Marine Plants as Emerging Sources of Pharmaceutical Compounds

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Abstract
The marine environment represents one of the most chemically diverse and biologically rich ecosystems on Earth, harbouring an extraordinary repertoire of organisms that have evolved unique biochemical adaptations in response to complex ecological pressures. As terrestrial plant resources face increasing constraints from overharvesting, habitat loss, and diminishing chemical novelty, the marine realm has emerged as a transformative frontier for pharmaceutical discovery. This review examines marine plants, including microalgae, macroalgae (seaweeds), and seagrasses, as prolific and largely underexplored sources of bioactive compounds with significant therapeutic potential. The primary objective of this article is to provide a critical and comprehensive evaluation of the pharmacological diversity inherent to marine plant-derived compounds, with particular attention to polysaccharides, polyphenols, terpenoids, alkaloids, and photosynthetic pigments. These compound classes have demonstrated a broad spectrum of biological activities encompassing antioxidant, anti-inflammatory, antimicrobial, antiviral, and anticancer effects. Additionally, this review addresses contemporary advances in extraction and isolation technologies tailored to the physicochemical challenges unique to marine matrices, including high salinity, complex polysaccharide matrices, and compound instability. Preclinical and early-phase translational research are critically evaluated alongside industrial scalability, regulatory pathways, and sustainability concerns associated with marine bioprospecting. The review concludes by identifying critical knowledge gaps and proposing future research directions, with the aim of accelerating the translation of marine plant bioactives into clinically validated therapeutics. Marine plants represent a scientifically compelling and strategically important resource for next-generation drug discovery.

Keywords: Marine plants, Bioactive compounds, Marine natural products, Drug discovery, Seaweeds, Translational research

1. Introduction

The global burden of disease continues to challenge pharmaceutical scientists and clinicians to identify novel therapeutic agents that transcend the structural and mechanistic limitations of existing drugs. Terrestrial plants have historically constituted a primary source of pharmacologically active molecules; however, the progressive exhaustion of chemically novel scaffolds from land-based flora has necessitated a deliberate expansion into alternative biological domains [1, 2]. In this context, the marine environment has attracted sustained scientific interest, encompassing approximately 71% of the Earth's surface and supporting an estimated 500,000 to one million distinct species, the majority of which remain pharmacologically uncharacterised [3]. Within this biosphere, marine plants occupy a foundational ecological niche, functioning as primary producers, carbon sinks, and biodiversity reservoirs that sustain complex food webs and coastal ecosystems [4].

Marine plants, broadly defined to include photosynthetic marine organisms such as microalgae, macroalgae, and seagrasses,

have evolved under conditions of extreme osmotic pressure, high ultraviolet radiation, thermal variability, and intense biological competition, precipitating the biosynthesis of structurally and functionally diverse secondary metabolites rarely encountered in terrestrial systems [5, 6]. These metabolites, which include halogenated compounds, polyunsaturated fatty acids, sulphated polysaccharides, and novel terpenoid skeletons, have demonstrated potent and selective pharmacological activities across a broad spectrum of disease-relevant targets [7].

The scientific literature pertaining to marine natural products has expanded considerably over the past four decades, with several marine-derived compounds having progressed from preclinical discovery to clinical approval, including cytarabine, trabectedin, and omega-3 fatty acid formulations [8, 9]. Nevertheless, the pharmaceutical potential of marine plants specifically, as distinguished from marine animals or microorganisms, remains incompletely explored. The present review aims to consolidate current knowledge regarding the classification, bioactive chemistry, pharmacological mechanisms, extraction technologies, and translational pathways associated with marine plant-derived compounds, while critically addressing the environmental and regulatory dimensions of marine bioprospecting.

2. Classification of Marine Plants: Ecological and Biochemical Perspectives

Marine plants represent a phylogenetically diverse assemblage that is conventionally organised into three broad categories: microalgae, macroalgae, and seagrasses. Each category is distinguished by unique morphological, ecological, and biochemical characteristics that collectively determine the range and abundance of secondary metabolites available for pharmaceutical exploitation [10].

Microalgae constitute unicellular or simple colonial photosynthetic organisms distributed throughout pelagic and benthic marine zones. This category encompasses cyanobacteria (prokaryotic), diatoms, dinoflagellates, and green and red microalgae (eukaryotic). The biochemical profile of microalgae is characterised by high concentrations of chlorophylls, carotenoids, phycobiliproteins, polyunsaturated fatty acids including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), and exopolysaccharides [11]. Genera such as Spirulina, Chlorella, Dunaliella, and Haematococcus have attracted particular interest owing to their antioxidant, immunomodulatory, and cytoprotective activities [12].

