin, Liu, et al., 2025; Zhang et al., 2023).

6.3.4. *Alcoholic beverage applications*

Colloidal stability and mouthfeel are two factors that determine quality and shelf-life in alcoholic beverages (beer, wine, and ready-to-drink products). Beer haze develops from interactions between proteins and polyphenols, which can be stabilized with proteolytic treatment, fining agents, such as silica or Polyvinylpolypyrrolidone (PVPP), or cold stabilization treatment (Królak et al., 2023). As with the stabilization procedures in beer, hazing in wine can be controlled by regulating the protein and phenolic compounds using bentonite fining, protein removal, and PVPP, none of which impact the sensory properties of the wine. Alcohol changes the functionality of hydrocolloids (lower viscosity and hydration), so when making low-alcohol beverages or premixed cocktails with texture, it makes sense and is ideal to formulate with ethanol- and salt-compatible hydrocolloids. Artisanal alcoholic products (e.g., canned cocktails, de-alcoholized wines) require balancing clarity, mouthfeel, and flavour by utilizing custom proportions of stabilizers, enzymatic treatments, and minimal processing (Akhtar et al., 2025; Mastanjević et al., 2018).

Beyond bulk rheology, sensory perception is strongly influenced by lubrication behaviour under oral processing conditions. Hydrocolloids reduce friction between oral surfaces by forming hydrated polymer films, contributing to perceptions of smoothness and creaminess (Shukla et al., 2025). Tribological studies of polysaccharides demonstrate that molecular weight, flexibility, and hydration capacity govern boundary lubrication performance independently of bulk viscosity (Lin et al., 2025). Highly hydrated, flexible chains typically provide superior lubrication at low shear rates relevant to oral processing. Although tribological characterization of microalgal EPSs remains limited, their high molecular weight and strong hydration potential suggest potential to enhance mouthfeel in reduced fat and plant based beverages (Ji et al., 2023). However, systematic integration of rheology, tribology, and sensory evaluation is required to establish predictive relationships between structure and sensory perception.

6.4. *Meat, seafood, and plant-based alternatives*

6.4.1. *Water binding and juiciness enhancement*

The WHC and juiciness are important quality indicators in meat and seafood that are correlated with tenderness, yield, and perception. WHC pertains to the configuration and charge of myofibrillar proteins that immobilize water within the muscle matrix utilizing ionic and capillary forces (Pearce et al., 2011). Salt and phosphates can improve WHC through dissolution of myofibrillar proteins, leading to electrostatic repulsion of proteins, thereby allowing more moisture to be retained during cooking (Van Buren et al., 2023). In some processed items, hydrocolloids like carrageenan, alginate, and starches are utilized to better hold moisture and reduce syneresis (Marczak & Mendes, 2024). For fish products, low-temperature gelation systems to hold moisture, because protein denaturation and water loss are lower. In plant-based items, water is maintained through hydration and hydrogen bonds between plant proteins and polysaccharides; nonetheless, the hydrocolloid composition and processing conditions will also affect moisture distribution and the perception of juiciness (Jang & Lee, 2024). The formulation and processing conditions could be manipulated to control these interactions to maximize juiciness characteristics depending upon the desired sensory experience of meat.

6.4.2. *Texture improvement in processed products*

Texture is a key quality attribute for meat and seafood products influencing consumer's perception and acceptance of processed meat and seafood products. Texture is influenced by gelation of proteins, distribution of fat, and binding agents' interaction with the matrix (Duarte et al., 2020). The addition of salts, phosphates, and processes such as physical manipulation allows protein extraction, while emulsifying the fat components that provide a stable gel structure that produces tenderness and chewiness. Microbial transglutaminase (MTGase) is frequently used to provide covalent crosslinking between proteins, hence improving firmness and sliceability (Marczak & Mendes, 2024). Hydrocolloids (i.e., carrageenan, methylcellulose), can also improve mouthfeel and limit fat leaching. Textile development was achieved through the use of a functional component of plant protein, where textural aspects were developed via denaturation, alignment of protein, gelation or via both extrusion processing and shear-cell processing (Benković et al., 2023). Future considerations for research involving rheological modelling, and sensory relationships, provide opportunities for improved texture optimization.

