



Marine - derived nutraceuticals: Bioactive peptides, polysaccharides, lipids and polyphenols—mechanisms, bioavailability, health applications and translational perspectives

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DOI: <https://doi.org/10.66856/ijfsn.2026.11.4.11177>

Abstract

Marine-derived nutraceuticals have arisen as promising sources of biologically active compounds with potential applications in preventive nutrition and health promotion. Marine organisms such as fish, crustaceans, mollusks, macroalgae and microalgae provide a range of bioactive peptides, polysaccharides, lipids and polyphenols with antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, cardiometabolic and neuroprotective activities. This review summarizes the major classes of marine-derived nutraceuticals, their molecular and cellular mechanisms, gastrointestinal fate, bioaccessibility and bioavailability, and their relevance to human health. The biological pathways through which marine peptides, polysaccharides, omega-3 lipids, phlorotannins, carotenoids and related compounds may modulate oxidative stress, inflammatory signaling, lipid metabolism, intestinal function and immune regulation are given special emphasis. The review also deals with the influence of source, extraction, processing, chemical structure, food matrix and digestion on nutraceutical activity and bioavailability. Emerging delivery approaches including encapsulation, nanoemulsions, liposomal systems and other advanced formulations for improving stability and biological availability are discussed. *In vitro*, animal, and human studies are critically reviewed to distinguish mechanistic potential from clinical proven benefits. Also discussed are safety issues such as contaminants, allergenicity, compositional variability and regulatory issues. Finally, the opportunities related to sustainable use of marine biomass, valorization of by-products, precision nutrition and advanced biotechnology are highlighted. Increased standardization of bioactive characterization, dosage, preparation, safety assessment and clinical endpoints will be essential for the transition of marine-derived nutraceuticals from experimental investigation to reliable, evidence-based health applications.

Keywords: Bioactive peptides, marine nutraceuticals, marine polysaccharides, omega-3 lipids, polyphenols, bioavailability

Introduction

Growing interest in naturally derived compounds that can support physiological functions beyond basic nutrition has come about due to increasing emphasis on preventive nutrition and sustainable health. Fish, crustaceans, mollusks, macroalgae, microalgae and other marine resources are an extremely diverse repository of such bioactive components from marine organisms. Marine nutraceuticals are a class of structurally diverse compounds, particularly bioactive peptides, polysaccharides, lipids and polyphenols, that have been shown to possess antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, cardiometabolic and neuroprotective activities. Their biological activity is related to their interaction with cellular signaling pathways, oxidative stress responses, inflammatory mediators, lipid metabolism and intestinal processes. But biological activity demonstrated under experimental conditions does not necessarily translate to similar effects in humans.

The nutraceutical potential of marine bioactives is strongly dependent on the source, molecular composition, extraction and processing conditions, food matrix, gastrointestinal transformation, bioaccessibility and systemic bioavailability. These factors can considerably modify the amount and form of bioactive compounds that reach their physiological target. Therefore, understanding the marine bioactive composition, biological mechanisms and bioavailability is important for meaningful nutritional and

health applications. Contaminant exposure, compositional variability, standardization, safety, regulatory acceptance and sustainable resource allocation issues also continue to be significant barriers to broader translation. Therefore, this review covers the main marine-derived nutraceutical classes, their mechanisms of action and bioavailability, health applications, emerging delivery strategies and translational challenges, highlighting future opportunities for their development as evidence-based and sustainable health-promoting ingredients.

Review Methodology and Evidence-Synthesis Approach

A systematic narrative review approach was applied to critically synthesize recent evidence on marine-derived nutraceuticals, with a focus on bioactive peptides, polysaccharides, lipids, and polyphenols, including their molecular mechanisms, bioavailability, health applications, delivery strategies, safety, and translational potential. Considering the recent developments in the area of marine nutraceutical research, only literature from January 2021 to September 2026 was considered. We searched PubMed/MEDLINE, Scopus, Web of Science and ScienceDirect and also screened the reference lists of relevant review articles and key publications. Search terms were developed using combinations of marine nutraceuticals, marine bioactives, bioactive peptides, marine polysaccharides, fucoidan, alginate, chitosan, marine lipids,

omega-3 fatty acids, EPA, DHA, marine polyphenols, phlorotannins, fucoxanthin, astaxanthin, bioavailability, bioaccessibility, gut microbiota, molecular mechanisms, clinical trials, functional foods, nutraceutical delivery, safety and sustainability.

