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Marine Fish-Derived Bioactive Compounds: Nutritional Pathways Toward Human Health Benefits

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Abstract

Marine fish-derived bioactive compounds have emerged as pivotal agents in bridging nutrition and therapeutic innovation, offering multifaceted health benefits through anti-inflammatory, antioxidant, and metabolic regulatory mechanisms. This review synthesises current evidence on omega-3 fatty acids (EPA/DHA), bioactive peptides, polysaccharides, and micronutrients from marine fish, emphasising their roles in modulating critical pathways such as PPAR activation, Nrf2-mediated antioxidant responses, and gut microbiota interactions. These compounds demonstrate efficacy in mitigating chronic diseases, including cardiovascular disorders, diabetes, obesity, and cancer, while addressing nutrient deficiencies (e.g., vitamin D and selenium). However, challenges persist in optimising bioavailability, standardising extraction protocols, and validating clinical efficacy, necessitating advanced technologies like nanoencapsulation and omics-based approaches. The integration of fish bioactive compounds into functional foods aligns with global trends in preventive nutrition; however, sustainability concerns highlight the need for scalable aquaculture practices and the valorisation of underutilised species. Emerging research underscores the potential of AI-driven discovery, biotechnological production, and circular economy strategies to enhance therapeutic accessibility and ecological sustainability. This work provides a comprehensive analysis of molecular mechanisms, translational applications, and regulatory considerations, offering a roadmap for future studies to bridge preclinical findings with commercial and clinical implementation. By addressing existing gaps in dose-response relationships, long-term safety, and synergistic effects, marine fish bioactive compounds can solidify their role in personalised medicine and sustainable food systems.

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1. Introduction

Marine fish are a rich source of structurally diverse bioactive compounds with important implications for human health and nutrition. These compounds, including polyunsaturated fatty acids (PUFAs), bioactive peptides, proteins, polysaccharides, vitamins, and minerals, are increasingly studied for their roles in influencing metabolic pathways, immune responses, and chronic disease prevention (Kim *et al.* 2012, Khora 2013). The growing global burden of non-communicable diseases, such as diabetes, obesity, cardiovascular disorders, and autoimmune conditions, has intensified interest in marine-derived nutraceuticals as functional food ingredients (Noreen *et al.* 2025, Ghosh *et al.* 2022). Recent advances in marine biotechnology have enabled the isolation and characterisation of these bioactive molecules, providing insight into how they enhance

physiological functions and mitigate disease pathogenesis (Al-Hussaniy *et al.* 2025, Papon 2023).

Within this broad spectrum of compounds, fish-derived PUFAs such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), together with bioactive peptides, polysaccharides, and micronutrients, are particularly notable for their contributions to cardiovascular, metabolic, immune, and tissue health (Kim *et al.* 2012, Mirunalini and Maruthanila 2022, Noreen *et al.* 2025, Huang *et al.* 2021). These constituents act through multiple lipid-, peptide-, and polysaccharide-mediated pathways that affect lipid handling, vascular and immune function, and cellular repair, which are discussed in detail in subsequent sections of this review (Noreen *et al.* 2025, Ghosh *et al.* 2022, Al-Hussaniy *et al.* 2025). Marine-derived collagen peptides and sulfated polysaccharides further extend the relevance of fish

bioactives to applications in skin, wound, and oral health, reflecting their expanding use across nutrition, dermatology, and dentistry (Huang *et al.* 2021, Papon 2023).

Despite substantial progress, several challenges limit the full translational potential of marine fish-derived bioactive compounds, including the need to optimize extraction and processing methods, improve bioavailability, and establish standardized dosing regimens suited to different formulations (Noreen *et al.* 2025, Ghosh *et al.* 2022). Furthermore, the molecular pathways underpinning their efficacy—such as interactions with nuclear receptors, gut hormones, the gut microbiota, and epigenetic regulators—require deeper exploration to inform targeted and personalized interventions (Noreen *et al.* 2025, Ghosh *et al.* 2022, Al-Hussaniy *et al.* 2025). This review synthesizes current knowledge on marine fish-derived bioactive compounds, emphasizing their nutritional characteristics and mechanistic roles in promoting human health, and highlights future directions for harnessing marine biodiversity in functional food development and precision nutrition (Noreen *et al.* 2025, Al-Hussaniy *et al.* 2025, Ghosh *et al.* 2022).