6.4.3. Gel formation in restructured products

The formation of a gel is essential in restructured meat and seafood products, providing cohesiveness and mechanical strength to hold fragmented pieces together. Myofibrillar proteins undergo thermal gelation, enzymatic cross-linking takes place, or hydrocolloids are incorporated (Ren et al., 2024; Sun, 2009). The MTGase catalyzes covalent bonds of ε-(γ-glutamyl) lysines between proteins and modifies the elasticity and WHC, eliminating the requirement for excessive salt (Lee & Hong, 2020). Alternatively, alginate and carrageenan form either Ionic or cold-set gels with calcium ions, and both are especially beneficial for seafood or low salt formulations. The best gel formation improves sliceability and retention of moisture while maintaining desirable sensory characteristics (Hong & Chin, 2010). Too much cross-linking and hydrocolloid addition can lead to the loss of juiciness, however. The joint application of MTGase with hydrocolloids can have synergistic effects that can help develop a stable restructured product with specific textures, while reducing the ratio of additives (Ren et al., 2024).

6.4.4. Applications in plant-based meat analogues

The PBMAs (Plant-based meat analogues) are developed with similar cellular characteristics, and sensory textural properties to create meat-like experiences that incorporate different methods of ingredient and protein structuring. Combinations of various plant proteins (i.e., pea, soy, and wheat) and fats, hydrocolloids, and advanced high-moisture extrusion technologies are driving innovations that produce fibrous meat-like structures (Jang & Lee, 2024). The WHC of PBMAs is primarily derived from gelling polysaccharides (i.e., methylcellulose, gellan gum) and fat-protein emulsions that liberate moisture during cooking (Ozturk & Hamaker, 2023). Formulating plant proteins via high moisture extrusion can denature the proteins, with some even developing aligned anisotropic structures that produce acceptable and desirable products with respect to consumer's and connoisseurs' qualitative expectations of a meat-like product (Benković et al., 2023). As PBMAs are meant to be replacements for meat, it is important to consider that denatured plant proteins will not form solubility (or gelation) like animal proteins, and will not recreate the overall succulence of meat. There remains ongoing research to identify and develop process parameters to create a meat-like juiciness and increase WHC and enzymatic or physical forming strategies to avoid additives. Although PBMAs continue to improve, it remains vital to perform sensory (descriptive) and microstructural analyses to enhance the textural resemblance of PBMAs to meat's backbone (Jang & Lee, 2024).

6.5. Translational considerations for industrial application

Collectively, although microalgal EPSs demonstrate promising rheological and biofunctional attributes in controlled systems, evidence under industrial scale processing remains limited (Pessôa et al., 2024). Differences between model systems and real food matrices arise from compositional complexity, processing induced structural modifications, and sensory constraints (Mengucci et al., 2022). Yield stress, viscoelastic balance, and lubrication behaviour influence not only structural stability but also mouthfeel perception and consumer acceptance (Hernández-Figueroa et al., 2025). Future research should therefore integrate polymer characterization with pilot scale processing trials and sensory validation to avoid overgeneralization and to provide formulation relevant guidance for food scientists.

6.6. Novel and emerging applications

Table 3 summarizes emerging and novel technologies related to texturization and structuring that are reshaping modern food systems. The main techniques, mechanisms, and applications are described that are improving texture, functional properties, and sensory properties of food. These technologies and innovations are critical to designing sustainable plant-based or alternative protein foods and improving food product function and consumer acceptance.

Table 3
Cultivation and process parameters influencing microalgal EPS production, including trophic strategy, medium composition, stress conditions, and reactor configuration, with reported impacts on yield and techno-functional quality.

Technology	Functional Mechanism	Applications/ Benefits	Key References
3D Food Printing	Ink formulation of food materials (hydrocolloids, proteins, polysaccharides) using laser or layer-by-layer; rheological adjustments for extrusion and shape stability	Texture design, modernized nutrition, visual aspects, and injection of functional ingredients; employed in analogue meat, desserts, and nutraceutical delivery foods	(Liu, Chen, McClements, Peng, and Jin (2023); Sohel et al. (2025); Ritota et al. (2025))
Microencapsulation of Bioactives	Encapsulation of sensitive bioactives (vitamins, probiotics, polyphenols, omega-3) into microcapsules by spray drying, coacervation, or emulsification	Increases stability, controls release, masks off-flavours, and increases bioavailability in functional foods and beverages	(Huang et al. (2023); Arenas-Jal et al. (2020); Fang et al. (2010)
Edible Films and Coatings	Formation of thin biopolymer matrices (proteins, polysaccharides, lipids) as coatings or wrappers; can also incorporate antioxidants or antimicrobials	Increases shelf life, improves texture, reduces moisture and gas transfer, and acts as a carrier of bioactives in meats, fruits and seafood	(Al-Tayyar et al. (2020); Debeaufort and Voilley (2009); Priyadarshi and Rhim (2020))
Structured Delivery Systems	Design of emulsions, hydrogels, oleogels, and nano/microstructures for controlled delivery of nutrients and flavours	Increases stability and sensory performance of bioactives, fats, and flavours; employed in plant-based products, beverages, and functional emulsions	(McClements, 2021; Chen et al. 2024)

