BIOACTIVITIES AND POTENTIAL APPLICATION OF INDIAN RED AND BROWN ALGAE IN PHARMACEUTICS

Abstract

The marine ecosystems of India are rich in red (Rhodophyta) and brown (Phaeophyceae) algae, which offer a wealth of bioactive compounds with immense pharmacological potential from sustainable sources. These macroalgae are capable of synthesizing structurally diverse secondary metabolites, including sulfated polysaccharides (e.g., carrageenan, fucoidan), phlorotannins, polyphenols, sterols, and flavonoids. Recent investigations have unveiled their strong biological activities, such as anticancer, antidiabetic, antioxidant, anti-inflammatory, antimicrobial, neuroprotective, antihypertensive, and anti-obesity. This review summarizes and evaluates the therapeutic efficacy of Indian red and brown algae with a special emphasis on species-specific bioactivities and mechanisms of action. Specific importance is given to algae, which include *Gracilaria edulis, Kappaphycus alvarezii, Turbinaria conoides,* and *Padina tetrastromatica*. We also consider the pharmacological rationale of these actions and current challenges in clinical validation, standardization, and bioavailability. The review highlights the importance of further *in vivo* and translational research and modern biotechnological methodologies that would enable the exploitation of these marine sources to develop drugs. The sustainable availability of Indian algae with their biochemical richness is requisite for future pharmaceutical and nutraceutical approaches.

Keywords: Red algae, Brown algae, Bioactivities, Marine pharmacology, Sulfated polysaccharides, Indian coast

1. Introduction

Marine algae have been utilized traditionally in food, agriculture, and traditional medicine for a long time in the coastal areas of the world. In the last decades, scientific research has highlighted that red (Rhodophyta) and brown (Phaeophyceae) seaweeds are sources of powerful bioactive substances with several beneficial effects. Among others, these are represented by sulfated polysaccharides, including carrageenan and fucoidan, phlorotannins, phenolic compounds, and other secondary metabolites such as flavonoids, terpenoids, sterols, and peptides【1–4】. The compounds have shown antioxidant, anti-inflammatory, anticancer, antidiabetic, antimicrobial, antithrombotic, neuroprotection, and antihypertension activities in the preclinical models【2,5】.

India, having a vast coastline of over 7500 km and various marine ecosystems, is home to hundreds of red and brown algal species. Some of the notable species are *Gracilaria edulis, Gelidiella acerosa, Hypnea musciformis* (red algae), and *Sargassum wightii, Turbinaria conoides,* and *Padina tetrastromatica* (brown algae), showing excellent pharmacological prospective【6–8】. With the growing resistance to synthetic drugs and awareness of the need for eco-friendly therapeutic agents, Indian marine algae are now touted as a potential source of new drug candidates and functional food products【9】.

Despite numerous *in vitro* and *in vivo* studies confirming their efficacy, the commercial and clinical translation of algal-based therapies remains limited. Challenges such as variability in

metabolite content, lack of standardized extraction protocols, poor bioavailability, and insufficient clinical validation hinder their pharmaceutical development【10,11】.

The present review tries to present an overall summary of the biological activities of Indian red and brown algal species, particularly focused on their pharmacological mechanisms and therapeutic potentials. Furthermore, it highlights important research gaps and plans for the development of medicinal alternatives to synthetic drugs for chronic diseases.

2. Anticancer Activity

Cancer is an erosion disorder with multiple etiologies, which has been linked to the abnormal growth of cells and their ability to penetrate the surrounding organs and eventually migrate to different places. It remains one of the top killers globally, accounting for 10 million deaths and over 19 million new cases in 2020. Of these, breast, lung, colorectal, prostate, skin, and stomach cancer are the most common cancers in the world, and cervical cancer is still a significant health issue in many developing countries 【12】.

