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Materials Engineering of Microalgae-Derived Protein Ingredients: Processing-Structure-Property-Performance Relationships, Scale-Up, and Economic Considerations

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ABSTRACT

Microalgae-derived proteins are promising functional food materials whose performance depends on cell architecture, protein molecular state, particle structure, associated components, and processing history. This review examines microalgal protein ingredients through a processing-structure-property-performance framework covering cell disruption, fractionation, concentration, and drying. Processing conditions influence protein accessibility, conformation, aggregation, particle size, surface characteristics, and interactions with pigments, lipids, and polysaccharides, thereby governing solubility, surface charge, rheology, emulsification, gelation, dispersibility, and stability. Particular attention is given to trade-offs between protein recovery and functional preservation, together with scale-up constraints and economic considerations related to processing severity, energy demand, ingredient yield, and co-product value.

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1. INTRODUCTION

Feeding a growing global population while reducing the environmental burden associated with conventional protein production has intensified interest in alternative protein sources. Microalgae are attractive in this context because they can be cultivated in water-based systems, require limited dependence on arable land, and can, under appropriate cultivation configurations, be integrated with carbon dioxide utilization or nutrient-recovery processes [1, 2]. Selected microalgal species also contain substantial amounts of protein together with pigments, lipids, carbohydrates, minerals, and other bioactive components, providing a compositionally diverse platform for food-material development [2-4]. However, protein content alone does not determine the functional performance of a microalgal ingredient. Microalgal biomass is a hierarchical multicomponent material in which proteins are distributed within cellular structures and coexist with cell-wall polymers, membranes, pigments, lipids, carbohydrates, minerals, and low-molecular-weight compounds. Consequently, biomasses with similar total protein contents may exhibit substantially different protein accessibility, digestibility, solubility, dispersibility, rheological behavior, interfacial activity, and storage stability. These differences arise from variations in cellular architecture, molecular organization, particle structure, and processing history [5-8].

Cell-envelope architecture represents the first structural constraint governing the conversion of microalgal biomass into protein ingredients. *Spirulina* biomass has a comparatively accessible cellular organization, whereas *Chlorella* and several other microalgae possess more resistant cell envelopes that restrict protein accessibility and frequently require mechanical, chemical, enzymatic, or combined disruption treatments [9-11]. Cell disruption should therefore not be regarded solely as an extraction operation. It is also a material-transformation step that changes cell integrity, particle-size distribution, exposed surface area, intracellular-component release, and subsequent solid-liquid separation behavior.

Subsequent fractionation, concentration, precipitation, and drying further modify the structural state of the recovered material. Changes in pH, temperature, shear, ionic environment, and moisture history can influence protein solubilization, unfolding, aggregation, protein-polysaccharide association, particle morphology, porosity, and surface characteristics. Moderate structural modification may improve hydration or interfacial adsorption, whereas excessive processing can decrease solubility, promote aggregation, alter color, and reduce dispersibility [5, 6, 8, 12]. Protein recovery and purity are therefore insufficient as stand-alone indicators of process performance.

A materials-engineering assessment must instead connect processing-induced structural changes with measurable properties relevant to final performance. These properties include particle size and morphology, protein solubility, surface charge, thermal behavior, water- and oil-holding capacity, rheology, emulsification, gelation, dispersibility, and stability under defined pH, ionic-strength, temperature, and storage conditions. Such measurements provide the link between microscopic or molecular transformations and macroscopic ingredient behavior and are therefore important for comparing processing routes and defining reproducible material specifications [7, 12, 13]. Processing decisions also affect engineering scalability and economic performance. More intensive disruption, purification, concentration, and drying may improve protein release or compositional purity, but they can simultaneously increase energy demand, separation requirements, yield losses, and processing cost. Conversely, less intensive processing may preserve multifunctional components and reduce

process burden but can result in greater compositional and sensory complexity. Scale-up should therefore be evaluated not only in terms of production capacity but also in terms of the ability to preserve structure, functionality, and material consistency while maintaining acceptable process intensity and economic feasibility [13-15].

This review examines microalgae-derived protein ingredients through an integrated processing-structure-property-performance framework. Particular attention is given to how cellular architecture determines processing requirements; how disruption, fractionation, concentration, and drying modify molecular and particulate structures; and how these transformations govern interfacial, rheological, thermal, hydration, and stability-related properties. The review also considers engineering challenges associated with scale-up and economic considerations related to process intensity, energy demand, ingredient yield, and co-product utilization. Through this framework, microalgal protein ingredients are treated not simply as alternative protein sources, but as engineered multicomponent materials whose performance emerges from the interaction between composition, structure, processing history, and application conditions.

2. METHOD

This study employed a narrative review approach to examine microalgae-derived protein ingredients from a materials-engineering perspective. Relevant peer-reviewed literature was identified using Google Scholar, focusing on studies related to cell architecture, protein processing, material structure, functional properties, scale-up, and economic considerations. The selected literature was synthesized using a processing-structure-property-performance framework. Particular attention was given to cell disruption, extraction, fractionation, concentration, drying, protein molecular state, particle characteristics, solubility, rheology, emulsification, gelation, dispersibility, and stability. Scale-up and economic aspects were also evaluated in relation to processing intensity, energy demand, ingredient recovery, process consistency, and co-product utilization.