7. Technological challenges and opportunities

Molecular consistency, batch reproducibility, and regulatory compliance are as critical as production efficiency for hydrocolloid applications (Pirsa & Hafezi, 2023). Variations in polymer composition and structure arising from cultivation or processing differences can significantly affect rheological and interfacial behaviour, highlighting the need for integrated upstream and downstream control strategies (Lade et al., 2026).

7.1. Scalability and economic considerations

Microalgae-derived hydrocolloids remain significantly costlier than conventional seaweed-based hydrocolloids due to high cultivation, harvesting, and extraction costs. Techno-economic assessments estimate production costs for microalgal bioproducts at US$800–1100 per kg, compared with US$4–40 per kg for commercial hydrocolloids such as carrageenan, agar, and alginate (Valdovinos-García et al., 2023). High operating costs are mainly attributed to energy-intensive steps such as dewatering and drying (Wiatrowski et al., 2022). Life-cycle assessments show that energy requirements and greenhouse gas (GHG) emissions for algal systems can be up to ten times higher than for conventional plant-based feedstocks, particularly when powered by fossil energy sources (Ubando et al., 2022). However, integration with waste heat, wastewater nutrients, and renewable electricity can substantially reduce environmental footprints (Khandelwal et al., 2025). Given their high cost, microalgal hydrocolloids are best positioned for niche and premium markets, such as functional foods, cosmetics, and biomedical applications, where unique rheological properties or sustainability claims justify higher prices. The global hydrocolloid market is valued between US$9–17 billion, growing at 5–7 % annually, offering selective entry opportunities for high-value microalgal products (Future Market Insights, 2025). Integration within biorefinery frameworks is considered essential for economic feasibility. Coupling polysaccharide recovery with co-products such as pigments, proteins, and biofuels can lower production costs by 30–50 %, improving the overall profitability of algal operations (Figueroa-Torres & Theodoropoulos, 2023). Such multi-product valorization, combined with sustainable feedstock sourcing, is expected to enhance scalability and competitiveness in future markets (Fig. 8).

7.2. Quality control and standardization

Ensuring molecular consistency and functional reproducibility is essential for hydrocolloid ingredients, as rheological performance, gelation behaviour, and interfacial stability are highly sensitive to structural variability (Nwankwo et al., 2025). Batch-to-batch variability is particularly critical because small changes in molecular architecture can significantly alter rheological and interfacial performance (Pawde & Dave, 2025). Variations in molecular weight distribution, sulfation degree, or monosaccharide composition may affect intrinsic viscosity, gelation behaviour, and emulsion stabilization capacity, leading to inconsistent texture or stability in formulated food products. Therefore, quality control must extend beyond compositional analysis to include functional characterization such as rheological profiling, molecular weight determination, and charge density measurement. Establishing standardized specifications and acceptable variability ranges is essential to ensure reproducible techno-functional performance and industrial applicability (Alshehry et al., 2015). Conversely, studies in analogous regulated industries (topical/pharmaceutical products) have shown that applying standard regulatory equivalence criteria can flag substantial batch differences, i.e., statistical analyses sometimes conclude that “none of the same product batches can be considered equivalent” when strict criteria are applied (Miranda et al., 2020). Practically, food manufacturers therefore aim to reduce critical-parameter CVs to the single-digit or low-teens percent range for key chemical markers and to use nested sampling (lots → sublots → analytical replicates) to partition variance components and identify dominant sources (process vs analytical). Statistical process control (SPC) tools, control charts, capability indices (Cp, Cpk), and ANOVA variance component models are recommended to maintain within-batch CV targets (e.g., $\leq$10–15% for potency markers where feasible) and to trigger corrective actions when control limits are breached (Montgomery, D. C. 2020).