Macroalgae, or seaweeds, are multicellular photosynthetic organisms classified into three phyla based on their primary photosynthetic pigments: Chlorophyta (green algae), Phaeophyta (brown algae), and Rhodophyta (red algae). Brown algae, including genera such as Fucus, Laminaria, Ascophyllum, and Sargassum, are particularly rich sources of fucoidan, alginate, phlorotannins, and fucoxanthin, compounds that have demonstrated anticancer, anticoagulant, and anti-inflammatory properties [13]. Red algae, including Gracilaria, Porphyra, and Chondrus, are notable for their carrageenan and agar content, as well as a variety of bioactive peptides and brominated secondary metabolites [14]. Green algae, including Ulva, Codium, and Caulerpa, contribute to the pharmaceutical portfolio through their production of sulphated polysaccharides, terpenoids, and amino acid-derived bioactives [15].

Seagrasses are the only group of fully submerged marine angiosperms, comprising approximately 72 species distributed across tropical and temperate coastal zones. Genera including Posidonia, Zostera, Thalassia, and Cymodocea have been investigated as sources of phenolic acids, flavonoids, terpenoids, and fatty acids with antioxidant and antimicrobial activities [16]. Although seagrasses are less extensively studied than algae, their structural complexity and ecological specialisation suggest a rich and relatively untapped secondary metabolite chemistry.

3. Bioactive Compounds Derived from Marine Plants

The secondary metabolite repertoire of marine plants encompasses a chemically diverse array of compound classes, each characterised by distinct structural features and pharmacological properties.

Polysaccharides represent one of the most extensively studied classes of marine plant-derived bioactives. Fucoidan, a sulphated heteropolysaccharide predominantly derived from brown algae, has been demonstrated to exhibit anticoagulant, antiviral, antitumour, and immunostimulatory activities through a variety of receptor-mediated and signalling mechanisms [17]. Carrageenan, a family of sulphated galactans obtained from red algae, has applications in antiviral formulations and as a drug delivery matrix, while alginates derived from brown algae are utilised extensively in wound healing and encapsulation technologies [18].

Polyphenols, particularly phlorotannins, represent a class of phenolic polymers exclusive to brown algae, biosynthesised through the acetate-malonate pathway and exhibiting structural complexity not observed in terrestrial polyphenols. Phlorotannins including eckol, phloroglucinol, and dieckol have demonstrated potent antioxidant, anti-inflammatory, antidiabetic, and neuroprotective activities *in vitro* and in preclinical animal models [19]. Seagrasses additionally contribute flavonoids and hydroxycinnamic acid derivatives that display significant radical scavenging and enzyme inhibitory activities [20].

Terpenoids constitute a structurally heterogeneous class of isoprenoid-derived natural products present in both microalgae and macroalgae. Diterpenes and sesquiterpenes from genera such as Laurencia, Dictyota, and Caulerpa have been characterised as potent antimicrobial, antifouling, and cytotoxic agents [21]. Fucoxanthin, a xanthophyll carotenoid exclusive to brown algae and diatoms, has attracted considerable interest for its antiobesity, antidiabetic, and antitumour properties, which are mediated through modulation of peroxisome proliferator-activated receptors and oxidative stress pathways [22].

Pigments including phycocyanin from cyanobacteria and astaxanthin from Haematococcus pluvialis represent high-value bioactives with established antioxidant, anti-inflammatory, and photoprotective properties [23]. Phycocyanin has additionally demonstrated apoptotic activity in cancer cell lines through mitochondrial pathway activation, while astaxanthin has been evaluated in clinical trials for neurodegenerative and cardiovascular disease prevention.

Marine plant-derived alkaloids and peptides, although less prevalent than those from marine animals, include compounds such as kainic acid from Digenea simplex, which has pharmacological relevance as a neuroexcitatory agent, and various bioactive peptides from microalgal hydrolysates

that exhibit angiotensin-converting enzyme inhibitory and antihypertensive activities [24].