Eligible studies studied marine-derived bioactive compounds with known chemical or biological characterization and provided information regarding biological activity, mechanisms of action, gastrointestinal fate, bioavailability, health outcomes, formulation, safety or translational relevance. Priority was given to peer-reviewed primary research, human studies, reviews and systematic reviews of good quality and recent (2021-2026). Studies lacking sufficient information regarding the marine source or bioactive component, non-peer-reviewed materials, conference abstracts, duplicate publications and studies unrelated to nutraceutical applications were excluded.

The evidence was screened and organized according to marine source, bioactive class, molecular mechanism, experimental model, health outcome and level of evidence. Findings were subsequently synthesized thematically rather than quantitatively because of substantial heterogeneity in marine species, extraction procedures, compound composition, doses, delivery matrices, experimental models and clinical endpoints. Evidence was therefore interpreted separately across *in vitro*, animal, observational and controlled human studies, with greater emphasis placed on well-characterized preparations and clinically relevant evidence. The review also examined bioavailability, formulation and safety to differentiate between documented biological effects and mechanistic or preclinical potential. The overall reporting structure was informed by the principles of PRISMA 2020 to improve transparency in literature identification, screening and evidence synthesis.

Marine-Derived Nutraceuticals: Sources, Diversity and Bioactive Potential

Marine environments are an extremely diverse reservoir of nutritionally and biologically active constituents of increasing relevance to nutraceutical science. Marine-derived nutraceuticals are derived from fish, crustaceans, mollusks, echinoderms, macroalgae, microalgae and marine micro-organisms, as well as from processing by-products of the seafood industry. They are chemically made up of peptides and proteins, polysaccharides, long-chain polyunsaturated fatty acids, phospholipids, carotenoids and polyphenolic compounds with different structures and biological activities. The increasing interest in these compounds is motivated not only by their potential contribution to health promotion but also by the opportunity to valorize marine biomass and processing residues within a circular bioeconomy ^[1].

Marine-derived bioactive peptides are of special interest because enzymatic hydrolysis can release short peptides with antioxidant, antihypertensive, antimicrobial, anti-inflammatory, antidiabetic and immunomodulatory properties. Their activity, is greatly associated with amino-acid composition, sequence, molecular size, hydrophobicity and structural conformation ^[2, 3]. Marine polysaccharides such as fucoidan, alginate, laminarin, carrageenan, chitosan and glycosaminoglycans possess physicochemical functionality and biological activity, and the reported effects include oxidative balance, inflammation, intestinal microbiota and metabolic regulation ^[4, 5].

Marine lipids are dominated by nutritionally important omega-3 fatty acids such as eicosapentaenoic acid and docosahexaenoic acid, in addition to phospholipids and other specialized lipid classes. They are biologically relevant for the regulation of the cardiovascular system, inflammation and the nervous system ^[6]. Marine polyphenols and pigments, particularly phlorotannins, fucoxanthin and associated carotenoids, provide further antioxidant and signaling activities ^[7, 8].

Table 1: Major classes of marine-derived nutraceuticals and their biological relevance