To effectively monitor and minimize such variability, analytical methods for characterization play a critical role in ensuring the chemical, physical, and functional uniformity of production batches. Advanced chromatographic and spectrometric tools such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography–Mass Spectrometry (GC–MS), Nuclear Magnetic Resonance (NMR), and Fourier Transform Infrared Spectroscopy (FTIR) provide high-

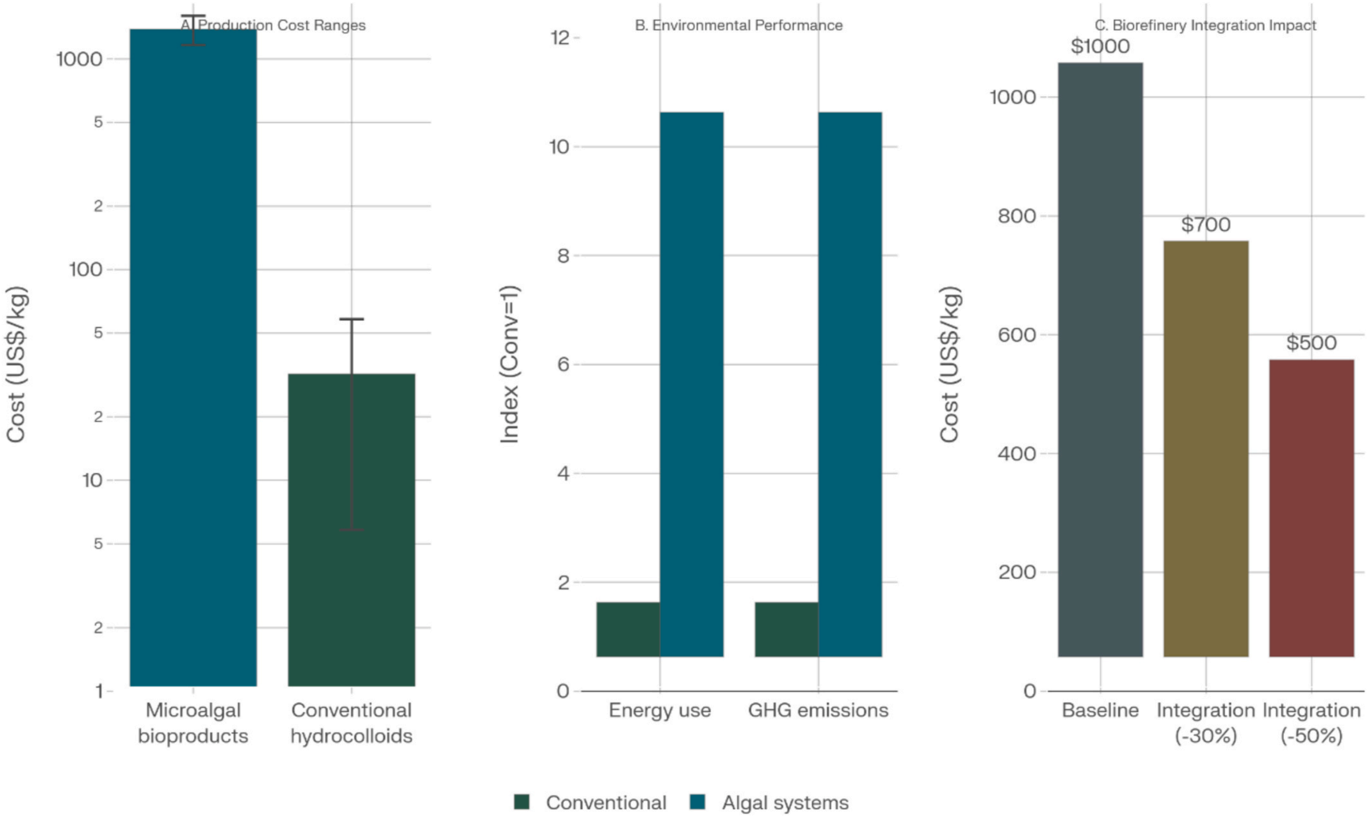


Fig. 8. Conceptual comparison of economic and environmental performance of microalgal versus conventional hydrocolloids, and the potential of biorefinery-based co-product integration to improve cost-effectiveness and sustainability.

resolution analytical fingerprints that can identify even minor deviations among batches.

Analytical characterization methods such as HPLC, GC–MS, NMR, and FTIR provide high-resolution fingerprints to detect even minor deviations among batches, Fig. 9 illustrates a schematic overview of these analytical methods used for characterization and their integration into quality control workflows. These measurements form the basis for quality specifications, which are quantitative, risk-based release criteria linked to safety and functional endpoints. Specifications typically leverage historical batch data and statistical measures (mean ± 2–3 SD, Cpk $\geq$1.33) to ensure robust performance and regulatory compliance (Rathore, Bhambure, & Ghare, 2010).

