Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 04 (JULY-AUG, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Marine-Derived Nutraceuticals and Bioactive Compounds

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Oceans cover more than 70% of the Earth's surface and support an extraordinary diversity of organisms — algae, microorganisms, sponges, molluscs, crustaceans, and fish — making the marine environment a promising, still under-exploited reservoir of bioactive compounds with nutritional, preventive, and therapeutic value. Growing scientific attention has focused on their antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, and anticancer effects, positioning marine organisms as an important source for functional foods, dietary supplements, nutraceuticals, and pharmaceuticals (Okeke et al., 2024; Ghosh et al., 2022).

The term "nutraceutical," coined by Stephen DeFelice in 1989, describes food or food-derived products offering health benefits beyond basic nutrition, contributing to disease prevention or management. Marine-based nutraceuticals are health-promoting foods, ingredients, or bioactive compounds obtained from seaweeds, marine animals, fish, shellfish, and marine microorganisms (Suleria et al., 2015).

Marine habitats — characterized by high salinity, variable pressure and temperature, limited light, and intense ecological competition — have driven organisms to evolve unique biochemical pathways and defence mechanisms, yielding structurally diverse secondary metabolites rarely found on land. Marine microorganisms are especially rich reservoirs of chemically diverse natural products, while macroalgae contribute widely to nutrition, medicine, and biotechnology (Negreanu-Pirjol et al., 2022; Ragozzino et al., 2025).

Major classes of marine nutraceuticals include omega-3 polyunsaturated fatty acids (PUFAs, notably EPA and DHA), bioactive peptides, polysaccharides (alginate, fucoidan, carrageenan, chitosan), pigments (astaxanthin, fucoxanthin), polyphenols, and minerals, each contributing antioxidant, cardiovascular, antihypertensive, antimicrobial, or anti-inflammatory benefits (Okeke et al., 2024; Venkatesan et al., 2017; Cadar et al., 2025; Siddhnath et al., 2024).

Rising consumer interest in functional foods, preventive healthcare, and healthy ageing, combined with advances in marine biotechnology, has expanded industrial capacity to identify and utilize these compounds (Daniotti & Re, 2021). Sustainable practices — including valorization of fish by-products (skin, bones, scales) and controlled algal or microbial cultivation — can diversify nutraceutical sourcing while protecting marine biodiversity (Ghosh et al., 2022). This article reviews the major marine sources of nutraceuticals, their principal bioactive compounds, and their nutritional and therapeutic significance.

Major Marine Sources of Nutraceuticals

Marine Algae

Marine algae comprise macroalgae (green, brown, red seaweeds) and microalgae. Seaweeds are traditionally consumed and used medicinally in Asia, containing polysaccharides, proteins, pigments, polyphenols, vitamins, and minerals — notably alginate, fucoidan, and carrageenan, with antioxidant, anti-inflammatory, and antimicrobial activity. Microalgae

supply astaxanthin, phycobiliproteins, carotenoids, proteins, and PUFAs valuable for functional foods and supplements (Cadar et al., 2025).

Fish and Fish By-products

Fish provide high-quality proteins, omega-3 fatty acids, and bioactive peptides; fish oils are rich in EPA/DHA, while hydrolyzed fish proteins yield antioxidant, antimicrobial, and antihypertensive peptides. Processing by-products — skin, bones, scales, viscera — are increasingly converted into collagen, gelatin, peptides, and minerals, reducing waste and supporting a circular economy (Venkatesan et al., 2017).

Crustaceans and Mollusks

Crustacean shells (shrimp, crab, lobster) are key sources of chitin and chitosan, along with astaxanthin, proteins, and minerals, used across food, nutraceutical, and biomedical applications. Mollusks (oysters, mussels, clams, squid) provide high-quality protein, zinc, selenium, taurine, and bioactive peptides.

Marine Microorganisms

Marine bacteria, fungi, cyanobacteria, and microalgae produce enzymes, pigments, antimicrobial peptides, PUFAs, and diverse secondary metabolites. Over 20,000 marine metabolites have reportedly been isolated in six decades; some compounds attributed to invertebrates actually originate from symbiotic microorganisms, underscoring the importance of marine microbial biotechnology (Bhatnagar & Kim, 2010; Ragozzino et al., 2025).

Sea Cucumbers and Other Invertebrates

Sea cucumbers, consumed as luxury foods and used in traditional medicine, contain saponins, phenolics, polysaccharides, collagen, peptides, and carotenoids with antioxidant and health-promoting properties. Other echinoderms (starfish, sea urchins) offer steroids and triterpene glycosides of nutraceutical interest (Hossain et al., 2022).