2. Nutritional Profile of Marine Fish

Marine fish constitute a vital component of the human diet, offering a rich and diverse array of nutrients that contribute significantly to health maintenance and disease prevention. The nutritional profile of marine fish is uniquely characterized by high-quality proteins, essential fatty acids—particularly long-chain omega-3 polyunsaturated fatty acids (PUFAs) vitamins, minerals, and bioactive compounds with functional health properties. The protein content of marine fish typically ranges from 15–20% of fresh weight and provides all essential amino acids in highly digestible forms, making it a superior source of dietary protein compared to many terrestrial meats (Kris-Etherton *et al.* 2002). These proteins also serve as precursors for bioactive peptides released during digestion or food processing, which exhibit antioxidant, antihypertensive, and immunomodulatory functions (Kim and Wijesekara 2010).

One of the most distinguishing nutritional attributes of marine fish is the presence of omega-3 PUFAs, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids are essential for human health and play pivotal roles in cardiovascular protection, neurodevelopment, and inflammation modulation (Calder 2015). Cold-water fatty fish species such as mackerel, sardines, salmon, and herring are especially rich in EPA and DHA, with concentrations often exceeding 1,000 mg per 100 g serving (Mozaffarian and Rimm 2006). These fatty acids are efficiently incorporated into cell membranes, influencing fluidity and signal transduction, and are precursors to specialized pro-resolving mediators that modulate immune responses (Serhan *et al.* 2008).

In addition to fats and proteins, marine fish are excellent sources of several micronutrients. Fat-soluble vitamins such as vitamin A and vitamin D are abundant in species like cod liver and salmon, contributing to vision health, immune function, and calcium homeostasis (Cashman 2007). Water-soluble B vitamins—including B12, niacin, and riboflavin—are found in appreciable amounts and are crucial for energy metabolism and red blood cell formation. Marine fish also provide essential minerals such as selenium, iodine, zinc, and iron. For example, iodine from marine sources plays a critical role in thyroid hormone synthesis, while selenium contributes to antioxidant enzyme systems like glutathione peroxidase (Rua *et al.* 2023).

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The nutrient composition of marine fish can vary depending on species, geographic location, diet, age, and environmental conditions such as water temperature and salinity. For instance, wild-caught fish generally exhibit higher variability in fat content compared to farmed counterparts, although aquaculture practices increasingly aim to replicate natural nutrient profiles (Tocher 2015). Seasonal variations also influence lipid accumulation in fish tissues, with higher concentrations of PUFAs typically observed in colder months due to metabolic adaptations (Özogul and Özogul 2007). Processing methods—such as freezing, smoking, and canning—may affect nutrient stability, particularly for sensitive compounds like omega-3 fatty acids and vitamin D, though modern techniques are being refined to minimize nutrient loss.

Overall, the dense and diverse nutritional content of marine fish supports its role as a functional food with both macronutrient and micronutrient benefits. Understanding the detailed nutritional profile is essential for optimising dietary recommendations and maximising health outcomes through marine fish consumption.

2.1 Omega-3 Polyunsaturated Fatty Acids (EPA and DHA): Sources, Extraction Methods, Molecular Forms, and Bioavailability

Cold-water marine fish—including salmon (*Salmo salar*), mackerel (*Scomber scombrus*), sardines (*Sardina pilchardus*), and tuna (*Thunnus* spp.)—are the principal dietary reservoirs of the long-chain ω -3 polyunsaturated fatty acids eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3) (Alijani *et al.* 2025, Calder 2015; Mozaffarian and Wu 2011). These lipids can be recovered through a variety of techniques: steam-distillation or cold-pressing followed by molecular distillation yields triacylglycerol-rich oil, which may then undergo enzymatic re-esterification or supercritical CO₂ extraction to enhance purity, while enzymatic hydrolysis affords higher overall yields (Harnedy and FitzGerald 2012, Zhou *et al.* 2023). To improve stability and palatability, advanced microencapsulation strategies have recently been applied, protecting against oxidative degradation and masking fishy odors (Zhou *et al.* 2023).