Sensory impact considerations complement chemical and physical specifications by ensuring that allowed variability remains acceptable to consumers. Psychophysical metrics such as just-noticeable differences (JND) and rejection thresholds help determine the minimum perceptible changes in taste, aroma, or texture. For instance, fruit nectar studies found sugar reductions of ~4–8% were often undetectable, while larger reductions affected overall liking (Oliveira et al., 2018). Integrating sensory evaluation with chemical data through sensory-chemical mapping allows manufacturers to set limits that maintain both analytical accuracy and consumer acceptability, forming a holistic quality management framework (Fig. 9).

7.3. Regulatory status and safety aspects

Regulatory approval of novel hydrocolloids requires not only demonstration of toxicological safety but also consistent compositional and functional properties. Regulatory authorities typically require detailed characterization of molecular composition, purity, and production processes to ensure reproducibility and safety under intended conditions of use. Variability in polymer structure arising from cultivation or processing differences may affect both functional behaviour and regulatory classification. Consequently, standardized production protocols and analytical validation are essential to support regulatory approval and to establish microalgal EPSs as reliable food-grade hydrocolloids suitable for commercial applications. In the European Union (EU), novel foods are defined under Regulation (EU) 2015/2283 as foods not consumed to a significant degree before 15 May 1997, and the European Food Safety Authority (EFSA) is responsible for safety evaluation. Statistical analyses of EFSA submissions indicate that the average duration from submission to publication of a safety opinion is 2.56 ± 1.19 years, highlighting the thoroughness and complexity of the process (Le Bloch et al., 2025). In the United States, the Food and Drug Administration (FDA) manages novel food safety through the Generally Recognized as Safe (GRAS) notification system, where products can enter the market if the FDA does not object within 90 days (U.S. Food and Drug Administration, 2023). Similarly, in India, the Food Safety and Standards Authority (FSSAI) regulates novel foods under the Food Products Standards and Food Additives Regulations, 2011, requiring safety assessments that may include toxicological and nutritional studies (Rai et al., 2023).

Novel food approval pathways generally involve comprehensive dossiers that provide detailed information on composition, nutritional value, intended use, and potential risks. EFSA evaluates these dossiers to ensure safety under proposed conditions of use (Le Bloch et al., 2025). Safety evaluation studies often include toxicological analyses, allergenicity assessments, and nutritional profiling, ensuring that potential health risks are identified prior to market entry (World Health Organization/Food and Agriculture Organization, 2021).

Consumer perception and clean label considerations play a growing role in market acceptance of novel foods. Research indicates that attributes such as less-processed ingredients, elimination of undesired additives, and ethical sourcing strongly influence consumer preference, with surveys showing that healthiness, social responsibility, and sensory appeal are key motivators (Cao & Miao, 2022; Giacalone et al., 2023). Consequently, regulatory compliance, rigorous safety evaluation, and alignment with consumer expectations remain critical factors in the development and commercialization of novel foods.

7.4. Opportunities for targeted modifications

To better summarize the various strategies available for targeted modifications of food ingredients, Table 4 provides an overview of the key approaches, their specific methods or techniques, and the resulting functional improvements. These modifications can be broadly categorized into enzymatic, physical, chemical, and techno-functional strategies, each offering distinct advantages for enhancing the solubility, emulsification, gelation, foaming capacity, water-holding ability, antioxidant activity, and other functional properties of proteins and polysaccharides. By consolidating this information into a single table, readers can easily compare the different modification methods and their outcomes, providing a clear understanding of how targeted interventions can be applied to improve the functionality and application