Marine nutraceutical class	Representative sources, bioactives and biological relevance
Bioactive peptides	Sources: Fish, molluscs, crustaceans, marine algae and seafood-processing by-products. Examples: Collagen peptides, ACE-inhibitory peptides and antioxidant peptides. Activities: Antioxidant, antihypertensive, anti-inflammatory, antimicrobial and metabolic regulation.
Marine polysaccharides	Sources: Brown, red and green algae, crustaceans and marine invertebrates. Examples: Fucoidan, alginate, laminarin, carrageenan, chitosan and chitoooligosaccharides. Activities: Immunomodulatory, antioxidant, anti-inflammatory, gut-microbiota modulation and metabolic effects.
Marine lipids	Sources: Fatty fish, fish oils, microalgae and marine microorganisms. Examples: EPA, DHA, DPA and marine phospholipids. Activities: Cardiovascular protection, inflammatory regulation, neurological function and lipid metabolism.
Marine polyphenols	Sources: Mainly macroalgae. Examples: Phlorotannins and other phenolic compounds. Activities: Antioxidant, anti-inflammatory, antimicrobial and metabolic effects.
Marine carotenoids/pigments	Sources: Microalgae, macroalgae and marine animals. Examples: Fucoxanthin and astaxanthin. Activities: Antioxidant, anti-inflammatory, metabolic and neuroprotective effects.
Marine collagen-derived ingredients	Sources: Fish skin, scales, bones and connective tissues. Examples: Collagen hydrolysates and collagen peptides. Activities: Antioxidant, tissue-supporting and potential metabolic activities.
Chitin/chitosan derivatives	Sources: Crustacean shells and other marine exoskeletal materials. Examples: Chitosan and chitoooligosaccharides. Activities: Antioxidant, antimicrobial, lipid-interaction and gastrointestinal effects.

Footnote: Biological activities represent reported experimental or clinical effects and should not be interpreted as established therapeutic efficacy. Activity may vary according to marine species, geographical origin, molecular structure, extraction and processing conditions, dose and delivery matrix.

Source: Adapted and synthesized from Sridhar *et al.* (2021), Cunha and Pintado (2022), Ou *et al.* (2022), Chi and Wang (2023), Falch (2023), Carrasqueira *et al.* (2025) and Cadar *et al.* (2025).

Major Classes of Marine-Derived Nutraceuticals and Their Mechanisms of Action

1. Marine Bioactive Peptides

Peptide sequences encrypted in fish, mollusks, crustaceans, algae and seafood-processing by-products can be released upon enzymatic hydrolysis, fermentation and other processing techniques. The peptides resulting may have activities not present in the parent proteins. Recent reviews highlight the close relationship between the biological properties of marine peptides and the molecular size, amino-acid composition, sequence, hydrophobicity and terminal residues, forming important structure–activity relationships [9, 10].

One of the most frequently reported properties is antioxidant activity. Marine peptides can directly scavenge reactive oxygen species, chelate pro-oxidant metals or stimulate endogenous antioxidant systems. Peptides from red algae, fish and marine invertebrates have been shown to protect against experimentally induced oxidative damage, but much of the evidence is still based on cellular or animal models [11, 12].

Another extensively studied function is antihypertensive activity. Some of the marine peptides can inhibit angiotensin converting enzyme and may influence the renin-angiotensin system. Peptides derived from mussel and tuna proteins have been shown to possess ACE-inhibitory activity and their sequences have been identified by purification, molecular docking and cellular validation [13, 14]. These findings support the potential of marine peptides as nutraceutical ingredients for targeting cardiovascular risk factors. However, experimentally observed enzyme inhibition should not be automatically interpreted as clinically meaningful blood pressure reduction.

Marine peptides also have effects on glucose and lipid metabolism. Selected peptides have been shown experimentally to affect pathways involving AMP-activated protein kinase, oxidative-stress responses and inflammatory mediators. For example, monkfish peptides have been investigated in models of diet-induced hepatic steatosis, where effects were related to lipid metabolism, Nrf2-related antioxidant responses and inflammatory regulation [15]. The evidence therefore points to multifunctionality but dose equivalence, digestion and peptide absorption are still important barriers to translation.

2. Marine Origin Polysaccharides

Marine polysaccharides are a structurally diverse group of compounds, mainly obtained from algae and marine animals. Important examples are fucoidan, alginate, laminarin, carrageenan, agar, chitosan, chitooligosaccharides, glycosaminoglycans and marine exopolysaccharides. Their activity is affected by molecular weight, monosaccharide composition, branching, degree and position of sulfation, conformation and extraction conditions [4, 5].