3. RESULTS AND DISCUSSION

Microalgae-derived protein ingredients exhibit substantial variations in composition, cellular architecture, molecular organization, and processing response. These differences determine not only protein accessibility but also the structural and functional characteristics of the resulting materials. From a materials-engineering perspective, the performance of microalgal protein ingredients should therefore be interpreted based on the relationships among initial biomass structure, processing-induced transformations, measurable material properties, and final functionality. The following discussion examines these relationships from cellular and molecular characteristics to processing, scale-up, and economic considerations.

3.1. Material Composition and Cell Architecture of Microalgae-Derived Protein Ingredients

Microalgal biomass should be considered a hierarchical multicomponent material rather than a homogeneous protein source. Proteins coexist with cell-wall polymers, membranes, pigments, lipids, carbohydrates, minerals, and low-molecular-weight components, and their relative proportions vary among species, strains, and cultivation conditions. Consequently, total protein content alone is insufficient to predict processing behavior or final ingredient functionality [7, 9, 16]. The composition and material characteristics of representative microalgae are summarized in **Table 1**.

Table 1. Protein content, material characteristics, and processing relevance of microalgae.

MICROALGA/TAXON	PROTEIN CONTENT (% DRY WT)	KEY CHARACTERISTICS	MATERIAL	PROCESSING RELEVANCE	REF.
Spirulina biomass (<i>Arthrospira/Limnospira</i> spp.)	60-70	High protein content; relatively accessible cellular structure; phycocyanin-rich composition		Comparatively limited cell disruption can facilitate protein accessibility and utilization; suitable for whole-biomass and protein-enriched ingredients	[4, 16]
<i>Chlorella vulgaris</i>	45-60	Chlorophyll-rich biomass with a resistant cell envelope; protein accessibility depends strongly on cell disruption		Mechanical, enzymatic, or combined disruption can improve protein release, digestibility, and subsequent functional performance	[9, 13, 16]
<i>Aphanizomenon flos-aquae</i>	50-60	Protein-rich cyanobacterial biomass with composition dependent on biomass source		Variability in biomass composition requires control of raw-material characteristics and processing conditions	[17]
<i>Dunaliella salina</i>	20-30	Beta-carotene-rich, halotolerant biomass with moderate protein content and antioxidant components		Processing should preserve pigment-protein functionality while controlling compositional and oxidative changes	[18]
<i>Nannochloropsis</i> spp.	30-50	Protein associated with EPA-rich lipids; relatively resistant cellular structure		Cell disruption and fractionation are required to improve protein accessibility and regulate protein-lipid interactions	[19, 20]
<i>Scenedesmus/Desmodesmus</i> spp.	30-50	Robust freshwater biomass with relatively resistant cell structures		Processing intensity influences protein accessibility, particle disruption, and the amount of residual insoluble material	[21-23]
<i>Tetraselmis</i> spp.	30-40	Contains protein, starch, and bioactive polysaccharides; relatively large cells		Multicomponent composition can influence hydration, structural behavior, and functionality after processing	[24]
<i>Haematococcus pluvialis</i>	30-45	Astaxanthin-rich biomass with a thick cell wall; protein remains associated with pigment-rich fractions		Strong cell-wall resistance increases disruption requirements; protein recovery can be integrated with pigment fractionation	[25, 26]
Other taxa, including <i>Isochrysis</i> and <i>Phaeodactylum</i>	30-40	Proteins coexist with marine lipids, pigments, and other functional components		Processing and fractionation determine the balance among protein recovery, retention of associated compounds, and multifunctionality	[13, 16]

Note: Protein contents are approximate and vary with species, strain, cultivation conditions, and analytical method. “Spirulina” is used as the common commercial term, whereas *Arthrospira/Limnospira* is used where taxonomic precision is required.

Among the most widely investigated microalgae, *Spirulina* biomass generally contains approximately 60-70% protein on a dry-weight basis, whereas *Chlorella* commonly contains approximately 45-60%. Several marine and freshwater microalgae, including *Nannochloropsis*, *Scenedesmus*, *Desmodesmus*, and *Tetraselmis*, contain lower but still substantial protein fractions [2, 4, 16, 20]. However, these values vary considerably with strain, nutrient availability, cultivation conditions, and harvesting stage. Protein quality also differs among taxa because of variations in amino-acid composition and digestibility [7, 20]. Protein percentage should therefore be interpreted together with cellular architecture and biochemical composition rather than as an isolated indicator of material performance.

Cell-envelope architecture represents another important distinction among microalgal materials. *Spirulina* has a comparatively accessible cellular organization, whereas *Chlorella* and several other green microalgae possess more resistant cell envelopes that restrict protein accessibility [9-11]. Consequently, *Chlorella* commonly requires mechanical, chemical, enzymatic, or combined disruption treatments to improve intracellular protein release. Cell disruption is therefore not merely an extraction step; it is a material-transformation process that modifies cell integrity, particle-size distribution, exposed surface area, and the release of intracellular components. These structural changes directly influence downstream material behavior. Disruption can modify dispersibility, sedimentation tendency, surface characteristics, and solid-liquid separation requirements while simultaneously releasing proteins, pigments, lipids, and other intracellular components [5, 6, 10, 11]. The initial cellular architecture should therefore be regarded as an important material attribute governing both processing intensity and the structural state of the resulting ingredient.

Non-protein components are also integral to the resulting material structure. Pigments, polysaccharides, lipids, and minerals can contribute to antioxidant activity, color, hydration, water retention, and interfacial behavior, but may also increase sensory intensity, oxidation susceptibility, ash content, or variability in protein-protein interactions [4, 7, 12]. Greater purification does not therefore necessarily produce superior material functionality. Partially enriched protein fractions may retain useful protein-polysaccharide or protein-pigment interactions, whereas highly purified fractions may be preferred when neutral color, controlled gelation, or predictable interfacial behavior is required.