Various treatment protocols have contributed to the improvement of the prognosis of cancer, including those such as surgery, chemotherapy, radiotherapy, immunotherapy, targeted therapy, and stem cell transplantation, as the most available form in the world today. Nevertheless, most of these therapies have strong side effects, are toxic, expensive, and generate resistance to agents, which drives the need to find safer and more effective agents 【13】.Nature remains a rich reserve of anticancer drugs, as many chemotherapeutic agents (e.g., paclitaxel, vincristine, doxorubicin, and actinomycin D) have been identified from plants and microbes. Marine organisms, too, have known in recent years an increasing interest due to their peculiar chemical scaffolds and bioactivities. Among them, red and brown macroalgae are promising sources rich in sulfated polysaccharides, phlorotannins, and sterols with cytotoxic, antiproliferative, and pro-apoptotic activities in different cancer cell lines 【14,15】.

This section discusses the anticancer activities of some of the Indian red and brown algae species, focusing on the molecular mechanisms of action and their relevance to drug discovery.

2.1 Anticancer Activities of Red Algae

In preclinical studies, several Indian red seaweeds have shown potent anticancer activities, which include induction of apoptosis, reduction in cell proliferation, modulation of signaling pathways, and generation of reactive oxygen species (ROS).

Gracilaria edulis has antiproliferative effects on A549 human lung adenocarcinoma cells both *in vitro* and *in vivo* without systemic toxicity 【16】. Zinc oxide nanoparticles (ZnO-NPs) prepared from its extract exhibit specific cytotoxicity toward cervical cancer cells (SiHa) through the induction of ROS-mediated apoptosis 【17】. Similarly, the sterol-rich fraction of *Porphyra dentata* has been shown to reduce tumor growth in 4T1 breast cancer models by suppressing myeloid-derived suppressor cell (MDSC) activity, with β-sitosterol and campesterol as key active compounds 【18,19】.

Porphyra umbilicalis dietary supplementation significantly decreased the formation of dysplastic skin lesions in HPV16 transgenic mice, suggesting protective effects against virus-induced tumorigenesis 【20】. *Gelidium amansii* exerted anti-adipogenic and antioxidant activities in 3T3-L1 cells and is expected to inhibit cancer-related metabolic disorder 【21】. *Kappaphycus alvarezii* and its sulfated polysaccharides (carrageenans) have shown antiproliferative effects in breast, colon, and liver cancer cells, suggesting their potential use as chemopreventive agents 【22】. And *Laurencia papillosa* extracts also showed dose-dependent cytotoxic effect on human breast cancer cell line MCF-7, and caused apoptosis via apoptotic signaling cascades 【23】.

Novel ceramides were proved from the methanolic extract of *Hypnea musciformis* and exhibited appreciable cytotoxicity against MCF-7 cells *in vitro* as well as anticancer activity against EAC by down-regulating VEGF-B and midkine growth factor 【24】. Inhibition of the PI3K/Akt pathway, activation of GSK3β, and apoptosis were induced by *Gracilaria acerosa* extract. It also exhibited antimetastatic function through the down-regulation of MMP2, implying its bivalency in tumorigenesis suppression and metastasis inhibition. 【25】.The methanol extract of *Acanthophora spicifera* exhibited cytotoxic activity against Dalton's ascitic lymphoma (DAL) cells, and the crude polysaccharides of *Gracilariopsis lemaneiformis* induced apoptosis of breast, liver, and lung cancer cells 【26,27】

2.2 Anticancer Activities of Brown Algae

Indian brown algae are known to possess a wide variety of bioactive compounds, viz., fucoidans, phlorotannins, terpenes, polyphenols, sterols, and alkaloids, some of which have exhibited significant anticancer bioactivity *in vitro* as well as *in vivo*.

The most expedient aspects of the Fucoidan from *Sargassum ilicifolium* are a very potent cytotoxic activity in the cell lines, indicating its possibility as a natural anticancer chemotherapeutic agent 【28】. As well, the extracts of *Padina tetrastromatica* significantly decreased the number and survival of tumors in EAC models in a dose-dependent manner, corroborating its apoptotic and antiproliferative effect【29】.