One of the most interesting mechanisms is the interaction with the intestinal environment. Marine polysaccharides can be partially degraded or fermented by microbial fermentation. They can affect microbial composition, microbial metabolites, and epithelial-barrier function. Their possible prebiotic-like effects have been linked to the modulation of dysbiosis, short chain fatty-acid production and intestinal inflammatory responses [4]. The effects of

marine animal polysaccharides on obesity, lipid metabolism, glucose regulation and inflammation have also been studied. Particular attention has been devoted to fucoidan and related sulfated polysaccharides, as the sulfate groups and the molecular architecture can influence the interactions with proteins, receptors and cellular signaling systems. However, comparison across studies is hampered by structural heterogeneity. This is because the two fucoidan preparations from different species have different molecular weights, sulfation, and monosaccharide compositions. Thus, biological effects should not be automatically generalized to all fucoidan preparations.

3. Lipids of Marine Origin

Marine lipids include triacylglycerols, phospholipids, sterols, glycolipids and long-chain polyunsaturated fatty acids. DPA and marine phospholipids are other components of interest, but the most prominent nutraceutical lipids are still EPA and DHA [6]. Their biological effects relate to membrane composition, production of lipid mediators, inflammatory signaling, cardiovascular physiology and neurological function.

The chemical form and food matrix influence the nutritional significance of marine omega-3 fatty acids. EPA and DHA may be present as triglycerides, ethyl esters or phospholipids, and these forms may differ in their digestion, absorption and incorporation into tissues. Marine phospholipids, in particular, have attracted attention due to their amphiphilic structure which could affect transport and tissue availability. Hence, the term “omega-3” should not be regarded as adequate to describe nutraceutical functionality without specifying molecular form, dose and source.

Marine lipids are also a technological challenge. They are prone to oxidation during extraction, processing and storage due to their high degree of unsaturation. Oxidation can create unwanted compounds and decrease nutritional quality. Marine oils incorporated in nutraceutical products need stabilization, antioxidant protection, controlled processing and encapsulation.

4. Marine Polyphenols and Pigments

Marine polyphenols are mainly related to the macroalgae and comprise phlorotannins and other phenolic structures. They are reported to have antioxidant, anti-inflammatory, antimicrobial and cardioprotective activities. The differences in activity between the extracts and purified compounds may be partly due to structural features such as the degree of polymerization that affect their interaction with biological targets [7].

Fucoxanthin is another important marine derived nutraceutical due to its unique carotenoid structure and wide pre-clinical activity. Studies have investigated antioxidant, anti-inflammatory, metabolic, neuroprotective and anti-obesity effects. However, fucoxanthin is poorly soluble in water and is unstable during passage through the gastrointestinal tract, which could affect its efficient bioavailability [8, 17].

Other carotenoids in the marine environment like astaxanthin also show antioxidant and anti-inflammatory activity. However, their biological importance depends on their absorption, metabolism, tissue distribution and dose. Therefore, mechanistic evidence should be considered along with pharmacokinetic and human intervention data, rather

than interpreted in isolation by means of cellular antioxidant assays.

Advanced Delivery of Marine Nutraceuticals Bioavailability and Health Applications

1. Gastrointestinal Fate and Bioavailability

The efficacy of a nutraceutical is not determined by biological activity alone. Marine bioactives are exposed to a complex gastrointestinal environment after oral intake that involves changes in pH, digestive enzymes, bile salts, interactions with the food matrix, microbial transformation and epithelial transport. Thus, the concentration of a compound given via the oral route may be quite different from that at the biological target.

Marine peptides might be largely hydrolyzed in the gastrointestinal tract. Some short peptides may survive digestion or produce bioactive fragments during digestion, while others may lose activity prior to absorption. The physiological relevance of an identified peptide thus depends on the intact sequence or an active digestion product to reach the target site. Studies on marine peptides

are progressively focusing on simulated gastrointestinal digestion, transport models and bioavailability, rather than just pre-digestion activity assays [3, 16].