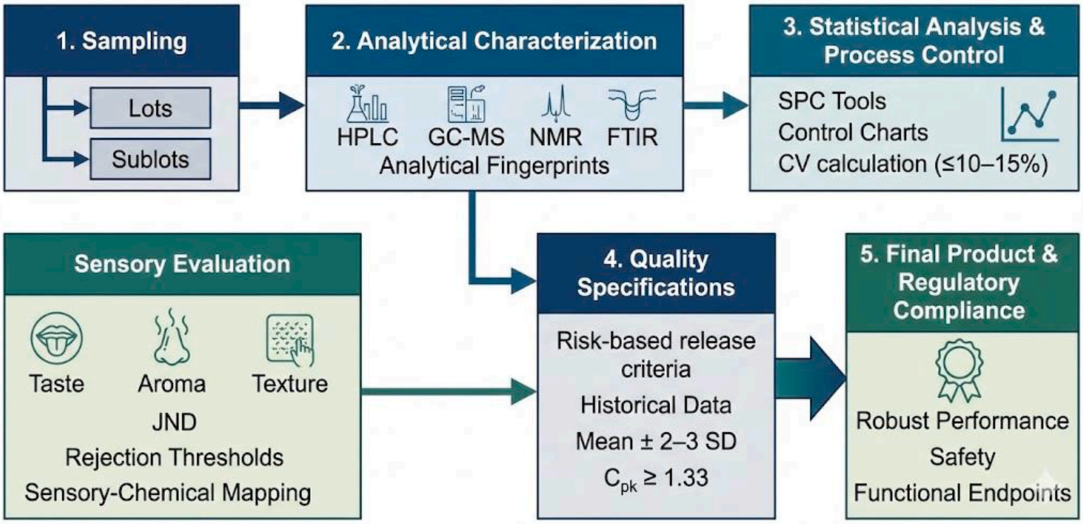


Fig. 9. Schematic overview of analytical characterization and quality-control workflows for managing batch-to-batch variability in complex microalgal EPS ingredients, integrating chromatographic/spectrometric methods, statistical process control, and sensory evaluation.

Table 4
Extraction and purification methods for microalgal EPSs, outlining unit operations, process advantages/limitations, and typical purity and recovery levels achievable for food applications.

Modification Type		Functional Improvements	Reference
Enzymatic Modifications	Proteolysis and treatment with transglutaminase	Increased solubility, emulsifying and foaming capacity, gelling capacity	(Panyam & Kilara, 1996)
Physical Treatments	High shear processing, freeze-drying, ultrasound, hydrostatic pressure	Better water holding capacity (WHC), fat binding, swelling, emulsifying capacity	Yi et al. (2023)
Chemical Derivatization	Phosphorylation, acetylation, Maillard conjugation	Enhanced solubility, gelling, emulsifying, antioxidant and antimicrobial properties	(Li et al., 2022)
Techno-Functional Improvements	Dry fractionation, reducing particle size	Improved solubility, foam stability, gelling capacity, incorporation in bakery and protein-rich foods	(De Angelis et al., 2024)

potential of food ingredients in various formulations.

8. Future perspectives and research needs

The future perspectives and research needs related to EPSs production, identifying four important research directions that could serve as a platform for future application and research in this area. These involve first, Advances in Production Technologies, with an emphasis on fermentation process optimization and genetic engineering modification, second, Expanding EPSs Repertoire, concentrating on exploring microbial diversity and developing new sources of EPSs, third, Multifunctional Food Ingredients, with a focus on the enhancement of functional properties and the expansion of applications in food; and lastly, Sustainable Production, prioritizing efficiency in resource utilization and waste emission reductions.

8.1. Advances in Production Technologies

Recent new technologies in production have improved biomanufacturing efficiency and sustainability in multiple areas (Fig. 10). Continuous cultivation systems, in particular, have gained interest due to their ability to maintain steady-state growth and increase productivity significantly achieving viable cell density greater than 50 $\times$ 10^6 cells·mL^{-1}, and titer increasing from 3.9 g L^{-1} in fed-batch systems to more than 24 g L^{-1} using intensified perfusion mode, which represents a 6-fold increase in production and cost of goods (Kittler et al., 2025; Schwarz et al., 2023). The global continuous bioprocessing market was valued at USD 349.3 million in 2024 and is expected to top over USD 900 million by 2030 (Precedence Research, 2026). At the same time, cell-free protein synthesis (CFPS) has become a flexible alternative for producing synthetic biomolecules faster and on demand with the ability to decouple synthesis from living cells. Current CFPS systems can achieve mg-g scale yields of a given protein or biomolecule in hours, with an anticipated valuation of USD 267-300 million, which is expected to grow at a compounded annual growth rate of 8-10% in 2023 (Yue et al., 2023; Caschera, 2025) While genetic improvements made possible by CRISPR/Cas type technologies certainly allow for beneficial strains to be optimized, it is also possible to multiplex pre-integration filamentous fungi strains and transcriptionally regulate them to take full advantage of their elicitous production potential. With CRISPRi based repression strategy, free fatty acid production levels were increased to 35.1 g L^{-1} with a productivity of 0.84 g L^{-1}·h^{-1}, the titers of CoQ10 in *Rhodobacter sphaeroides* improved by 37–44% by modifying the target pathways (Fang & Bhandari, 2010; Zhang et al., 2022). Further, precision fermentation, the practice of using synthetic biology, metabolic engineering, and controlled bioprocessing, has established a valuable platform for naturally-identical ingredients. The precision fermentation market was expected at USD 4.01 billion in 2024, with annual growth also expected between 35 and 45%, with estimates projecting the precision fermentation market will exceed USD 34–100 billion by 2035 (Fortune Business Insights, 2024) collectively, these technological advancements are representative of a movement toward more efficient, sustainable, and programmable biomanufacturing systems.