Once extracted, EPA and DHA exist in multiple molecular forms—free fatty acid (FFA), natural triacylglycerol (TAG), re-esterified TAG (rTAG), phospholipid (PL), or ethyl ester (EE)—each of which differentially influences intestinal uptake and incorporation into biological membranes (Mozaffarian and Wu 2011, Alijani *et al.* 2025). Acute bioavailability follows the rank order NEFA (non-esterified fatty acids) > PL > rTAG > TAG > EE, reflecting more efficient micellar integration of polar and re-esterified species, although chronic dosing studies demonstrate that, over time, erythrocyte membrane levels of EPA and DHA equilibrate across these forms, underscoring the need for standardized dosing regimens and biomarker selection in comparative trials (Alijani *et al.* 2025). Notably, phospholipid-bound EPA and DHA exhibit superior absorption kinetics and higher plasma incorporation than TAG or EE preparations, making them especially promising for targeted nutraceutical formulations (Mozaffarian and Wu 2011).

2.2 Marine-Derived Bioactive Peptides and Proteins: Extraction, Structure, and Bioavailability

Marine-derived bioactive peptides and proteins—isolated from species such as Atlantic cod (*Gadus morhua*),

yellowfin tuna (*Thunnus albacares*), and mackerel (*Scomber japonicus*)—exhibit potent antioxidant, antihypertensive, and immunomodulatory activities, which are largely attributable to their low molecular weight (<500–3 000 Da) and specific amino acid motifs (e.g., Pro-Hyp, Hyp-Gly, Gly-Pro-Hyp) (Kristinsson and Rasco, 2000; Shahidi and Ambigaipalan 2018, Virgilio *et al.* 2024). Extraction typically employs enzymatic hydrolysis—with proteases such as Alcalase or papain at controlled pH and temperature (e.g., 60°C, pH 7.8)—or fermentation with lactic acid bacteria to yield peptides <3 kDa for optimal bioavailability (Harnedy and FitzGerald 2012). Collagen and gelatin are solubilized from fish skins, scales, and bones via acidic treatment (0.5 M acetic acid) or pepsin digestion (0.1% pepsin, 48–72 h), followed by controlled hydrolysis to generate hydrolysates enriched in Gly-Pro-Hyp motifs, which govern solubility and functional activity (Ahmed *et al.* 2020). Supercritical CO₂ extraction prior to hydrolysis has also been shown to improve the yield and purity of the protein fraction (Harnedy and FitzGerald 2012). Pharmacokinetic studies demonstrate rapid absorption of these low-molecular-weight peptides, with Pro-Hyp peaks detectable in human plasma within 1h post-ingestion, underscoring their hydrophilic nature and efficient gastrointestinal uptake (Virgilio *et al.* 2024).

2.3 Chitin, Chitosan, and Marine Sulfated Polysaccharides: Extraction Methods, Structural Attributes, and Bioactivity

Chitin—isolated from fish-scale waste (e.g., tilapia, *Oreochromis niloticus*) or crustacean shells—undergoes sequential demineralization (HCl, 0.5–6.5 M) and deproteinization (NaOH, 0.5–2.5 M), followed by alkaline deacetylation (NaOH, 40–60% at 80–100 °C) to produce chitosan with a degree of deacetylation >70%, yielding soluble glucosamine oligomers (<50 kDa) that exhibit superior solubility, collagen-binding affinity, and cellular uptake (Younes and Rinaudo 2015, Akinbomi *et al.* 2025). Chitosan's low molecular weight (<50 kDa) and hydrophilicity optimise its gastrointestinal absorption and confer pronounced prebiotic and anticoagulant effects (Muxika *et al.* 2017, Younes and Rinaudo 2015). Sulphated polysaccharides—such as fucoidan from seaweed-associated species and glycosaminoglycan-like polymers from gray triggerfish (*Balistes caprisus*) and smooth hound (*Mustelus mustelus*) skins—are extracted via hot-water hydrolysis (80 °C) or enzymatic/acid treatments followed by DEAE-cellulose chromatography, producing chains of 50–150 kDa with 0.5–1.2 SO₃²⁻ groups per monosaccharide; these sulfation patterns dictate mucosal adherence, antimicrobial potency and anticoagulant activity upon oral administration (Krichen *et al.* 2015, Saidani *et al.* 2021).