The seaweed *Dictyopteris australis* is a source of a specific combination of C11-hydrocarbons, sulfur-containing compounds, quinone derivatives, and terpenoids that are all related to cytotoxicity or chemoprevention【30】. *Turbinaria ornata*, commercially rich with fucoxanthin, fucosterol, polyphenols, saponins, and terpenes, also demonstrates widespread anticancer activity due to the synergistic action of the metabolites【31】.

Hormophysa cuneiformis is a brown alga and exhibits a strong inhibitory effect against various cancer cells, including HepG2, HL60, A549, and HCT116, with low IC_{50} values such as 44.6μg/mL, showing strong cytotoxicity against different types of tumors 【32,33】. In a recently conducted research, the ethanolic extract of *Stoechospermum marginatum* was found to induce concentration- and time-dependent apoptosis in cancer cells, and exhibited comparable cytotoxicity with that of quercetin, a standard antioxidant compound【34】.

Extracts from *Cystoseira indica* suppressed the proliferation of MCF-7 human breast adenocarcinoma cells, while organic extracts of *Colpomenia sinuosa* decreased the viability of cervical, breast, and colon cancer cell lines, especially HCT-116, in a dose and time-

dependent manner【35,36】. Antiproliferative activity was also reported for *Spatoglossum asperum*, which inhibited 35% growth in Huh7 (liver) and 26% in HeLa (cervical) cells【37】.

All these findings highlight the wide pharmacological capability of Indian brown algae, which can provide the basis of further studies on the development of advanced anticancer treatments.

3. Antidiabetic Activity

Diabetes mellitus is a group of chronic metabolic diseases characterized by defects in insulin secretion, insulin action, or both, resulting in increased blood glucose. Global health data indicate that the main disease is diabetes, and more than 324 million people are expected to have diabetes by 2025【38】. Some chemical drugs provide palliative treatment with undesirable long-term side effects, such as toxicity of the liver and possible carcinogenesis【39,40】. This has raised a growing interest in natural products, in particular of marine origin, because they are safe, cheap, and efficacious.

Seaweeds, particularly red and brown macroalgae, are rich in various bioactive compounds, including sulfated polysaccharides, phlorotannins, sterols, flavonoids, and peptides. These compounds have shown potential in the treatment of diabetes *in vitro* and *in vivo* by inhibiting enzymes, insulin sensitizing, and antioxidant effects【41,42】.

3.1 Antidiabetic Activities of Red Algae

The potential of red algae for diabetes management is highlighted, mainly by inhibiting carbohydrate-hydrolyzing enzymes and pancreatic function.

The hypotensive and antihyperglycemic effects of *Hypnea cornuta* have been attributed to its polysaccharide content, which was found to cause a significant decrease in postprandial blood glucose levels and anti-β-cell damage in animal models【43,44】. Moreover, high α-amylase inhibition activity was also revealed in the *Gracilaria corticata*, which was attributed to the presence of its polyphenolic compounds, supporting their involvement in the control of carbohydrate digestion【45】.

Stigmasterol, a phytosterol with antioxidant and α-amylase inhibitory activities, was isolated from *Gelidium spinosum*. *In vivo* studies proved that stigmasterol considerably lowered blood glucose, urea, and creatinine levels in streptozotocin-induced diabetic rats【46】. *Laurencia dendroidea* ethyl acetate extracts also showed high antioxidant activity (DPPH IC_{50} = 312.09μg/mL) and hypoglycemic effect in diabetic models【47】. *Jania rubens* extracts enhance glucose metabolism and insulin sensitivity; therefore, they are useful for type 2 DM management【48】. *Portieria hornemannii* has been shown to inhibit important diabetic enzymes, viz., α-amylase, α-glucosidase, and DPP-IV, resulting in preventing glucose release and absorption【49】.