Polysaccharides are another bioavailability problem. High molecular weight structures may not be systemically absorbed but can exert their biological effects locally in the gastrointestinal tract or in microbial transformation. This is especially true for fucoidan, alginate, laminarin and other complex polysaccharides. Their health effects may therefore be related to interactions with gut microbes and microbial metabolites rather than conventional systemic absorption [4] Li *et al.*, 2024).

Marine polyphenols and carotenoids are also characterized by low solubility, instability and extensive metabolism. Fucoxanthin is a very clear example of this problem. Encapsulation and targeted delivery approaches have attracted attention because of its gastrointestinal transformation and low oral bioavailability [17]. Recent work has also emphasized digestion, biotransformation, microbiome interactions and targeted delivery as critical determinants of fucoxanthin efficacy [18].

Table 2: Bioavailability barriers and delivery strategies for marine-derived nutraceuticals

Nutraceutical	Bioavailability challenge and potential delivery approach
Bioactive peptides	Gastrointestinal enzymatic degradation and variable intestinal absorption may reduce activity. Encapsulation, protective protein/polysaccharide carriers and controlled-release systems may improve stability and delivery.
Marine polysaccharides	High molecular weight and structural heterogeneity can restrict absorption. Their activity may occur through intestinal or microbiota-mediated mechanisms. Molecular-weight control and targeted gastrointestinal delivery are potential approaches.
EPA/DHA	Oxidative instability and differences in chemical form can influence absorption and biological activity. Microencapsulation, nanoemulsions, liposomes and antioxidant stabilization can improve protection.
Phlorotannins	Structural complexity, limited absorption and extensive metabolism can restrict systemic exposure. Encapsulation and food-matrix optimization may improve bioaccessibility.
Fucoxanthin	Poor aqueous solubility, chemical instability and gastrointestinal transformation limit oral bioavailability. Nanoemulsions, lipid carriers, liposomes and biopolymer-based systems have been investigated.
Astaxanthin	Poor water solubility and dependence on lipid digestion can limit absorption. Lipid-based systems, emulsions and encapsulation may improve bioavailability.
Marine collagen peptides	Gastrointestinal digestion produces multiple peptide fragments and may alter biological activity. Hydrolysate optimization and peptide-enriched formulations may improve consistency.
Chitosan derivatives	Molecular weight and degree of deacetylation influence gastrointestinal behaviour and biological activity. Molecular modification and nanoparticle-based delivery may improve functionality.

Footnote: Bioavailability should be interpreted alongside bioaccessibility, gastrointestinal transformation, metabolism and biological exposure. Increased encapsulation efficiency alone does not establish improved nutraceutical efficacy.

Source: Adapted from Cunha and Pintado (2022), Tie and Tan (2022), Galasso *et al.* (2023), Fernandes and Mamatha (2023), Falch (2023), Cadar *et al.* (2025) and Sun and Zhao (2026).

2. Cardiovascular Health

Marine nutraceuticals are of great promise in cardiovascular nutrition. EPA and DHA affect the metabolism of lipids, the composition of membranes and the production of inflammatory mediators, while marine peptides may inhibit ACE, have antioxidant effects or influence the metabolism of lipids. Marine polyphenols may also regulate oxidative and inflammatory pathways associated with endothelial dysfunction [6, 12].

Marine peptide studies have shown antihypertensive, antioxidant, anticoagulant and lipid-modulating activities, with microalgal compounds also being investigated for cardiovascular protection [19]. But the evidence base remains heterogeneous. Mechanistic support is provided by enzyme inhibition, antioxidant assays and animal studies, but cannot replace adequately powered human trials.

3. Metabolic Health

Nutraceuticals from marine sources have also been studied in obesity, dyslipidemia, impaired glucose regulation and related metabolic disorders. Marine polysaccharides may influence lipid digestion, satiety, adipocyte differentiation, and gut microbial composition, whereas peptides may modulate enzyme targets involved in glucose metabolism and lipid handling (Nair *et al.*, 2024; [9]).