2.4 Marine Antioxidants, Micronutrients, and Functional Peptides: Extraction, Bioactivity, and Bioavailability

Marine sources such as salmon (*Oncorhynchus* spp.) provide potent antioxidants—including astaxanthin—and essential vitamins D₃ (cholecalciferol) and B₁₂ (cobalamin), alongside trace minerals like selenium, all of which contribute synergistically to human health (Ngo *et al.* 2011, Cashman 2007, Zhu *et al.* 2024). Astaxanthin is typically extracted via solvent-based or supercritical fluid methods, with its esterified form demonstrating superior stability and enhanced bioavailability compared to the free form (Wang *et al.* 2025). Vitamin D₃ and B₁₂ absorption occurs through active transport mechanisms in the intestine, and their

Washikur and Hossain. 2026. *Marine Fish-Derived Bioactive Compounds* bioavailability is modulated by interactions with the food matrix and co-consumed lipids (Cashman 2007). Valorisation of salmon processing side-streams—such as head, backbone, and viscera—via supercritical CO₂ defatting (25 MPa, 40°C) followed by Alcalase hydrolysis yields low-molecular-weight antioxidant peptides (500–2 500 Da) that exhibit potent DPPH and ABTS radical-scavenging activities (IC₅₀ < 50 µg/mL) and deliver bioaccessible minerals (Fe, Zn, Se; 0.1–100% depending on matrix) (Hustad *et al.* 2022, Liu *et al.* 2025). Furthermore, fish-protein supplements derived from these by-products significantly increase serum vitamin B₁₂ (Δ + 2.4 µg/L) and selenium (Δ + 15 µg/L) over an 8-week human trial, demonstrating that enzymatic processing preserves both antioxidant peptide functionality and micronutrient bioavailability (Hustad *et al.* 2022, Zhu *et al.* 2024).

2.5 Marine Sterols, Carotenoids, and Emerging Lipid Metabolites: Extraction Techniques, Structural Diversity, and Bioavailability

Marine sterols—such as brassicasterol and stigmasterol—and carotenoids, including astaxanthin and fucoxanthin, alongside bioactive lipid mediators like resolvins and protectins, represent a versatile class of marine-derived metabolites with demonstrated anticancer, lipid-lowering, and pro-resolving activities (Kim and Van Ta 2012, Burri *et al.* 2012). Sterols and carotenoids are typically recovered via saponification or supercritical CO₂ extraction, processes that preserve lipophilic integrity and allow control over structural features—double-bond positions, hydroxylation patterns, and esterification status—that critically influence micellar incorporation and cellular uptake (Roy *et al.* 2024). For instance, 24S-hydroxycholesterol isolated from fish oil exhibits superior membrane permeability and receptor affinity compared to conventional plant sterols (Raffaele *et al.* 2023). Astaxanthin, responsible for the red–orange pigmentation of salmon and trout muscle, is tightly protein-bound and liberated by brine extraction (water or 1–6 M NaCl, pH 6–7) or supercritical fluid techniques; optimal yields occur at pH 7, where co-extraction of up to 90% of muscle protein enhances formulation homogeneity (Birkeland and Bjerkeng 2004). Human supplementation trials revealed that four weeks of daily consumption (250 g salmon delivering 5 µg/g astaxanthin) shifts the predominant plasma stereoisomer from (3S, 3'S) in wild *Oncorhynchus* spp. to meso (3R, 3'S) in farmed *Salmo salar*, underscoring the impact of stereochemistry and esterification on bioavailability and tissue deposition (Rüfer *et al.* 2008). Emerging pro-resolving mediators derived from EPA and DHA are increasingly formulated via nanoemulsions or liposomal encapsulation to enhance solubility, protect labile epoxy and hydroxyl motifs, and target inflamed tissues more effectively, thereby maximising their anti-inflammatory and homeostatic functions (Burri *et al.* 2012).