Table 1 Bioactivities of Indian red algae

S.No	Algal Species	Type	Bioactive Compounds	Reported Bioactivities	References
1	*Gracilaria edulis*	Red	Sulfated galactans, polyphenols	Anticancer, Antidiabetic, Antioxidant, Antithrombotic, Analgesic, Neuroprotective	【16,17,106】
2	*Gelidiella acerosa*	Red	Sulfated polysaccharides, phytol	Antioxidant, Anticancer, Neuroprotective, Antihypertensive, Antithrombotic	【25,98,28】
3	*Hypnea musciformis*	Red	Ceramides, carotenoids, sulfated galactans	Anticancer, Antioxidant, Antidiabetic, Anti-obesity, Antihypertensive	【24, 69,105】.
4	*Kappaphycus alvarezii*	Red	Carrageenan	Anticancer, Anti-obesity, Antihypertensive, Neurotrophic	【22,168,228】
5	*Laurencia papillosa*	Red	Diterpenes, acetogenins, sterols	Anticancer, Antioxidant, Neuroprotective	【23,161,162】
6	*Acanthophora spicifera*	Red	Apigenin, sterols	Anti-inflammatory, Antithrombotic, Antioxidant	【26,101】
7	*Gracilaria corticata*	Red	Phenolics, galactans	Antioxidant, Antibacterial, Antidiabetic	【27,97】
8	*Hypnea valentiae*	Red	Carrageenan	Antioxidant, Antidiabetic, Antimicrobial	【69】
9	*Gelidium pusillum*	Red	Agar, flavonoids	Antioxidant, Neuroprotective	【29】
10	*Jania rubens*	Red	Calcium carbonate, terpenoids	Antioxidant, Antithrombotic, Antihypertensive	【30,119】

Acanthopora muscoides reduced blood glucose levels and ameliorated haematological and biochemical indices of DM by enzyme inhibition【50】. The antioxidant and the hypocholesterolemic activities of the sulfated galactans of *Spyridia hypnoides* could be of interest for the therapy of diabetes-associated sequelae【51】. The antioxidant status and immune-related gene expression of fish models were enhanced by *Galaxaura oblongata*, indirectly indicating its metabolic regulatory role【52】.

3.2 Antidiabetic Activities of Brown Algae

Evidence from some Indian brown algae has shown that inhibition of carbohydrate-digesting enzymes, antioxidant activity, and glucose modulation mechanisms can be promising for the antidiabetic activity of the extracts.

Crude extracts of *Turbinaria conoides* strongly suppressed α-amylase, α-glucosidase, and dipeptidyl peptidase-IV (DPP-IV), which are involved in the postprandial hyperglycemia through the digestion of complex carbohydrate to glucose【53】. Another research group found that *Sargassum polycystum* extract decreased blood glucose as well as plasma insulin levels in diabetic obese mice, suggesting the systemic hypoglycemic effect of the extract【54】. *Cystoseira trinodis* exhibited the highest activity as an enzyme inhibitor, and its ethyl acetate extract was the most active in terms of α-amylase inhibition, while the methanolic extract was the most potent in terms of α-glucosidase inhibition. In addition, *Cystoseira trinodis* significantly decreased the fasting blood glucose in alloxan-induced diabetic hyperglycemic mice, demonstrating their antidiabetic potential *in vivo* 【55,56】.

Subsequently, *Dictyopteris australis* and *Dictyopteris hoytii* have been investigated for their α-glucosidase inhibitory potential. Two bromobenzene inhibitors were obtained from *D. hoytii*, and *Dictyopteris polypodioides* produced zonarol, a marine hydroquinone that displayed α-glucosidase inhibitory activity involving both competitive and mixed inhibition modes【57,58】. The protein hydrolysates from *Padina tetrastromatica* by subcritical water hydrolysis showed α-amylase inhibitory activity. Moreover, its antioxidant potential, particularly H_2O_2 scavenging, also reinforces its possible role in the prevention of oxidative stress-associated diabetic complications【59,60】.

That extracts of *Hydroclathrus clathratus* can reduce biochemical markers in alloxan-induced diabetic rats, probably via its antioxidant and anti-inflammatory activities【61】. Strong α-glucosidase inhibition (IC_{50} = 3.50±0.75 μg/mL) was exhibited by the 80% methanolic extract of the *Colpomenia sinuosa* at a higher potency than the reference drug acarbose (IC_{50} = 160.15±27.52 μg/mL). *Sirophysalis trinodis* extracts markedly reduced postprandial blood glucose in diabetic rats【62】. Another brown macroalga, *Padina pavonica*, has been described to have antioxidative capacity, which may combat oxidative stress, one of the factors contributing to the pathogenesis of diabetic complications【63】.