The potential effects of fucoxanthin on adipose metabolism and glucose regulation have been attracting considerable attention, albeit most evidence remains preclinical. The same distinction holds true for several marine polyphenols, for which antioxidant and anti-inflammatory mechanisms are often demonstrated in cellular and animal systems. Translation requires human studies with characterized compounds at physiologically relevant doses.

4. Microbiome and Gut Health Interactions

The gut is a primary interface for marine nutraceutical action. Marine polysaccharides can be substrates or modulators for intestinal microbial communities and may affect microbial metabolites and epithelial-barrier function. These interactions provide a mechanistic rationale for considering marine polysaccharides as microbiome-directed nutraceutical ingredients^[4].

Microorganisms may also transform marine polyphenols into metabolites with biological properties distinct from those of the parent compounds. Thus, the health effects of marine nutraceuticals may be in part due to the individual microbiome composition and metabolic capacity. This adds an important dimension of inter-individual variability that is poorly characterized.

5. Neuroprotective and Immune Applications

The nutritional importance of marine-derived DHA for neurological function is well known, and marine pigments and peptides have been studied for their neuroprotective activity. Fucoxanthin has been investigated for its effects on oxidative stress, neuroinflammation, apoptosis, autophagy, and other pathways relevant to neurological disorders^[20].

Marine peptides and polysaccharides may also impact immune responses through cytokine modulation, receptor interactions and antioxidant mechanisms. These effects may be more about maintaining immune balance than simply boosting immunity. This is important because too much immune activation can be harmful by itself.

6. Advances Delivery and Formulation Approaches

Poor bioavailability and stability have driven the development of advanced delivery systems. Encapsulation protects marine oils and pigments from oxidation, and nanoemulsions, liposomes, and protein- or polysaccharide-based carriers improve dispersion, gastrointestinal stability and controlled release. Protein, polysaccharide and lipid-based fucoxanthin delivery systems have been specifically studied in an effort to solve the problems of instability and low bioavailability^[21].

Marine polysaccharides themselves can act as delivery materials due to their biocompatibility, biodegradability, mucoadhesive properties and environmental responsiveness. These properties have resulted in their application as carriers for food polyphenols and other nutraceuticals^[22, 23]. However, the development of delivery systems should not be limited to showing improved encapsulation efficiency. The relevant endpoint is improved biological performance in physiologically relevant settings, including gastrointestinal digestion, absorption, tissue distribution, and human efficacy.

Safety, Sustainability, Translational Challenges and Future Directions

1. Safety and Regulatory Considerations

A nutraceutical from the marine environment does not automatically mean it is safe. Marine organisms are able to concentrate environmental contaminants and the chemical composition is strongly affected by the species, geographic origin, harvesting conditions and processing. Special attention should be paid to heavy metals, arsenic, iodine, persistent organic pollutants, marine toxins and allergenic proteins, especially in ingredients derived from seaweed (; Silva *et al.*, 2025)^[1].

Standardization thus includes authentication of species and source, characterization of active component, testing for contaminants, assessment of batch variability, and definition of appropriate intake levels. Differences in current regulatory approaches in different jurisdictions can also complicate commercialization. Products derived from seaweed are a case in point, as iodine and contaminant concentrations can differ widely between species and geographical locations.

2. Sustainability and Circular Marine Bioeconomy

The development of marine nutraceuticals has an important sustainability angle. Processing residues such as fish skin, bones, scales, viscera and shells can be converted into peptides, collagen, chitin, chitosan and lipids, thus providing a route to convert low value materials into high value ingredients. Green extraction and environmentally compatible processing can also decrease solvent use and energy demand^[24, 10].

But sustainability is not only about using marine waste. Overharvesting, habitat pressure, energy requirements, transportation, extraction yield and downstream purification must also be considered. Harvesting of vulnerable wild resources might be substituted by cultured microalgae and controlled production of marine biomass.

3. Translational Barriers

A big challenge is the disconnect between exciting experimental activity and validated human benefit. Most studies on marine nutraceuticals are still based on cell cultures or animal models, although human trials are less frequent and often vary in source material, dose, formulation and outcome measures. Major barriers to translation include standardization, human safety, compound characterization and regulatory structures, as reported in recent reviews (Hosseini *et al.*, 2022;)^[25].