Major Marine Sources and Derived Food Products

Table 1 summarizes the principal marine sources exploited for food and their commercial products.

Marine Source	Category	Food Products	Reference
Finfish (tuna, salmon, cod, sardine, mackerel)	Fish	Fresh/frozen fillets, canned fish, fish oil, fish meal	FAO SOFIA, 2022
Crustaceans (shrimp, crab, lobster, krill)	Shellfish	Fresh/frozen shrimp, crab meat, lobster tail, krill oil	FAO SOFIA, 2022
Molluscs (oysters, mussels, clams, squid, octopus)	Shellfish/Cephalopods	Raw/cooked shellfish, calamari, canned mollusc products	FAO SOFIA, 2022
Seaweed/Macroalgae (nori, kelp, wakame, dulse)	Algae	Sushi wrap, salads, thickeners (agar, carrageenan, alginate)	FAO, 2018
Microalgae (Spirulina, Chlorella)	Algae	Nutritional supplements, protein powders, colorants	Kumar et al., 2015
Marine mammals (whale, seal – limited use)	Mammals	Meat, blubber oil (traditional diets)	FAO, 2020
Echinoderms (sea urchin, sea cucumber)	Invertebrates	Uni (roe), dried sea cucumber (trepang)	Purcell et al., 2013
Marine plants (sea grapes, sea beans)	Plants	Salads, garnishes, fresh vegetables	FAO, 2019
Fish by-products	Processed	Fish sauce, fish paste, gelatin, omega-3 supplements	FAO SOFIA, 2022

Reference: FAO (Food and Agriculture Organization of the United Nations). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation. Rome, FAO. https://www.fao.org/documents/card/en/c/cc0461en

Bioactive Compounds from Marine Sources

Marine ecosystems' exceptional biodiversity, combined with extreme environmental pressures, has produced organisms rich in omega-3 fatty acids, proteins, peptides, polysaccharides, pigments, and other secondary metabolites with antioxidant, anti-

inflammatory, antimicrobial, immunomodulatory, cardiovascular, and anticancer potential (Rustad et al., 2011; Xie et al., 2024; Xu et al., 2025). This interest aligns with blue biotechnology — the sustainable use of marine resources for food, health, and industrial applications — and with circular-economy valorization of fishery by-products (Rustad et al., 2011; Xie et al., 2024).

Omega-3 Fatty Acids

The principal omega-3 PUFAs are alpha-linolenic acid (ALA, plant-derived, with limited human conversion), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Fatty fish (salmon, sardines, mackerel, tuna, anchovies), krill oil, and marine microalgae are the richest EPA/DHA sources, with microalgae offering a sustainable, vegetarian-compatible alternative (Hosomi et al., 2024; Sharma et al., 2025). EPA supports anti-inflammatory lipid mediators; DHA is structurally vital to the brain and retina, with roles in cardiovascular and neurological health (Calder, 2020; Rimm et al., 2019). Because their multiple double bonds make them prone to oxidation, microencapsulation, nanoencapsulation, and antioxidant co-formulation are used to preserve stability and bioavailability in functional foods (Hosomi et al., 2024; Sharma et al., 2025).

Marine Proteins and Bioactive Peptides

Marine proteins from fish muscle, skin, bones, viscera, crustaceans, mollusks, and algae can be converted into bioactive peptides via enzymatic hydrolysis, fermentation, or digestion. These peptides show antioxidant, antihypertensive (ACE-inhibitory), antimicrobial, antidiabetic, anticoagulant, anti-inflammatory, and immunomodulatory activities (Rustad et al., 2011; Bioactivity of Marine-Derived Peptides and Proteins, 2025). Fish by-products yield collagen, gelatin, and protein hydrolysates, supporting sustainable seafood-industry practices; nanoencapsulation is being explored to improve peptide stability and controlled release (Review of Fish Protein Hydrolysates, 2024).

Marine Polysaccharides

Alginate (from brown seaweed) offers gel-forming, thickening, and film-forming properties useful in food and drug delivery. Carrageenan (red seaweed) is a widely used food thickener/stabilizer, also studied for antiviral, anticancer, and immunomodulatory effects. Fucoidan (brown algae) shows antioxidant, anticoagulant, anti-inflammatory, and potential anticancer activity, with growing use in drug delivery systems (Barbosa et al., 2019; Menshova et al., 2023). Chitin, from crustacean shells, is deacetylated into chitosan, which is antimicrobial, biodegradable, and biocompatible, with applications in food preservation, wound healing, tissue engineering, and drug delivery (Barbosa et al., 2019; Bealer et al., 2019).