3. Marine Nutrient Deficiency Syndromes and Modulation of Molecular Pathways by Marine Fish Bioactive Compounds

Marine fish-derived bioactive compounds have a dual therapeutic role. They help correct nutrient-deficiency syndromes and also regulate intracellular signaling pathways that support systemic health. Together, these actions make them a multifaceted nutritional intervention strategy.

Table 1. — An extensive and categorized table of key bioactive nutrients from marine fish, with source species, bioavailability notes

Category	Compound		Source Species	Bioavailability/Structural Notes	Reference
Omega-3 PUFAs	Eicosapentaenoic acid (EPA, 20:5n-3)		Salmon (<i>Salmo salar</i>), Mackerel	rTAG form enhances plasma incorporation; NEFA > PL > rTAG bioavailability	Alijani <i>et al.</i> (2025)
	Docosahexaenoic acid (DHA, 22:6n-3)		Sardine (<i>Sardina pilchardus</i>), Tuna	PL-bound DHA shows faster micellar uptake vs. TAG and EE forms	Alijani <i>et al.</i> (2025)
	Docosapentaenoic acid (DPA, 22:5n-3)		Cod	Intermediate bioavailability between EPA and DHA; accumulates in RBCs	Yurko-Mauro <i>et al.</i> (2015)
Bioactive Peptides and Proteins	Collagen peptides (500–3 000 Da)		Atlantic cod (<i>Gadus morhua</i>), Mackerel	Rapid plasma appearance (Pro-Hyp peaks at ~1 h); high absorption efficiency	Virgilio <i>et al.</i> (2024)
	Gelatin hydrolysate (1–10 kDa)		Tilapia (<i>Oreochromis niloticus</i>)	Antioxidant IC ₅₀ (DPPH) < 50 µg/mL; good mucosal uptake	Zheng <i>et al.</i> (2018)
	ACE-inhibitory peptides		Sardine (<i>Sardina pilchardus</i>)	Competitive inhibition (IC ₅₀ ~100 µM); < 2 kDa favors intestinal absorption	Li <i>et al.</i> (2004)
Chitin/Chitosan and Sulfated Polysaccharides	Chitosan oligomers (0.5–5 kDa)		Fish scales (various)	High DDA (> 75%) enhances solubility and mucoadhesion	Sumathi <i>et al.</i> (2017)
	Sulfated polysaccharides (50–150 kDa)		Gray triggerfish (<i>Balistes capriscus</i>)	Sulfation degree (0.6–1.2 SO ₃ ²⁻ per sugar) governs anticoagulant activity	Krichenet <i>et al.</i> (2015)
	Glycosaminoglycans (20–100 kDa)		Skate (<i>Raja clavata</i>) cartilage	Rich in chondroitin-4/6-sulfate; high bioadhesive potential	Lignot <i>et al.</i> (2003)
Antioxidants and Vitamins/Minerals	Astaxanthin		Salmon (<i>Oncorhynchus</i> spp.)	(3S, 3'S) vs. meso stereoisomers affect plasma T _{max} and t _{1/2}	Rüfer <i>et al.</i> (2008)
	α-Tocopherol (Vitamin E)		Sardine (<i>Sardina pilchardus</i>), Tuna	Lipid-soluble; incorporated into chylomicrons for lymphatic transport	Özogulet <i>et al.</i> (2011)
	Selenium-enriched peptides		Salmon by-products	The S-methionine fraction shows > 80% bioaccessibility in Caco-2 model	Singhato <i>et al.</i> (2022)
	very high calcium levels (1500–2500 mg per 100 g)		Dried <i>Harpadon nehereus</i> (Bombay duck)	high bioavailability; calcium bound to peptides and bone matrix.	Washikur <i>et al.</i> (2025)
Sterols and Other Metabolites	Fucosterol-type sterols		Mackerel (<i>Scomber japonicus</i>), Tuna	Polar sterol fractions show enhanced incorporation into micelles	Ozogul <i>et al.</i> (2015)
	Cholesterol		Cod (<i>Gadus morhua</i>), Pollock	Predominant sterol; precursor for vitamin D ₃ synthesis in skin	Ozogul <i>et al.</i> (2015)
	Mycosporine-like amino acids (MAAs)		Reef-associated fish (<i>Pomacentrus</i> spp.)	Small, water-soluble UV-protectants; high oral uptake due to low MW	Shick and Dunlap (2002)