Another problem is that marine bioactives are often studied as complex extracts and not as chemically defined preparations. This complicates the comparison of doses and makes it difficult to determine whether the observed activity is due to a single compound, multiple constituents or synergistic interactions. Future nutraceutical development should therefore increasingly link chemical characterization to pharmacokinetics, biological markers and clinically relevant outcomes.

4. Future Perspectives

Future studies should progress toward standardized marine nutraceuticals specific to preparation rather than general statements based on marine species or classes of compounds. More integrated metabolomics, lipidomics, proteomics and microbiome profiling may help to define the molecular determinants of response. Artificial intelligence could assist in peptide sequence prediction, bioactive screening, formulation optimization, dose selection and the identification of structure–activity relationships.

Human bioavailability studies, realistic dietary doses, long-term safety assessment and well-designed randomized controlled trials should also be a priority for the next generation of marine nutraceutical research. Scalable routes may be available to high-value ingredients, including sustainable cultivation, precision fermentation, marine biotechnology and valorization of seafood-processing by-products. Integration of green extraction with advanced

purification and delivery technologies could further reduce the environmental impact while improving consistency. Ultimately, the field should move from “discovering marine bioactivity” to “engineering validated marine nutraceuticals”. This needs integration of marine biology, food chemistry, nutrition, microbiology, formulation science, toxicology, clinical nutrition and regulatory science.

Limitations of Current Evidence

There are several important limitations to the present body of evidence for marine-derived nutraceuticals. First, there is considerable heterogeneity in marine species, geographical origin, harvesting conditions, extraction procedures, purification methods, molecular composition and dosage, which makes direct comparison between studies difficult. For polysaccharides, the difference in molecular weight and sulfation is particularly relevant, while for peptides the sequence and digestion stability can differ substantially. Second, many reported biological activities are from *in vitro* assays and animal models, and there are relatively few well-powered human intervention studies [16, 1].

The other big limitation is bioavailability. The activity of an isolated compound does not demonstrate that similar concentrations can be achieved following oral administration. Moreover, many studies use extracts or mixtures that are not sufficiently chemically characterized, so that reliable identification of the active constituents is not possible. Safety data are also scarce, particularly for long-term consumption and for ingredients that may accumulate contaminants. Finally, the lack of standardized potency markers, the variability in analytical methods, and the differences in regulatory requirements continue to hinder reproducibility and commercialization.

Conclusion

Marine derived nutraceuticals are a diverse and an expanding important source for development of health promoting ingredients. Bioactive peptides, polysaccharides, lipids and polyphenols exhibit diverse chemical structures and biological activities which may play a role in regulating oxidative balance, inflammation, cardiovascular function, metabolic regulation, gut health, immune response and neurological processes. Furthermore, the availability of marine biomass and valorization opportunities of the side streams of seafood processing in a circular bioeconomy increase their potential.

However, a stronger evidence framework is required to bridge the gap between marine bioactive discovery and their credible nutraceutical application. Biological activity is not enough. The stability, gastrointestinal fate, bioaccessibility, bioavailability, dose, molecular target and clinical relevance of each preparation need to be considered. Similarly, species, geographic origin, extraction and processing can introduce large differences in composition and biological performance.

Scalable production can be facilitated by sustainable cultivation, green extraction and marine biotechnology while advanced delivery technologies can help tackle instability and poor bioavailability. The future of the field will depend on integration of chemical characterization, mechanistic biology, nutrition science, microbiome research, formulation technology, safety assessment and clinical validation. Marine-derived nutraceuticals therefore

represent a significant opportunity, but their successful translation will depend on moving beyond broad claims of marine bioactivity to standardized, safe, bioavailable and clinically-supported preparations. A tighter link between marine resource sustainability and evidence-based human nutrition may eventually establish marine nutraceuticals as a key pillar of next generation preventive nutrition.

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