The combined contribution of protein and non-protein components to material functionality is illustrated in **Figure 1**. Proteins, pigments, lipids, carbohydrates, and micronutrients collectively determine the physicochemical characteristics of microalgae-derived ingredients. Their engineering value therefore arises from the interaction among composition, cellular architecture, and processing history rather than from protein concentration alone.

3.2. Processing-Induced Structural Transformation

Processing determines the structural state of microalgae-derived protein ingredients. Because microalgal cultures are generally dilute, harvesting and dewatering are required before protein recovery and can contribute substantially to process complexity and energy demand. Centrifugation, filtration, flocculation, and drying are widely applied, whereas wet-processing strategies are increasingly considered to reduce unnecessary thermal exposure and energy consumption [13, 15, 16].

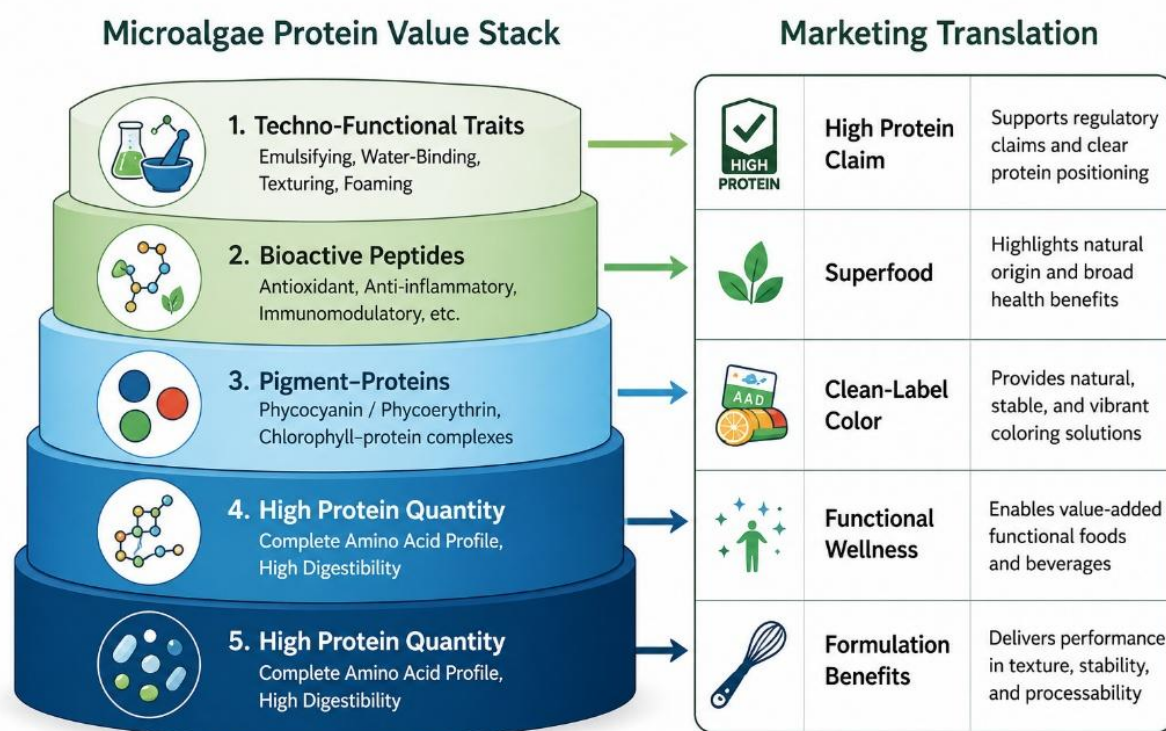


Figure 1. Conceptual relationship between microalgal biomass composition, material functionality, and application-related value.

Cell disruption is a critical material-transformation step because different methods impose different mechanical, thermal, and chemical stresses. Bead milling and high-pressure homogenization generate intense shear, impact, and particle fragmentation, whereas ultrasonication introduces cavitation. Enzymatic treatments and pulsed electric fields can increase cellular permeability with comparatively lower bulk thermal exposure [5, 6, 11]. The effectiveness of disruption should therefore not be evaluated only from the percentage of disrupted cells or recovered protein. Particle-size distribution, temperature rise, oxidation exposure, energy requirement, and the amount of insoluble debris generated during treatment are also important because they influence subsequent separation and functional performance.

Fractionation further modifies the composition and molecular organization of the recovered protein material. Aqueous extraction can retain interactions among proteins, pigments, polysaccharides, and lipids, whereas more intensive purification may selectively remove these components. Changes in pH and ionic conditions during extraction and precipitation can promote protein solubilization, unfolding, reassociation, or aggregation. Therefore, increasing protein purity may simultaneously alter hydration, interfacial activity, and redispersibility [5, 6, 8, 12].

Wet fractionation can reduce the structural changes associated with drying whole biomass before extraction. However, wet streams are generally dilute and remain sensitive to microbial deterioration, oxidation, pH changes, salts, and residual enzymatic activity. When drying is required, the drying route becomes a microstructure-forming operation. Spray drying can produce continuously processed powders but exposes droplets to thermal and interfacial stresses, whereas freeze drying can preserve relatively porous structures but

requires greater processing intensity and is more difficult to apply economically to bulk ingredients [8, 16]. Drying conditions consequently influence residual moisture, porosity, aggregation, rehydration behavior, color stability, and dispersibility.