Health Benefits and Therapeutic Applications

Cardiovascular health: EPA and DHA influence lipid metabolism, triglycerides, and inflammatory pathways, while marine peptides may aid blood-pressure regulation via ACE inhibition (Calder, 2020; Rimm et al., 2019).

Anti-inflammatory and immunomodulatory effects: omega-3s modulate inflammatory mediators, and polysaccharides such as fucoidan influence immune responses; marine antioxidants reduce oxidative stress linked to chronic inflammation (Xu et al., 2025; Xie et al., 2024).

Anticancer activity: bioactive peptides, polysaccharides, and antioxidants have shown effects on cancer-cell proliferation, apoptosis, and signaling, though further clinical validation is needed (Okeke et al., 2024; Xu et al., 2025).

Neuroprotection: DHA is essential to neuronal membranes, supporting cognitive and retinal function, while marine antioxidants may protect against age-related oxidative damage (Calder, 2020; Xie et al., 2024).

Antimicrobial/antiviral properties: peptides, polysaccharides, and chitosan in particular show activity against microorganisms and potential antiviral effects, useful in food preservation (Barbosa et al., 2019; Ghosh et al., 2022).

Wound healing and tissue regeneration: marine collagen, chitosan, and alginate form biocompatible hydrogels and scaffolds for wound dressings and controlled-release systems (Bealer et al., 2019).

Applications in Food and Pharmaceutical Industries

Marine bioactives are incorporated into functional foods (omega-3-enriched products, seaweed and microalgal ingredients, protein hydrolysates), dietary supplements (fish oil, krill oil, microalgal DHA, marine collagen), drug delivery systems (chitosan, alginate, and fucoidan nanoparticles and hydrogels), food additives (alginate and carrageenan as thickeners/stabilizers, chitosan as edible coating), and cosmeceuticals (collagen, peptides, and antioxidants for skin health) (Rustad et al., 2011; Xie et al., 2024; Barbosa et al., 2019; Menshova et al., 2023; Bealer et al., 2019).

Safety, Toxicity, and Regulatory Aspects

Marine organisms may accumulate heavy metals, contaminants, or biotoxins, and seafood ingredients can pose allergenicity risks. Safety depends on source species, extraction, purification, and processing. Regulatory oversight varies by region — the FDA/GRAS framework in the United States and EFSA requirements in Europe — and standardizing composition, purity, bioactivity, and dosage remains a key commercialization challenge.

Biotechnological Advancements

Valorization of fishery and aquaculture by-products recovers collagen, gelatin, proteins, and minerals, reducing waste through circular-economy models. Green extraction technologies — enzymatic, supercritical CO2, ultrasound-, and microwave-assisted extraction — improve efficiency while limiting solvent use. Marine microorganisms, supported by advances in genomics, metabolomics, and cultivation techniques, offer sustainable routes to novel bioactives. Nanotechnology and encapsulation improve the stability, bioavailability, and controlled release of oxidation-sensitive omega-3s, peptides, and polysaccharides.

Future Research Directions

Priorities include sustainable sourcing and blue biotechnology, valorization of processing by-products, and clinical validation of bioavailability, dosage, and long-term safety, since most evidence remains preclinical. Omics technologies (genomics, transcriptomics, proteomics, metabolomics), combined with artificial intelligence and computational biology, are expected to accelerate discovery of novel marine bioactives and strengthen their future role in functional foods, nutraceuticals, pharmaceuticals, and personalized nutrition (Xie et al., 2024; Ragozzino et al., 2025).

Conclusion

Marine ecosystems offer an exceptionally diverse reservoir of bioactive compounds — particularly omega-3 fatty acids, bioactive peptides, and polysaccharides — with demonstrated potential across cardiovascular health, inflammation, cancer research, neurological health, antimicrobial defence, and tissue regeneration. Their applications span functional foods, supplements, pharmaceuticals, drug delivery, food additives, and cosmeceuticals. Continued progress in safety evaluation, standardization, regulatory compliance, sustainability, and clinical validation — supported by blue biotechnology, green extraction, and omics-driven discovery — will be essential to realizing the full potential of marine-derived nutraceuticals.

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