Long-chain omega-3 polyunsaturated fatty acids (PUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), have been shown to improve conditions linked to omega-3 deficiency, including

hypertriglyceridemia, increased cardiovascular risk, and age-related cognitive decline. Evidence from large randomized trials and meta-analyses supports these benefits. In the GISSI-Prevenzione trial, daily intake of 1 g EPA/DHA for 3.5 years

reduced the combined risk of death, nonfatal myocardial infarction, and stroke by 15%, with a 20% reduction in total mortality (GISSI-Prevenzione Investigators 1999). In addition, meta-analytic evidence from more than 30 clinical studies found that omega-3 supplementation produced moderate but statistically significant improvements in depressive symptoms and cognitive performance in older adults, suggesting neuroprotective and psychotropic effects (Grosso *et al.* 2014).

At the mechanistic level, EPA and DHA act as endogenous ligands for peroxisome proliferator-activated receptors (PPAR- α and PPAR- γ). Through this interaction, they suppress sterol regulatory element-binding protein (SREBP)-mediated lipogenesis and increase the expression of genes involved in mitochondrial β -oxidation. These effects help lower circulating lipid levels and improve insulin sensitivity (Jump, 2008). In addition, EPA and DHA are precursors of specialized pro-resolving lipid mediators, including resolvins, protectins, and maresins. These molecules reduce nuclear factor- κ B (NF- κ B) signaling, decrease proinflammatory cytokine release, and promote the active resolution of chronic inflammation (Serhan *et al.* 2008).

Vitamin D deficiency causes rickets in children, osteomalacia in adults, and impaired immune regulation across age groups. Fish-derived cholecalciferol is an effective source for correcting this deficiency. Randomized trials have shown that daily supplementation with 10–20 μ g of cod-liver oil-derived vitamin D₃ raises serum 25-hydroxyvitamin D to optimal levels above 30 ng/mL and improves bone mineral density. This supplementation is also associated with a 25–30% reduction in nonvertebral fractures among elderly individuals (Vieth 1999). At the cellular level, vitamin D binds to the vitamin D receptor (VDR). The receptor then heterodimerizes with retinoid X receptor (RXR) and binds vitamin D response elements (VDREs) to regulate gene transcription. This process increases antimicrobial peptides such as cathelicidin and suppresses proinflammatory cytokines by interfering with NF- κ B nuclear translocation, thereby strengthening innate immunity and lowering autoimmune risk (Vieth 1999).

Iodine deficiency is a major global cause of preventable neurodevelopmental impairment and thyroid dysfunction. It is clinically associated with endemic goiter, hypothyroidism, and cretinism. Intervention studies in iodine-deficient coastal populations show that regular consumption of 150–300 μ g iodine per serving of marine fish restores urinary iodine levels and normal thyroid function within six months. These improvements are also associated with better cognitive outcomes in school-aged children (Andersson *et al.* 2012). Iodide also has a direct protective effect in thyroid tissue. It scavenges hydrogen peroxide and other reactive oxygen species in thyroid follicular cells, reducing oxidative damage and helping preserve gland integrity (Andersson *et al.* 2012).

Selenium deficiency contributes to Keshan disease, a form of dilated cardiomyopathy, and weakens antioxidant defense systems. Cohort studies indicate that populations consuming at least 40 μ g/day of fish-derived selenium have a 50% lower incidence of Keshan disease and higher glutathione peroxidase activity, which reflects stronger redox balance (Fairweather-Tait *et al.* 2011). At the molecular level, selenium is essential for the synthesis of selenoproteins such as glutathione peroxidases and thioredoxin reductases. These proteins support nuclear factor erythroid 2-related factor 2 (Nrf2)-mediated activation of cytoprotective genes. When

Washikur and Hossain. 2026. *Marine Fish-Derived Bioactive Compounds* selenium is deficient, this pathway is disrupted; when marine selenium is restored, Nrf2 signaling is reactivated and resistance to oxidative stress improves (Surh *et al.* 2008).