4. Antioxidant Activity

Oxidative stress, triggered by the imbalance between reactive oxygen species (ROS) and the antioxidant system of the organism, is a fundamental cause of chronic diseases such as cancer, neurodegeneration, cardiovascular diseases, and skin aging. Antioxidants are bioactive substances that can neutralize free radicals and protect cellular components such as DNA, proteins, and lipids against oxidative damage.

Indian red and brown macroalgae are rich in natural antioxidants such as polyphenols, flavonoids, carotenoids, phlorotannins, and sulfated polysaccharides. These agents work through various pathways, including ROS scavenging, metal ion chelation, increasing activity of endogenous antioxidant enzymes, or modulation of oxidative signaling pathways. Moreover, recent studies have demonstrated that algae extracts can greatly reduce oxidative stress, making them very attractive for the development of drugs, nutraceuticals, and cosmeceuticals【64】.

4.1 Antioxidant Activities of Red Algae

Gracilaria corticata showed significant antioxidant activity, having phenolic and flavonoid content of 4.00±0.35mg GAE/g and 3.33±0.12mg CE/g, respectively. Its DPPH and ABTS scavenging activities were 20.32% and 32.65% revealing its ROS-scavenging capacity【65】. *Gelidiella acerosa* and *Gelidium pusillum* showed prominent antioxidant effects by various mechanisms such as metal chelation and inhibition of oxidative enzymes. *G. pusillum* was linked with a higher total antioxidant activity than *Hypnea musciformis* due to its higher level of phenolics【66,67】.

The DPPH and OH radical scavenging of the carrageenan-rich *Hypnea valentiae* extracts showed scavenging activities of 65.74% and 65.72%, respectively. The carrageenan of this species showed an antioxidant activity of 70.1% at 250 µg/mL【68】. Methanol extract of *Gracilaria filicina* reduced 82% DPPH radical activity and 65% of superoxide anion, which were two-fold higher than positive controls BHT and a-tocopherol, indicating the strong free radical scavenging power【69】.

Halymenia porphyraeformis was found to induce the Nrf2 signaling pathway, which increases the levels of endogenous antioxidant enzymes, demonstrating the possible gene-regulatory MoA【70】. Despite demonstrating cytotoxicity in brine shrimp bioassay by LC_{50} at 635.47µg/mL (acute) and 275.72µg/mL (chronic), *Acanthopora spicifera* exhibited potential to regulate oxidative damage【71】. Extracts of *Asparagopsis taxiformis* (methanol, chloroform, petroleum ether, ethyl acetate) exhibited radical scavenging properties, where the methanol extract exhibited 85% of superoxide inhibition and strong FRAP activity, a likely consequence of its polyphenolic content【72】.

Eucheuma denticulatum ethyl acetate extract (EDEE) was found to have strong antioxidant and free radical scavenging activity with a total phenolic content of 81.34±0.99mg GAE/g and flavonoid content of 5.64±0.12mg QE/g. The DPPH IC_{50} value was 1031.5 ppm, and thus it can be an effective potential candidate for modulation of oxidative stress【73】.

4.2 Antioxidant Activities of Brown Algae

Sargassum wightii crude extract has as high DPPH scavenging activity as that of gallic acid and rutin at 200 µg/mL【74】. The highest antioxidant activity of DPPH (64.14%) and ABTS inhibition (15.02%) for *Turbinaria ornata* further justifies its activity in reducing oxidative stress【75,76】. The methanolic extracts of *Padina tetrastromatica* showed clearly the phenolic (85.61mg GAE/g) and the flavonoid (41.77mg QE/g) contents, the highest in brown algae. It showed 77.07% and 77.65% of DPPH and ABTS activities, respectively, and strong scavenging activities of H_2O_2 (67.89%) and nitric oxide (70.64%). The IC_{50} of DPPH inhibition was 0.96µg/mL, i.e., strong antioxidant capacity【77,78】.