The cumulative effects of harvesting, disruption, fractionation, concentration, drying, and quality control are summarized in **Figure 2**. These operations should be considered as interconnected engineering stages because structural changes generated at one stage can influence material behavior and processing requirements at subsequent stages. Processing intensity must therefore be optimized rather than simply maximized. Insufficient treatment may limit protein accessibility, whereas excessive mechanical, chemical, or thermal treatment can increase energy demand and promote aggregation, oxidation, loss of dispersibility, or deterioration of functional properties. The appropriate processing route depends on the initial cellular architecture and the structural and functional properties required in the final ingredient.

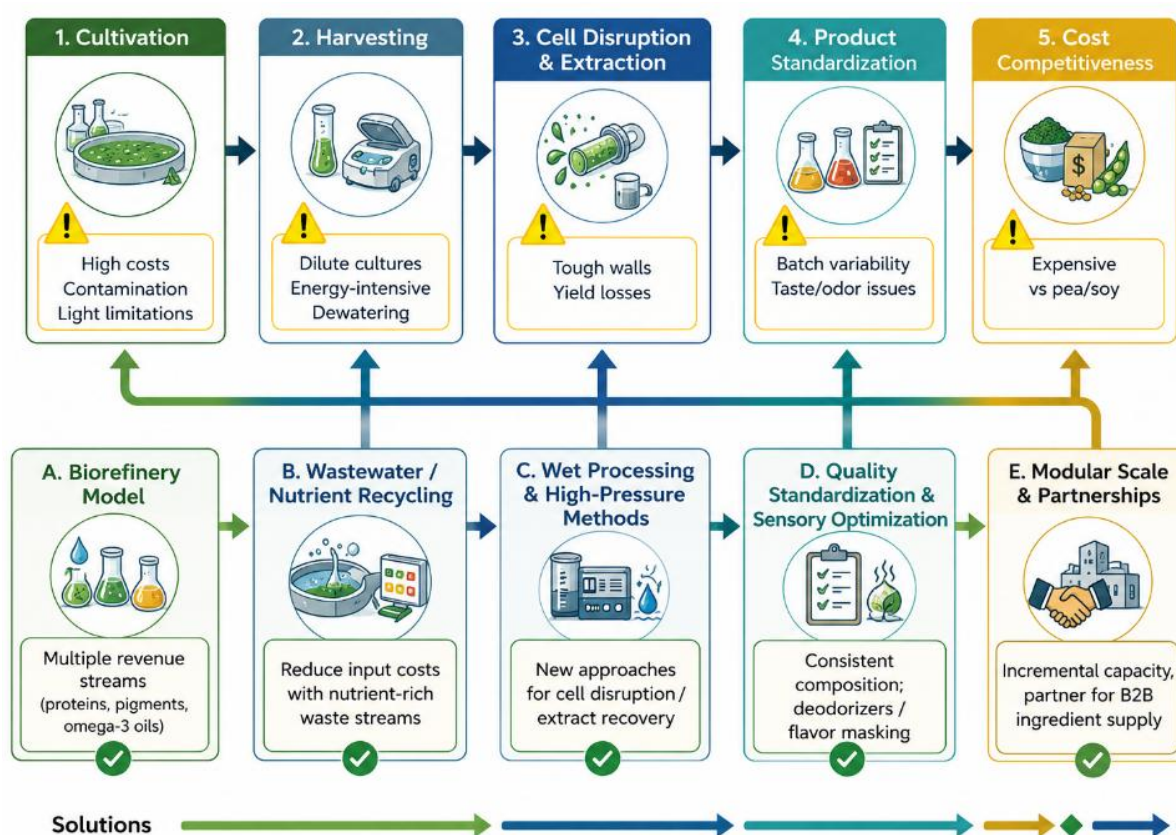


Figure 2. Processing and engineering bottlenecks governing the transformation of microalgal biomass into reproducible protein ingredients.

3.3. Processing-Structure-Property-Performance Relationships

A materials-engineering interpretation requires each processing operation to be linked with the resulting structure and the measurable properties governing final performance. Cultivation establishes the initial biochemical composition and cellular architecture, while disruption and fractionation transform the biomass into whole-cell materials, protein concentrates, isolates, or multifunctional pigment-protein fractions. These ingredient forms

differ in composition, particle organization, molecular state, and interactions among proteins and non-protein components. The main relationships among ingredient form, material structure, processing, functional performance, and engineering limitations are summarized in **Table 2**. The table emphasizes that increased purification does not necessarily produce improved functionality because each additional processing step may modify protein structure, remove interacting components, reduce yield, or increase process burden.

Table 2. Processing-structure-property-performance relationships of microalgae-derived protein ingredients.