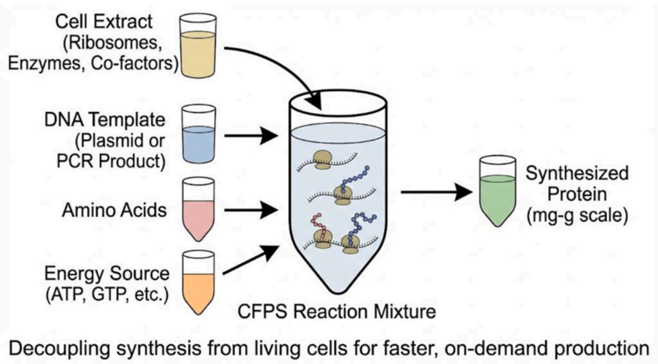


Fig. 10. Cell-Free Protein Synthesis (CFPS) Reaction Scheme Showing Input Components and On-Demand mg–g Scale Protein Production.

8.2. Expanding the repertoire of characterized EPSs

Bioprospecting into unexplored microalgal diversity is now a prominent frontier for discovering new EPSs. Although there are currently descriptions of approximately 44,000–50,000 species of microalgae and cyanobacteria, it is estimated that over 75% of them are uncharacterized organisms, clearly indicating that unexplored EPSs producers will exist on this still vast unexplored diversity of organisms (He et al., 2025; Novoveská et al., 2023). Guided bioprospecting, or environmental sampling combined with genomic tools, has improved the speed of discovering new EPSs-producing strains by a factor of 2–4 × compared to random isolation (Chiriví-Salomón et al., 2024; Rojas--Villalta et al., 2024).

New High-throughput screening (HTS) technology has now set the stage for rapidly screening EPSs from hundreds of strains in a matter of weeks, if not less. Colorimetric microplate assays, robotic mini-bioreactors, and LC-MS-based approaches to carbohydrate fingerprinting have reduced the time for screening EPSs from months to weeks, with validation correlations of $R^2 \approx 0.8$ with the gold standard of using gravimetric methods for drying down EPSs (Liu et al., 2021; Rühmann et al., 2015; Xiong et al., 2022).

New structure–function prediction tools, such as Carbohydrate Structure Database (CSDB), EPSs-DB, GLYCAM-Web, and CHARMM-GUI Glycan Modeler, now enable modelling polysaccharides in-silico, and predicting their rheological and/or bioactive properties, resulting in >50% reduction in experimental workloads (Akune-Taylor et al., 2024; Birch et al., 2019; Park et al., 2019)

Finally, synthetic biology enables the design of custom EPSs with desired attributes. Rewiring biosynthetic pathways using CRISPR/Cas and engineering glycosyltransferases have created a few variants that change viscosity and bioactivity in predictable ways. In fact, peer-reviewed research articles on EPSs engineered have increased ~170% in the past 10 years; indicating there is a burgeoning interest in functional biopolymers (Kong et al., 2022; Rütering et al., 2017; Wang et al., 2023).

8.3. *Multifunctional Food Ingredients*

8.3.1. *Combined texturizing and bioactive properties*

Functional plant-based ingredients, which are bioactive or have texturizing functions, are increasingly being used in the food industry. They enhance textural and sensory attributes of food products, while providing health benefits through bioactive compounds. Several plant-based gums and fibers, for instance, function as both texturizers and provide prebiotic benefits that can benefit gut health and immunity (Tolve & Simonato, 2024).

8.3.2. *Clean label opportunities*

The clean label movement is coming together with a healthier demand from consumers for transparent and simple food ingredients. In 2024, 51% of consumers in the U.S. were specifically looking for packaged foods with clean labels, which is a substantial aspect of a larger food trend for products perceived as having fewer identifiable ingredients (Freedonia Group, 2024). The clean label is causing food manufacturers to reformulate certain products that contain artificial flavour, colour, and preservatives. An example of this is Walmart announcing it will get rid of synthetic dyes (along with 30 more artificial ingredients) in its private label food products by 2027 which responds to consumer demand for more clean labels (Asioli et al., 2017).