4. Mechanisms of Action of Marine Plant-Derived Compounds

The pharmacological activities of marine plant bioactives are mediated through diverse and interconnected molecular mechanisms. Antioxidant activity, a property common to polyphenols, carotenoids, and phycobiliproteins, is principally exerted through direct radical scavenging, metal chelation, and upregulation of endogenous antioxidant enzymes including superoxide dismutase, catalase, and glutathione peroxidase via the Nrf2/ARE signalling pathway [25]. The capacity of fucoxanthin and phlorotannins to activate Nrf2-dependent transcription has been demonstrated in hepatocellular and neuronal model systems, supporting their potential in oxidative stress-associated pathologies.

Anti-inflammatory mechanisms involve the suppression of pro-inflammatory cytokine synthesis and the inhibition of key inflammatory mediators. Fucoidan and sulphated polysaccharides have been shown to inhibit nuclear factor-kappa B (NF-κB) activation, thereby reducing the transcription of interleukin-6, tumour necrosis factor-alpha, and cyclooxygenase-2 [26]. Phlorotannins additionally inhibit phosphodiesterase and lipoxygenase enzymes, producing downstream anti-inflammatory effects in macrophage and neutrophil models.

Antimicrobial activity of marine plant compounds is exerted through multiple mechanisms including disruption of bacterial cell membrane integrity, inhibition of biofilm formation, interference with quorum sensing, and inhibition of essential metabolic enzymes [27]. Halogenated terpenes from red algae have demonstrated activity against both Gram-positive and Gram-negative pathogens, including methicillin-resistant Staphylococcus aureus, by compromising membrane permeability and disrupting electron transport chain function.

Anticancer mechanisms of marine plant bioactives are multifactorial, encompassing induction of apoptosis through both intrinsic and extrinsic pathways, inhibition of cell cycle progression, anti-angiogenic effects, and immunostimulatory activities. Fucoidan has been reported to activate caspase-3 and caspase-9-dependent apoptosis in multiple cancer cell lines, while fucoxanthin suppresses tumour growth through downregulation of the PI3K/Akt/mTOR signalling cascade [28]. Phlorotannins have demonstrated inhibitory effects on matrix metalloproteinases implicated in cancer invasion and metastasis.

5. Extraction and Isolation Techniques for Marine Plant Bioactives

The extraction of bioactive compounds from marine plants presents distinct technical challenges attributable to the complex chemical matrix of marine biological material, including high salt content, abundant polysaccharides, and the instability of many target compounds under conditions of elevated temperature, light, or oxygen exposure [29]. Conventional extraction methods such as maceration, Soxhlet extraction, and aqueous-organic solvent partitioning have been applied extensively to marine plants; however, these approaches are increasingly supplemented or replaced by advanced extraction technologies that offer improved selectivity, yield, and environmental compatibility.

Pressurised liquid extraction (PLE), also referred to as accelerated solvent extraction, employs elevated temperatures and pressures to enhance solvent penetration into biological matrices, significantly reducing extraction time and solvent consumption while maintaining compound integrity. Supercritical fluid extraction (SFE) using carbon dioxide as the primary solvent is particularly advantageous for the isolation of lipophilic compounds such as fucoxanthin and omega-3 fatty acids, as it avoids thermal degradation and eliminates residual solvent concerns [30]. Microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) have also been widely applied to marine plant matrices, exploiting acoustic cavitation and electromagnetic energy to disrupt cell walls and facilitate the release of intracellular metabolites with minimal processing time.

Isolation and purification of target compounds typically involves sequential chromatographic procedures including solid-phase extraction, size-exclusion chromatography, ion-exchange chromatography, and high-performance liquid chromatography coupled to diode array or mass spectrometric detection [31]. The characterisation of novel bioactive structures increasingly relies on nuclear magnetic resonance spectroscopy and high-resolution mass spectrometry, enabling unambiguous structural elucidation of complex marine natural products. Challenges specific to marine plant extracts include the presence of co-eluting pigments, the gel-forming properties of polysaccharides that impede chromatographic resolution, and the sensitivity of halogenated compounds to nucleophilic displacement under standard chromatographic conditions.

6. Preclinical and Translational Research

The transition of marine plant-derived bioactives from laboratory discovery to clinical application requires systematic evaluation across a hierarchy of experimental models. *in vitro* investigations using established cell lines and primary cell cultures have provided foundational evidence for the pharmacological activities described in the preceding sections, demonstrating cytotoxicity against cancer cell lines, inhibition of inflammatory mediators in macrophage models, and antimicrobial activity in broth dilution and biofilm assays [32]. These studies are indispensable for mechanistic characterisation but are limited in their predictive capacity for *in vivo* efficacy and safety.