INGREDIENT FORM	MATERIAL STRUCTURE	KEY PROCESSING	FUNCTIONAL PERFORMANCE	MAIN ENGINEERING CONSTRAINT
Whole biomass	Intact or partially disrupted cells containing proteins, pigments, lipids, minerals, and cell-wall polymers	Harvesting, washing, stabilization, drying or wet preservation, and disruption when required	Nutrition, water binding, texture, color, and multifunctional activity	Variable digestibility, strong color or flavor, compositional variability, and limited protein accessibility
Protein concentrate	Partially enriched protein fraction containing residual pigments, lipids, and polysaccharides	Cell disruption, aqueous extraction, solid-liquid separation, and concentration	Increased protein density with water-holding and emulsifying functionality	Yield-purity trade-off, fouling, residual non-protein components, and sensory carry-over
Protein isolate	Highly enriched protein fraction with reduced non-protein solids	Selective solubilization, clarification, membrane separation or precipitation, and drying	More controlled solubility, interfacial behavior, gelation, and formulation performance	Higher processing intensity, aggregation risk, yield loss, and increased energy and separation requirements
Pigment-protein or co-product fraction	Protein associated with pigments, lipids, or other functional compounds	Integrated fractionation, concentration, and stabilization against pH, light, oxygen, and temperature	Combined protein, color, antioxidant, or interfacial functionality	Stability control, selective separation, process complexity, and application-specific specification

Whole biomass requires comparatively limited fractionation but retains the greatest structural and compositional complexity. Protein concentrates provide an intermediate state in which protein is enriched while some pigments, polysaccharides, and lipids remain associated with the material. These residual components can either support functionality or interfere with formulation, depending on the intended application. Protein isolates provide greater compositional control but require more intensive separation and may undergo structural changes during solubilization, precipitation, concentration, and drying.

The effect of material structure is strongly application dependent. In oil-in-water emulsions, proteins must migrate toward newly formed interfaces, adsorb, undergo sufficient conformational rearrangement, and form a protective interfacial layer. Solubility, surface

charge, molecular flexibility, and aggregation state therefore affect emulsion formation and stability [12, 13]. In gels and structured foods, hydration, intermolecular interactions, thermal transitions, and protein-polysaccharide compatibility become more important. In beverages, high solubility, small particle size, suitable surface charge, and resistance to sedimentation may be more important than high gel strength. Consequently, functional testing must be conducted under application-relevant pH, ionic strength, temperature, concentration, and processing conditions.

Membrane-assisted concentration further illustrates the importance of connecting processing with material state. Soluble proteins, protein-polysaccharide complexes, pigment assemblies, lipids, and cell fragments can interact differently with membrane surfaces and pores. Consequently, nominal molecular-weight cut-off alone cannot predict protein recovery. Transmembrane pressure, shear conditions, concentration polarization, fouling, pH, ionic strength, and cleaning conditions can influence both separation performance and the structural stability of the recovered ingredient. Scale-up assessment should therefore consider protein recovery, purity, flux decline, cleaning recovery, and changes in material functionality rather than initial membrane flux alone. Selectivity, fouling, cleanability, chemical compatibility, and long-term stability are therefore important engineering considerations in membrane-assisted protein concentration.

Precipitation and drying produce additional structural transformations. Isoelectric precipitation can improve protein enrichment but may generate dense aggregates with limited redispersibility. Spray drying provides continuous powder production but introduces thermal and interfacial stresses, whereas freeze drying can retain a more porous structure at substantially greater processing burden [8, 12]. Therefore, selection of a processing route should consider retained functional performance together with recovery, energy demand, and process intensity.

A minimum characterization framework is required to determine whether processing has improved or deteriorated the resulting material. The relevant material scales, properties, measurements, and design implications are summarized in **Table 3**.

3.4. Scale-Up, Process Integration, and Economic Considerations

The transition from laboratory-scale protein recovery to industrial production requires simultaneous control of material functionality, process consistency, energy demand, and production cost. Cultivation, harvesting, cell disruption, fractionation, concentration, and drying contribute cumulatively to the processing burden. Scale-up can also amplify variations in light availability, carbon dioxide transfer, mixing, temperature, contamination, and biomass composition, thereby affecting both protein yield and the structural characteristics of the resulting ingredient [13-15].

Processing intensity represents a central engineering and economic trade-off. Stronger disruption can increase protein accessibility but may require greater energy input and generate smaller cell fragments that complicate downstream clarification. Additional purification can increase protein concentration but may reduce overall yield and remove pigments, lipids, or polysaccharides that contribute to material functionality. Similarly, drying improves storage stability and handling but introduces additional energy demand and can alter protein aggregation, powder porosity, rehydration, and dispersibility [5, 6, 8].

Table 3. Material characterization framework for microalgae-derived protein ingredients.

MATERIAL SCALE	PRIORITY ATTRIBUTES	REPRESENTATIVE MEASUREMENTS	DESIGN RELEVANCE
Composition	Protein, pigments, lipids, carbohydrates, ash, moisture, and contaminants	Compositional analysis, amino-acid profile, moisture or water activity, and contaminant analysis	Defines composition, purity, safety, and the contribution of non-protein components
Cell and particle structure	Cell integrity, fragment size, morphology, porosity, and aggregation	Microscopy, particle-size distribution, bulk density, and dispersibility	Links disruption and drying conditions with protein accessibility, sedimentation, rehydration, and powder handling
Protein molecular state	Solubility, conformation, aggregation, surface hydrophobicity, and thermal transitions	Solubility-pH profile, electrophoresis, spectroscopy, differential scanning calorimetry, and turbidity	Identifies processing-induced molecular changes controlling hydration, gelation, and interfacial activity
Colloidal and interfacial behavior	Surface charge, emulsion formation, droplet stability, and foam behavior	Zeta potential, emulsion capacity, droplet-size evolution, interfacial measurements, and creaming index	Predicts dispersion and interfacial stability under application-relevant conditions
Bulk functionality	Water and oil binding, viscosity, viscoelasticity, gel strength, and texture	Holding-capacity tests, flow curves, oscillatory rheology, texture analysis, and thermal processing tests	Connects material structure with processability, water retention, texture, and structural stability
Stability and sensory expression	Color, aroma, oxidation, sedimentation, moisture uptake, and storage-induced changes	Colorimetry, volatile analysis, oxidation markers, accelerated storage, sensory analysis, and moisture-sorption testing	Determines whether functional properties remain stable during storage and application

Note: Measurements should be conducted under application-relevant pH, ionic strength, temperature, concentration, and storage conditions. Selection of analytical methods should be based on the intended material function and processing route.