Vitamin B₁₂ deficiency leads to megaloblastic anemia, neuropathy, and elevated homocysteine levels. Fish-derived cobalamin can effectively correct this deficiency. Clinical trials in vegetarian and older adult populations found that 2–5 μ g/day of fish-sourced B₁₂ normalized serum methylmalonic acid and homocysteine, restored hematologic indicators, and improved neurologic symptoms within 8–12 weeks (Allen 2008). Vitamin B₁₂ acts as a cofactor for methionine synthase in one-carbon metabolism. This supports DNA methylation and myelin synthesis, while also helping prevent homocysteine-induced endothelial dysfunction by maintaining endothelial nitric oxide availability (Allen 2008).

Taken together, marine fish-derived nutrients help correct several deficiency syndromes, including hypertriglyceridemia, bone demineralization, thyroid dysfunction, cardiomyopathy, and anemia. At the same time, they regulate major intracellular pathways such as PPARs, VDR, NF- κ B, and Nrf2, and may also support brain-derived neurotrophic factor (BDNF) expression through DHA-mediated CREB activation. This combined effect supports both disease prevention and systemic homeostasis, underscoring the value of marine bioactive compounds as preventive and therapeutic agents in human health.

4. Conclusion and Future Recommendations

Marine fish-derived bioactive compounds sit at the intersection of nutrition and therapeutic innovation. This group includes omega-3 polyunsaturated fatty acids, bioactive peptides, polysaccharides, vitamins, and other marine metabolites with broad health-promoting potential. Through coordinated effects on metabolic balance, immune regulation, and cellular protection, they contribute to both disease prevention and health maintenance.

A key advantage of these compounds is their dual capacity to correct nutrient deficiencies and reduce disease risk. They are relevant for addressing shortages of vitamin D, vitamin B₁₂, selenium, and omega-3 fatty acids, while also supporting cardiovascular health, metabolic function, cognitive performance, and immune homeostasis. Their incorporation into functional foods and nutraceuticals further strengthens their public health value, especially within preventive nutrition strategies.

In addition, these compounds may help mitigate chronic diseases such as cardiovascular disorders, diabetes, cancer, and autoimmune conditions by interacting with molecular targets including PPARs, NF- κ B, Nrf2, and gut microbiota pathways. This mechanistic diversity enhances their appeal as both nutritional and therapeutic agents, particularly when combined with delivery strategies designed to improve performance in biological systems.

Despite this promise, several barriers continue to limit translation. Variability in raw materials, differences in extraction methods, limited bioavailability, and incomplete clinical validation all remain important challenges. Standardized processing protocols and rigorous quality control are therefore essential. At the same time, bioavailability-enhancing systems such as nanoencapsulation and liposomal formulations should be further explored to improve stability and absorption.

Future research should prioritize large-scale clinical studies to confirm efficacy, safety, and dose-response relationships. Mechanistic work is also needed to clarify how

these compounds interact with molecular pathways and biological targets. Advanced omics platforms and artificial intelligence may accelerate discovery, improve mechanistic insight, and support identification of novel compounds with therapeutic value.

Sustainable aquaculture, responsible use of underutilized marine resources, and interdisciplinary collaboration across nutrition science, biotechnology, pharmacology, and food technology will also be essential. Regulatory frameworks must continue to evolve to ensure product safety, consistency, and environmental sustainability. With stronger evidence, improved delivery systems, and sustainable production strategies, marine-derived bioactive compounds can become reliable functional ingredients and therapeutic resources.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Author contributions

M. R. Washikur 01: Conceptualisation, formal analysis, investigation, illustration, writing – original draft, writing – review & editing, referencing. Mohammad Nazir Hossain 02: Original idea, formal analysis, project administration, supervision, and critical review.

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Declaration of competing Interest

The authors declare no competing interests.

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