8.3.3. *Personalized nutrition applications*

Integrated health “optimized” personalized nutrition is an emerging health and wellness vertical that provides dietary suggestions to individuals based on their genetics, lifestyle, and health situation. The personalized nutrition market size was estimated to be at USD 17.9 billion by 2025 going up to USD 60.94 billion by 2034 globally at a compound annual growth rate (CAGR) of 14.63% (Precedence Research, 2025), which is a sign of the rapid growth of its popularity and creation of products that promote personalized nutrition for health optimization.

8.3.4. *Integration with other emerging food technologies*

For perspective, there is a range of functional food ingredients, in conjunction with utilizing new food technology that provides additional functionality and sustainability, innovations in fermentation, encapsulation and nanotechnology are being used to enhance bioactive delivery and effectiveness of bioactive compounds in food products (Sutovsky, 2025). Not only will new technologies provide greater efficacy than previously made functional foods, they will be valuable for functional food development that produces consumer satisfaction and exceeds consumer criteria for taste and texture, while integrating health and safety improvements. In turn, the food industry will undergo advancements.

8.4. *Sustainable production and circular economy*

8.4.1. *CO_2 utilization and carbon footprint reduction*

Globally, CO_2 emissions from energy consumption reached a record level of 37.8 gigatons in 2024, a rise of 0.8% over 2023 (International Energy Agency, 2025). This increase highlights the potential of options for CO_2 utilization as a climate change mitigation strategy. Technologies, such as carbon capture and utilization (CCU), play an important role in converting CO_2 into valuable end-products, such as fuels, chemicals, and building materials. For example, the Brevik cement plant in Norway has integrated a CCU system that captures roughly 400,000 metric tons of CO_2 each year to produce the 'evoZero' net-zero cement (Heidelberg Materials AG, 2025).

8.4.2. *Integration with wastewater treatment*

Globally, around 380 billion cubic meters of municipal wastewater is produced annually, of which nearly half is untreated and released into the environment. The transition of municipal wastewater treatment into a circular economy can improve resource recovery, decrease the energy consumption of disposal and recycling processes, and lower operating costs. For instance, the Nimbus project in Barcelona is supplying biogas produced from sewage sludge to buses, resulting in an 85% reduction in CO_2 emissions compared to operating on natural gas (Kundu et al., 2022).

8.4.3. *Valorization of side streams*

Agricultural and industrial side streams, which are often viewed as waste, have much potential for valorization. The Global Food Innovation 2024 report projects that, in the US, a large proportion of side streams generated from major crops could be utilized as processing feedstock to generate plants-based protein and amino acids by 2030. Additionally, dairy by-products have an estimated annual opportunity for valorization ranging from approximately 63.6 to 3180 million metric tons by 2031 (Ozcelik et al., 2024).

8.4.4. *Life cycle assessment considerations*

Life cycle assessment (LCA) is an important tool for evaluating the environmental sustainability of hydrocolloid production systems, as it considers impacts across the entire product lifecycle, including raw material production, processing, use, and end of life management (Amponsah et al., 2024). For microalgal EPSs, LCA can help identify opportunities to improve resource efficiency, reduce waste generation, and minimize energy consumption during cultivation, extraction, and downstream processing (Cogo Badan et al., 2024). These insights are essential for designing sustainable production pathways and supporting the development of microalgal EPSs as environmentally responsible alternatives to conventional hydrocolloids.

9. Conclusion

Microalgal exopolysaccharides represent more than an alternative biomass source, they constitute a structurally versatile and designable class of emerging food hydrocolloids. Their value lies in the inherent tunability of molecular architecture, including charge distribution, sulfation degree, branching topology, and molecular weight heterogeneity, which collectively determine hydration, rheology, gelation, and interfacial performance. When interpreted through a structure–property–function lens, microalgal EPSs demonstrate the potential to expand the functional design space of hydrocolloids beyond the constraints of conventional plant and seaweed gums. Future progress will depend on systematic mapping of molecular architecture to techno functional performance, standardised rheological characterisation, and integration within economically viable biorefinery platforms. By advancing from descriptive diversity toward rational hydrocolloid engineering, microalgal EPSs can be positioned as programmable, clean label structuring agents for sustainable and high value food applications.

CRediT authorship contribution statement

A. Rizwan: Writing – review & editing. **Yuvaraj Dinakarkumar:** Writing – review & editing, Supervision, Resources, Conceptualization. **Sagayaraj Ivo Romauld:** Software. **Arokiyaraj Selvaraj:** Writing – review & editing, Conceptualization. **Maheswara Reddy Mallu:** Visualization. **Muthezhilan Radhakrishnan:** Validation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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