Process integration can partly offset these limitations. A biorefinery approach allows proteins to be recovered together with pigments, omega-3-rich lipids, antioxidants, or other valuable fractions, thereby distributing cultivation and downstream-processing costs across several products [14, 20, 26]. Residual biomass can also be directed toward feed or other applications when its quality is appropriate. Studies combining protein and oil production indicate that co-product utilization can improve economic performance compared with single-product processing [19, 21]. The principal engineering and economic trade-offs associated with major processing stages are summarized in **Table 4**.

The economic relevance of energy efficiency is illustrated in **Figure 3**. Algal fuel-and-feed co-products exhibited an energy return on investment of approximately 1.2, whereas algal aquafeed was approximately 0.7. These values demonstrate that process configuration and co-product utilization influence the energetic boundary of microalgal production [19].

Economic interpretation should nevertheless extend beyond energy return alone. Process feasibility depends on biomass productivity, recovery yield, separation intensity, product specification, energy and material consumption, and the value assigned to co-products. Thus, the economically preferable route is not necessarily the route that produces the highest protein purity. A less extensively purified concentrate may provide better overall process efficiency when its material functionality is sufficient for the intended application.

Table 4. Engineering and economic considerations for major processing stages in microalgae-derived protein production.

PROCESSING STAGE	MAIN MATERIAL EFFECT	POTENTIAL BENEFIT	ENGINEERING LIMITATION	ECONOMIC CONSIDERATION
Harvesting and dewatering	Increases biomass concentration and modifies particle aggregation	Reduces downstream liquid volume	Dilute cultures require substantial separation capacity	Energy and equipment requirements increase with processed water volume
Mechanical disruption	Breaks cellular structures and reduces particle size	Improves intracellular protein accessibility	High shear, heat generation, fine debris, and equipment wear	Higher disruption intensity increases energy demand
Enzymatic disruption	Increases cell-wall permeability with relatively mild mechanical stress	Can preserve protein functionality	Enzyme activity depends on pH, temperature, and biomass composition	Enzyme cost and treatment time must be considered
Aqueous extraction and fractionation	Changes protein solubilization and interactions with non-protein components	Improves protein recovery and enrichment	Requires solid-liquid separation and process-water management	Greater fractionation intensity increases processing cost and may reduce yield
Membrane concentration	Selectively concentrates soluble or colloidal fractions	Reduces water content while avoiding severe thermal exposure	Fouling, concentration polarization, cleaning, and flux decline	Membrane replacement, pumping, and cleaning contribute to operating cost
Precipitation	Promotes protein separation and enrichment	Can increase protein concentration	Aggregation and reduced redispersibility may occur	Chemicals, neutralization, recovery loss, and wastewater treatment add cost
Spray drying	Produces stable powders in continuous operation	Facilitates storage, transportation, and formulation	Thermal and interfacial stresses can alter structure and dispersibility	Energy demand becomes important at high water-removal loads
Freeze drying	Produces porous structures with relatively mild thermal exposure	Can preserve rehydration and structural characteristics	Long processing time and limited throughput	High energy and equipment costs restrict bulk application
Integrated biorefinery	Separates proteins together with pigments, lipids, or other co-products	Improves resource utilization and product diversification	Requires coordinated separation and quality control	Co-product value can distribute processing costs across multiple product streams