Preclinical *in vivo* studies employing rodent models of cancer, metabolic syndrome, neurodegeneration, and infection have advanced the evidence base for several marine plant compounds. Fucoxanthin has been evaluated in diet-induced obesity mouse models, demonstrating significant reductions in body weight, adipose tissue accumulation, and plasma triglyceride concentrations [33]. Fucoidan has been assessed in xenograft tumour models, producing measurable reductions in tumour volume and metastatic dissemination. However, the translational gap between animal model efficacy and human clinical benefit remains a fundamental challenge, compounded by species-specific differences in drug metabolism, bioavailability, and pharmacokinetics.

Bioavailability represents a critical barrier for many marine plant bioactives. The oral bioavailability of fucoxanthin, for instance, is substantially limited by first-pass metabolism and the physicochemical properties of the intact xanthophyll, necessitating formulation strategies such as nanoemulsification, lipid-based delivery systems, and biopolymer encapsulation to enhance absorption and

systemic exposure [34]. Similarly, sulphated polysaccharides face challenges associated with enzymatic degradation in the gastrointestinal tract and poor mucosal permeability.

Clinical trials involving marine plant-derived compounds remain limited in number and scope. Omega-3 fatty acid formulations derived from microalgae have advanced furthest through the regulatory process, with Lovaza and Vascepa receiving approval for the treatment of hypertriglyceridaemia. Spirulina and Chlorella extracts have been evaluated in phase I and phase II trials for various indications, though definitive evidence of clinical efficacy remains elusive for most other marine plant bioactives [35].

7. Industrial and Pharmaceutical Applications

The industrial exploitation of marine plant bioactives extends beyond pure pharmaceutical applications to encompass nutraceuticals, functional foods, cosmeceuticals, and biomaterial sciences. The global market for seaweed-derived products was estimated at several billion US dollars annually, with carrageenan and agar as the highest-volume commodity polysaccharides [36]. Alginates derived from Laminaria and Macrocystis species are used extensively in pharmaceutical formulations as controlled-release matrices, wound dressings, and biopolymer scaffolds for tissue engineering.

The scalable production of microalgal biomass through photobioreactor technology represents a significant advance in the industrial application of marine plant bioactives. Closed photobioreactor systems allow precise control of culture conditions including light intensity, temperature, carbon dioxide concentration, and nutrient supply, enabling optimised biomass productivity and consistent compound profiles suitable for pharmaceutical manufacturing [37]. However, capital and operational costs associated with photobioreactor cultivation remain substantially higher than those for open raceway pond systems, limiting economic competitiveness for bulk commodity applications.

Formulation science plays a critical role in converting raw marine plant extracts into pharmaceutical-grade products with defined potency, stability, and bioavailability profiles. Nanoencapsulation of fucoxanthin in solid lipid nanoparticles and polymeric micelles has been shown to enhance oral bioavailability by three to five-fold in preclinical models [38]. Spray-drying and freeze-drying technologies are employed for the production of microalgal powders and standardised extracts suitable for inclusion in capsule, tablet, and functional food formulations.

8. Environmental, Regulatory, and Sustainability Considerations

The sustainable exploitation of marine plants for pharmaceutical purposes demands careful consideration of the ecological consequences of wild harvesting and the regulatory frameworks that govern the collection, processing, and commercialisation of marine biological resources. Wild harvesting of macroalgae and seagrasses, if conducted without adequate management, poses risks of overexploitation, habitat degradation, and disruption of coastal food webs and carbon sequestration processes [39]. Several historically important seaweed harvesting regions have experienced significant population declines attributable to unregulated collection practices, highlighting the necessity of evidence-based harvest quotas and biodiversity impact assessments.

The Convention on Biological Diversity and its Nagoya Protocol on Access and Benefit Sharing provide the principal international regulatory framework governing the collection and utilisation of marine genetic resources. Under this framework, researchers and commercial entities are required to obtain prior informed consent from the competent national authority of the country of origin and to negotiate mutually agreed terms for the sharing of any benefits arising from the utilisation of genetic resources [40]. Compliance with access and benefit sharing obligations represents a significant operational consideration for pharmaceutical companies engaged in marine bioprospecting, particularly in jurisdictions with complex or evolving national regulations.