The diterpenoids from *Dictyota dichotoma* displayed powerful antioxidant activity in the ABTS assay. Its most abundant component, fucoxanthin, had 13.5-fold higher hydroxyl radical scavenging activity than vitamin E【79】. The ethyl acetate extract of *Turbinaria conoides* exhibited strong DPPH-radical scavenging activity, which was due to its high phenolic content (105.97mg GAE/g)【80】.

Colpomenia sinuosa dichloromethane: methanol extract exhibited remarkable antioxidant activity, and was also cytotoxic toward colon cancer cells, which may be attributed to the presence of phenolic compounds, diterpenes, and carotenoids 【81】. Sulfated polysaccharide (fucan) fraction from *Lobophora variegata* was highly active in both the phosphomolybdate and radical scavenging assays (EC for hydroxyl radicals = 0.12mg/mL)【82】. Finally, the ethyl acetate extract of *Gracilaria edulis* showed high antioxidant potentials in a range of assays (FRAP, DPPH, ABTS, and metal chelation), thereby validating the potential secondary metabolites【83】.

5. Anti-inflammatory Activity

Inflammation is a dynamic and complex biological response that involves the action of immune cells such as macrophages and neutrophils to pathogens, tissue injury, or irritants. This process is characterized by the release of pro-inflammatory mediators, including TNF-α, interleukins, and prostaglandins, and activation of signaling molecules COX-2, iNOS, and NF-κB. Although acute inflammation helps in tissue healing, chronic inflammation promotes the pathogenesis of several disorders, including arthritis, cardiovascular diseases, and cancer【84-86】.

Marine macroalgae, especially red and brown algae, are important sources of bioactive secondary metabolites such as halogenated diterpenes, acetogenins, sulfated polysaccharides, and phlorotannins. Several studies have reported their potential to modulate inflammation by inhibiting significant signaling pathways such as NF-κB and MAPK, suppressing the production of pro-inflammatory cytokines, and inducing anti-inflammatory mediators【87-90】.

5.1 Anti-inflammatory Activities of Red Algae

Gracilaria salicornia produced new drimane-type quinols that selectively exhibited 5-lipoxygenase and COX-2 inhibition, as confirmed by *in silico* molecular modeling【91-93】. *Laurencia majuscula* provided the maneonene acetogenins and sesquiterpenes that highly decrease nitric oxide release from activated macrophages; compounds 5 and 18 were found to display the most potent inhibitory activity【94】. *Gelidiella acerosa* attenuated inflammation through suppression of NF-κB and via induction of IL-10. Its actions were similar to anti-inflammatory drugs, such as dexamethasone, and could be considered for the treatment of lung inflammation【95】. *Eucheuma denticulatum* has displayed remarkable anti-inflammatory activity in carrageenan-induced paw oedema models, especially at 50mg/kg, which is probably associated with its phenolic constituents【96】.

Apigenin, contained in the red seaweed *Acanthophora spicifera*, inhibited pain and inflammation in animal models through suppression of TNF-α, IL-1β, IL-6, and PGE2 【97,98】. *Pterocladiella capillacea* had *in vivo* antinociceptive, anti-inflammatory, and antioxidant activities by inhibiting xanthine oxidase and bacterial agglutination, suggesting a broad therapeutic application for this alga【99–101】. Extracts of *Hypnea musciformis* were found to inhibit inflammation up to 78.64% in vitro anti-inflammatory activity at a concentration of 200μg/mL【102】. *Gracilaria edulis* inhibited COX-2, PGE_2 production, and NF-κB translocation in hepatitis C virus-infected cells, substantiating the immunomodulatory roles of its polyphenols and ascorbic acid【103,104】.

Laurencia papillosa extracts exhibited a moderate cytotoxicity in leukemia cells, and bioactivity was affected by both seasonal variation and extraction solvents. The cytotoxicity occurred, but its mechanism still needs to be clarified【105】.