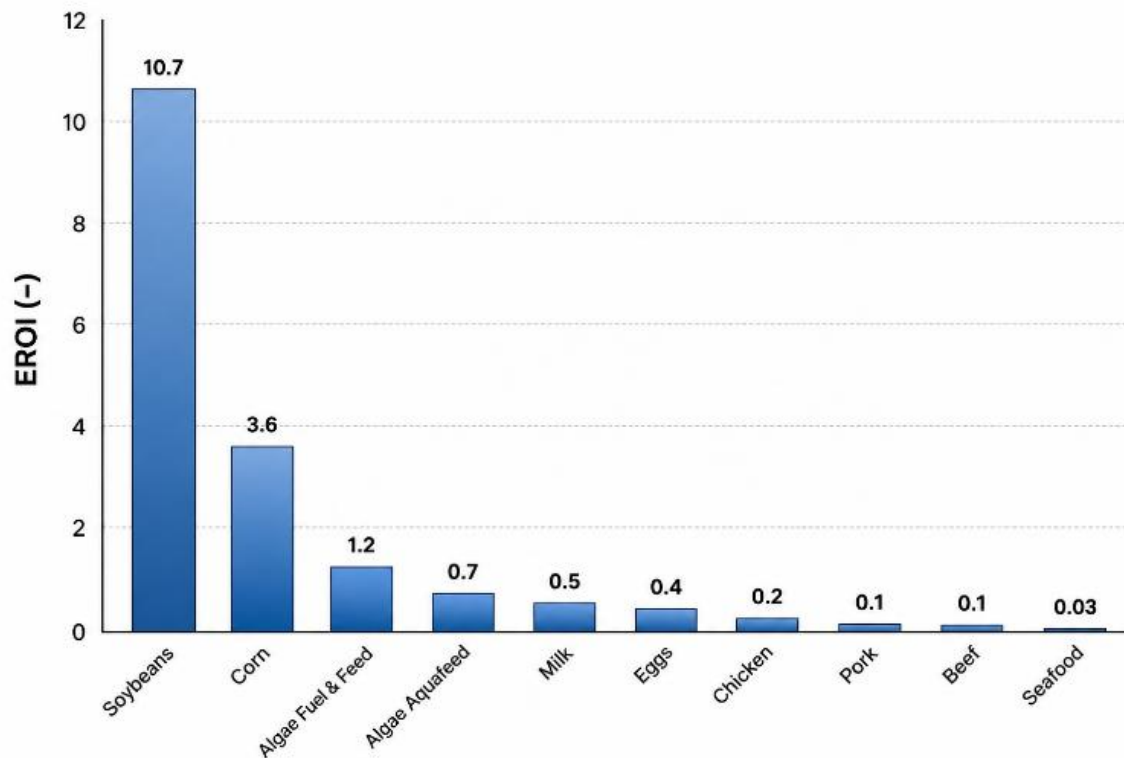


Figure 3. Energy return on investment (EROI) comparison for algal fuel-and-feed products, algal aquafeed, and conventional food/feed proteins. The figure was reproduced from reference [19].

Consistency is equally important during scale-up. Species or strain, cultivation conditions, harvest age, washing, disruption intensity, concentration factor, and drying history can introduce batch-to-batch variation in composition and functional behavior. These factors should therefore be treated as critical material and process attributes. Material specifications should combine identity parameters, such as composition, moisture, contaminants, and color, with performance parameters, including particle size, solubility, rheology, emulsification, gelation, and stability under relevant processing conditions [9, 16].

3.5. Application Performance, Commercialization, and Future Design

The commercial potential of microalgae-derived protein ingredients ultimately depends on the compatibility between their material properties and the requirements of the intended food matrix. Whole biomass, protein concentrates, isolates, and pigment-protein fractions differ in composition, particle structure, molecular state, color, flavor, and processing tolerance. They should therefore be treated as distinct material forms requiring application-specific specifications.

Material performance must also satisfy safety and regulatory requirements. Food-grade ingredients require control of contaminants, microbiological quality, moisture, composition, and batch-to-batch variability [9, 13, 26]. Processing history is equally important because disruption, fractionation, concentration, and drying can modify both ingredient identity and functionality. The relationship among safety assurance, regulatory acceptance, and product adoption is illustrated in **Figure 4**.



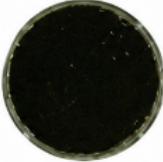
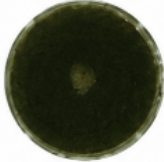
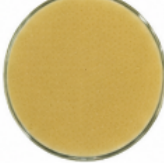
Figure 4. Trust pathway from safety assurance to consumer acceptance of microalgae-based protein products.

Sensory characteristics are closely related to material composition and processing. Pigments, lipids, volatile compounds, minerals, and residual cellular materials influence color, aroma, flavor, and texture. Fractionation, deodorization, processing conditions, and inclusion level can therefore be used to control these characteristics. Spirulina-containing smoothies provide an example in which formulation, high-pressure processing, and storage influenced product appearance, as shown in **Table 5**.

The effects of formulation and storage were also reflected in the sensory profiles presented in **Figure 5**. **Panel (a)** compares the sensory attributes of the control (C), chickpea protein concentrate (PC), Spirulina (S), and combined PC-S formulations, whereas **panel (b)** compares the overall sensory profiles at day 0 and day 21. These results demonstrate that ingredient composition and storage can influence multiple sensory attributes simultaneously and should therefore be considered together with physicochemical material properties when evaluating application performance.

Application requirements differ among food systems. Beverages prioritize dispersibility, limited sedimentation, and color stability; bakery products require hydration and thermal stability; emulsified foods depend on interfacial activity; and structured foods require suitable rheology and gelation. Consequently, no single microalgal protein ingredient can provide optimum performance in all food matrices.

Table 5. Visual appearance of smoothie formulations containing wet Spirulina and/or chickpea protein concentrate before and after HPP and 21-day storage. The table was reproduced from reference [27].