Aquaculture-based cultivation of marine plants offers a more sustainable and controllable alternative to wild harvesting for pharmaceutical-scale production. Integrated multi-trophic aquaculture systems, in which seaweeds are cultivated in the effluent streams of fish and shellfish operations, have been demonstrated to achieve significant biomass productivity while simultaneously providing water quality remediation services [41]. The development of seaweed cultivation technologies adapted to pharmaceutical quality standards, including good agricultural and collection practices (GACP) guidelines, is an important area of ongoing research and regulatory development.

9. Conclusions and Future Directions

Marine plants represent a scientifically rich and pharmacologically promising but incompletely explored resource for pharmaceutical drug discovery. The present review has demonstrated that microalgae, macroalgae, and seagrasses collectively produce a structurally diverse array of bioactive compounds, including sulphated polysaccharides, phlorotannins, carotenoids, terpenoids, and alkaloids, with activities spanning antioxidant, anti-inflammatory, antimicrobial, antiviral, and anticancer domains. The molecular mechanisms underlying these activities are increasingly well characterised at the level of receptor binding, enzyme inhibition, and gene expression modulation, providing a rational basis for target-directed drug development.

Critical challenges impeding the translation of marine plant bioactives into clinical therapeutics include limited oral bioavailability, the complexity of large-scale extraction and purification, regulatory uncertainty, and a relative paucity of well-designed clinical trial data. Addressing these challenges will require coordinated investment in formulation science, the development of scalable biosynthetic or aquaculture-based production systems, and the conduct of rigorously designed phase II and III clinical trials for the most promising lead compounds.

Future research directions of particular importance include the application of metabolomics and systems biology approaches to comprehensively characterise the secondary metabolite profiles of underexplored marine plant species, the application of synthetic biology and heterologous expression systems to enable the scalable production of rare or structurally complex marine natural products, and the integration of artificial intelligence-driven drug target prediction with empirical pharmacological screening to accelerate hit identification. Additionally, the ecological and genetic diversity of deep-water and polar marine plant communities remains almost entirely unexplored,

representing a frontier of exceptional scientific and pharmaceutical potential. With sustained interdisciplinary investment, marine plants have the capacity to contribute significantly to the next generation of pharmaceutical discoveries.

Figures

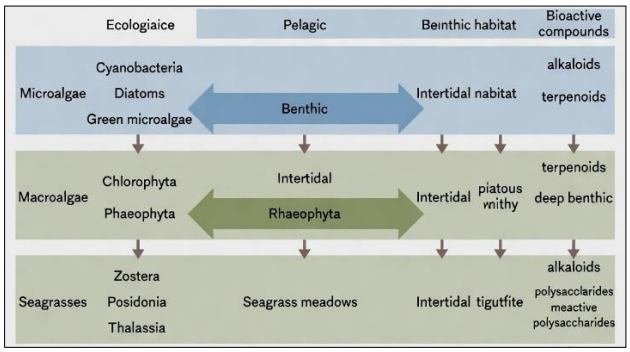

Fig 1: Classification and ecological distribution of marine plants used in pharmaceutical research.

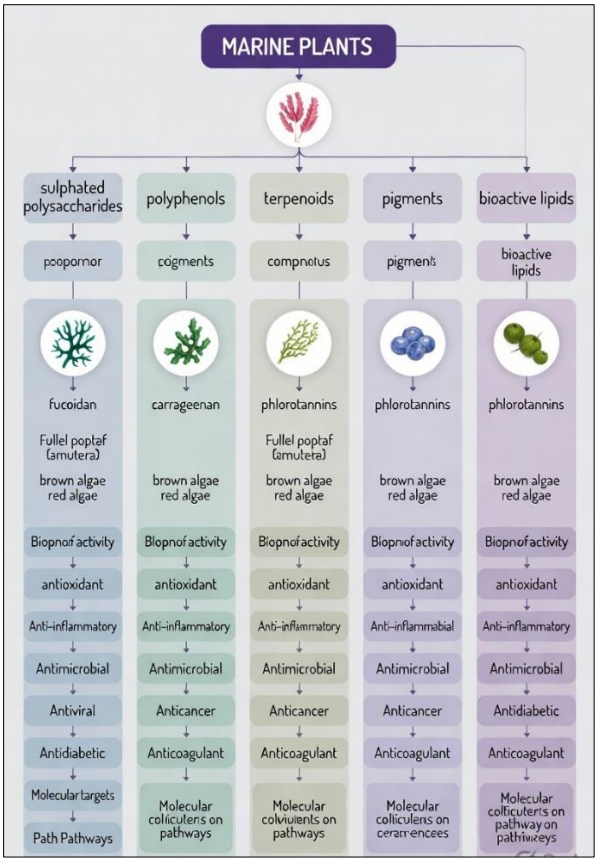

Fig 2: Major classes of bioactive compounds derived from marine plants and their biological activities.