5.2 Anti-inflammatory Activities of Brown Algae

Ascophyllan, an inhibitor of adipogenesis from the brown alga, *Padina tetrastromatica*, leading to a reduction in the inflammation in adipocytes and rats, demonstrating its antiobesity and anti-inflammatory activity【106,107】. Lipid extracts from *Sargassum ilicifolium* inhibited NO production and displayed potent radical scavenging and ferric-reducing activity. It is a rich source of sterols, omega-3 PUFAs, and fucoxanthin, and has been demonstrated to be an important anti-inflammatory agent【108–110】. In addition, substituted 2H-pyrano [3, 2-c] pyranoids were obtained with selective activity toward little inflammatory mediators, demonstrating their therapeutic potentials【111】.

Fucoidan isolated from *Dictyota bartayresiana* inhibited ROS, NF-κB activation, and induced apoptosis in an LPS-stimulated macrophage; therefore, fucoidan could be considered as a candidate drug【112】. The anti-inflammatory effect of fucoidan isolated from *Sargassum swartzii* was attributed to the inhibition of TLR-mediated MAPK and NF-κB signals. Non-polar lipophilic compounds of the same alga also revealed anti-inflammatory activity【113】. *Sargassum wightii* alginic acid lowered the expression of inflammatory markers in the collagen-induced arthritic model, which was supported by its flavonoids and sulfated polysaccharides【114】. *Padina gymnospora* showed anti-inflammatory and wound-healing effects as it can enhance the fibroblast migration and reduce the NO production, which led to the potent healing activity and exhibited foliage pattern from the fatty acid profile【115】.

Cystoseira indica demonstrated potent phenolic contents and *in vivo* anti-inflammatory activity at 50mg/kg. A comparative study on fucoidans from some of the Cystoseira species also confirmed their antioxidant and anti-inflammatory potential [116]. Hyaluronidase, the important enzyme in allergic inflammation, was significantly inhibited by *Sargassum tenerrimum* phlorotannins, suggesting that this would be a potential natural agent for the treatment of allergies and inflammation【117】. Polysaccharides of *Sargassum vulgare* and *S. macrocarpum*, including fucans, have demonstrated anticoagulant, antioxidant, and anti-inflammatory activity. Their water extracts also made substantial contributions to the anti-inflammatory activity【118,119】.

6. Antimicrobial Activities

The increasing threat of antimicrobial resistance (AMR) has created an urgent need for new therapeutic agents that are safer and more effective than conventional drugs. Marine macrolagae red and brown have been shown to be a prolific source of antimicrobial compounds such as alkaloids, flavonoids, terpenoids, phenols, sulfated polysaccharides, fatty acids, and steroids 【120】. These bioactive metabolites have broad-spectrum antiviral, antifungal, and antibacterial properties. Disrupting membrane integrity, changing cellular permeability, preventing the synthesis of macromolecules, and interfering with replication and protein synthesis pathways are some of their antimicrobial mechanisms 【121, 122】.

6.1 Antibacterial Activities of Red and Brown Algae

Its dual antibacterial and antifungal potential is suggested by the methanolic extract of *Gracilaria corticata*, which has shown antibacterial effects against *Bacillus subtilis* and a variety of fungal pathogens, including *Trichophyton mentagrophytes, Microsporum canis*, and *M. gypseum*【123】. Cholesterol derivatives from *Laurencia papillosa* exhibited broad-spectrum antibacterial activity against Gram-positive and Gram-negative bacteria, indicating their possible use in pharmaceuticals offers promise【124,125】. *Gelidiella acerosa* has antibacterial, antioxidant, and anticancer potential, and the nanoparticles silver and gold synthesized using this algal extract showed enhanced antibacterial efficacy【126-128】.