Time (days)	Treatment	C	PC	S	PC-S
0	NT				
0	HPP				
21	NT				
21	HPP				

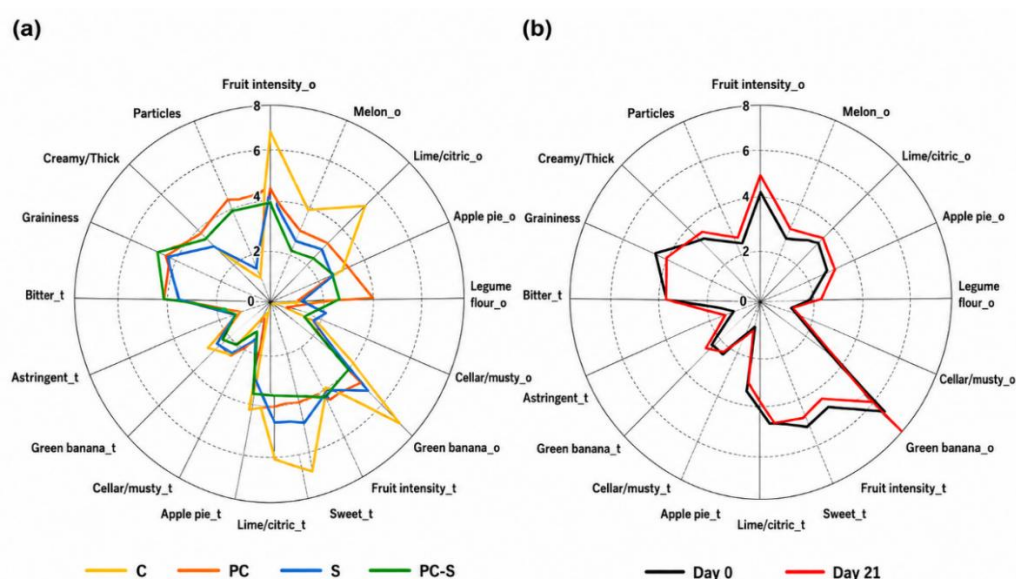


Figure 5. Sensory profiles of smoothie formulations as affected by formulation and storage time: (a) comparison among control (C), chickpea protein concentrate (PC), Spirulina (S), and combined chickpea protein concentrate-Spirulina (PC-S) formulations; and (b) comparison of sensory profiles at day 0 and day 21 of storage. The table was reproduced from reference [27].

These material requirements directly influence commercialization. Whole biomass requires less processing but retains greater compositional and sensory complexity. Concentrates can provide a compromise between protein enrichment, functionality, recovery, and cost, whereas isolates require more intensive separation but can offer greater formulation flexibility. Multifunctional pigment-protein fractions may provide additional economic value when protein functionality is combined with color, antioxidant activity, or other co-product functions.

The transition toward broader applications therefore requires improvements in material consistency, processing efficiency, sensory compatibility, and production economics, as illustrated in **Figure 6**.

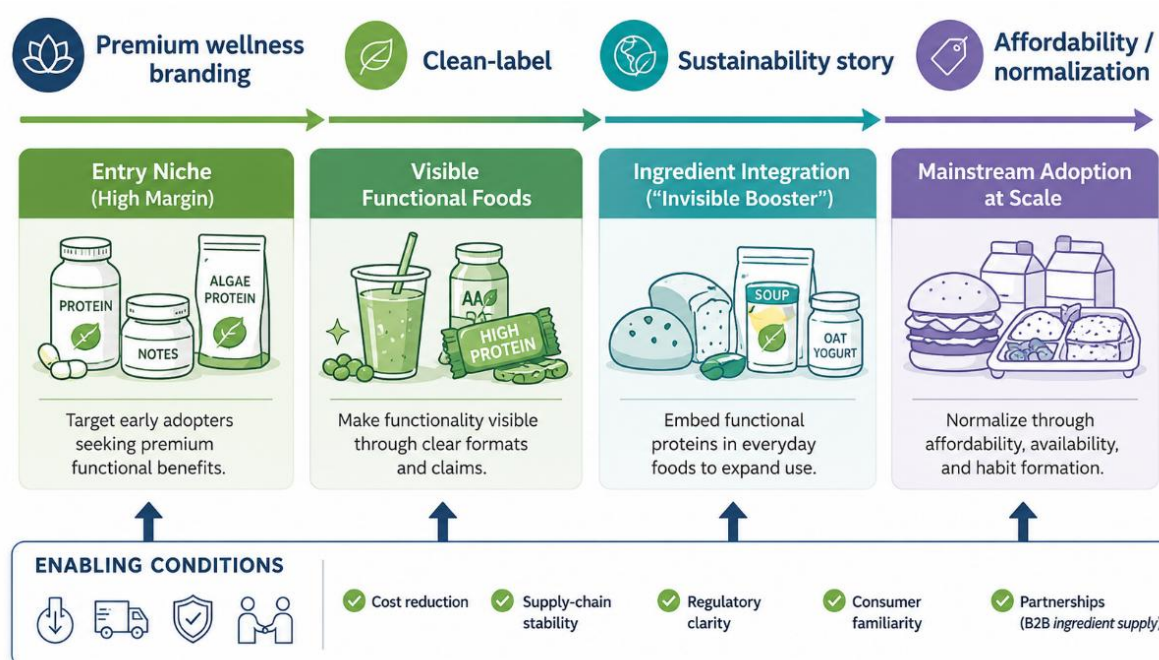


Figure 6. Staged market-entry pathway for microalgae-based proteins across premium, ingredient, and mainstream applications.

Future development should integrate materials engineering with economic considerations. Controlled disruption, mild fractionation, energy-efficient concentration and drying, improved dispersibility, and reproducible functionality can reduce processing burden while maintaining ingredient performance. Biorefinery strategies can further improve economic feasibility by integrating protein recovery with pigments, lipids, antioxidants, and other co-products. Commercialization will therefore depend on achieving an appropriate balance among material functionality, process scalability, sensory performance, product value, and production cost.

4. CONCLUSION

Microalgae-derived protein ingredients should be developed as application-specific engineered materials. Their performance depends on cellular architecture, composition, molecular state, particle structure, and processing history. Cell disruption, fractionation, concentration, and drying must therefore balance protein recovery and purity with solubility, dispersibility, interfacial activity, rheology, and stability. Scale-up further requires consistent specifications, controlled processing intensity, and acceptable energy demand. Economic

feasibility is strengthened when processing costs are distributed through biorefinery strategies and valuable co-products. Commercialization will depend on matching material functionality, sensory quality, regulatory requirements, scalability, and cost with appropriate food applications and market positions under realistic industrial production and storage conditions.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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