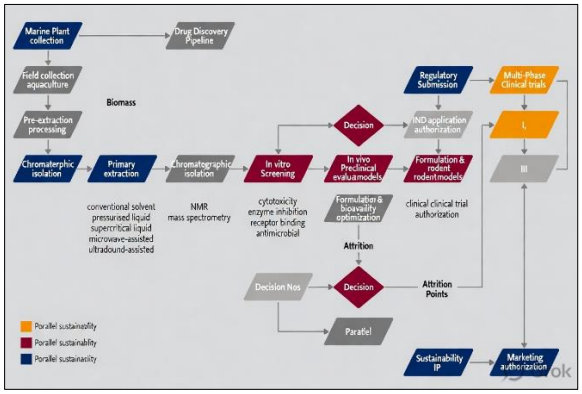

Fig 3: Drug discovery pipeline from marine plant extraction to clinical application.

Table 1: Representative Marine Plants, Bioactive Compounds, and Pharmacological Activities

Marine Plant	Taxonomic Class	Bioactive Compound	Pharmacological Activity
Fucus vesiculosus	Brown alga (Phaeophyta)	Fucoidan	Anticoagulant, antitumour, antiviral, anti-inflammatory
Laminaria japonica	Brown alga (Phaeophyta)	Laminarin, alginate	Immunomodulatory, antidiabetic, wound healing
Undaria pinnatifida	Brown alga (Phaeophyta)	Fucoxanthin	Antiobesity, anticancer, antidiabetic
Ecklonia cava	Brown alga (Phaeophyta)	Phlorotannins (eckol, dieckol)	Antioxidant, anti-inflammatory, neuroprotective
Chondrus crispus	Red alga (Rhodophyta)	Carrageenan	Antiviral, antitumour, mucosal protection
Gracilaria gracilis	Red alga (Rhodophyta)	Agar, bioactive peptides	Antihypertensive, antimicrobial
Ulva lactuca	Green alga (Chlorophyta)	Ulvan	Antioxidant, antihyperlipidaemic, antiviral
Spirulina platensis	Cyanobacterium	Phycocyanin, gamma-linolenic acid	Anti-inflammatory, antioxidant, anticancer, antiviral
Haematococcus pluvialis	Green microalga	Astaxanthin	Antioxidant, anti-inflammatory, neuroprotective
Zostera marina	Seagrass (Zosteraceae)	Flavonoids, hydroxycinnamic acids	Antioxidant, antimicrobial, anti-inflammatory

Table 2: Advantages, Limitations, and Challenges in Marine Plant-Based Pharmaceutical Development

Dimension	Advantages	Limitations	Key Challenges
Chemical Diversity	Structurally unique metabolites absent from terrestrial flora; novel pharmacophores; broad bioactivity spectrum	Difficult structural elucidation; complex mixtures requiring extensive chromatographic separation	Dereplification of known compounds; standardisation of extract composition
Extraction	Range of advanced extraction technologies available; improving selectivity and yield	Salt interference; polysaccharide co-extraction; compound instability under processing conditions	Scale-up from laboratory to pilot and industrial scale; economic competitiveness
Bioavailability	Some compounds naturally suited to oral delivery; nanotechnology can enhance absorption	Poor oral bioavailability for many bioactives; extensive first-pass metabolism of carotenoids and polyphenols	Development of appropriate drug delivery systems; *in vitro*-in vivo correlation
Production	Aquaculture and photobioreactor cultivation feasible; integrated multi-trophic systems reduce environmental impact	High capital costs of closed photobioreactors; batch-to-batch variability in wild-harvested material	Achieving pharmaceutical-grade consistency; GACP implementation for marine plants
Regulatory	Precedent from approved marine-derived drugs (cytarabine, trabectedin); established nutraceutical markets	Complex regulatory pathways for novel marine bioactives; limited clinical trial data	Meeting ICH guidelines; demonstrating clinical efficacy and safety; intellectual property protection
Sustainability	Aquaculture-based production supports renewable supply; seaweed cultivation provides ecosystem services	Wild-harvesting risks overexploitation and habitat degradation; climate change affecting species distribution	Compliance with Nagoya Protocol; environmental impact assessment; biodiversity conservation

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