The extracts from *Padina tetrastromatica* showed powerful antibacterial activity, where the ethyl acetate fraction was the most potent against *Staphylococcus aureus* and had the lowest effects against *E.coli*【129】. Methanol and ethyl acetate extracts of *Turbinaria conoides* inhibited *Bacillus subtilis, E. coli,* and other pathogens, *E. faecalis*, and *P. aeruginosa*. The ethyl acetate extract has shown results comparable to streptomycin【130,131】. Hexane extracts of *Sargassum ilicifolium* inhibited the growth of Gram-positive bacteria, reportedly due to the presence of sterols and polyphenols, considered the main active compounds. These extracts are also non-toxic and well-tolerated. These extracts can also be exploited for drug development【132,133】. Sulfated polysaccharides obtained from *Sargassum swartzii* showcase effective antibacterial activity, especially against *E. coli* strains, which were confirmed as promising antimicrobials【134】.

6.2 Antifungal Activities of Red and Brown Algae

Some species of red algae show strong antifungal activity. *Gracilaria corticata* has previously demonstrated activity against pathogenic yeast and other fungi by inhibiting fungal growth and mycelial formation in a human and plant model of pathogenicity【135】. *Laurencia obtusa* has been found to contain C12 acetogenins, halogenated metabolites, and antifungal sesquiterpenes. These compounds, such as palmitic acid methyl ester and trichloromethyloxirane, are active against many fungal species【136】. *Halymenia floresii* produced the non-toxic halymeniaol, a hydroxylated sterol that has shown antifungal as well as antimalarial activity, exhibiting promising activity *against Plasmodium faliciparum*【137】.

Among the brown algae, *Padina pavonica* has exhibited cytotoxic and antifungal activities towards tumor and fungal cells 【138】. *Sargassum polycystum* showed activity against the fungus *Candida albicans* and has also been identified with hepatoprotective and antiviral activity. Nanoparticles of silver biosynthesized by it had increased antifungal activity towards some fungal strains【139,140】.

6.3 Antiviral Activities of Red and Brown Algae

Sulfated polysaccharides from red algae have been extensively investigated for antiviral activity. Zinc oxide Nanoparticles, synthesized using Halymenia pannosa, exhibited promising antiviral activity against Coxsackie B4 and HSV-1【141】. Algal Sulfated polysaccharides appear to be promising candidates in the search for new drugs, as *Laurencia obtusa* crude extract was also highly inhibitory against the Hepatitis C virus at 82.36% inhibition【142】. Sulfated galactans isolated from the red algae *Gracilaria corticata* have previously shown effectiveness in the prevention of infection of various viruses, including HSV, HIV, Influenza, and even SARS-CoV-2, proving the versatility of red algal polysaccharides' therapeutic potentials【143】.

In silico docking studies of *Sargassum polycystum*, a brown alga, indicated its potential as an anti-COVID agent through inhibitory effects on the SARS-CoV-2 PLpro enzyme【144,145】. Though some of the compounds obtained from *Turbinaria conoides* did not show significant activity against viruses, the existence of bioactive structures could justify further investigation【146】. Aqueous extracts of *Lobophora variegata* also strongly inhibited HIV-1 replication in vitro and were non-toxic, supporting its application in anti-HIV therapies, irrespective of being elaborated from local algae【147】.

7. Neuroprotective Activities

Neurodegenerative diseases (NDs), including Alzheimer’s Disease (AD), Parkinson's disease (PD), Huntington's Disease, amyotrophic lateral sclerosis (ALS), and multiple sclerosis, are classically defined as disorders involving the progressive loss of neuronal structure and function in the central nervous system (CNS). These diseases are typically associated with permanent motor disability and cognitive decline that is largely mediated by oxidative stress, neuroinflammation, protein misfolding, and mitochondrial dysfunction【148,149】.

Currently, neurodegenerative diseases impact about 50 million individuals worldwide, and this number is predicted to exceed 115 million by 2050 due to the increasing world population age【150,151】. As no definitive cure exists, this has created an increasingly urgent need for measures that are protective at the level of the neuron. Red and brown marine algae have recently been identified as prospective natural sources of neuroprotective compounds with antioxidant, anti-inflammatory, anti-amyloidogenic, and cholinesterase-inhibitory activity 【152-153】.

7.1 Neuroprotective Activities of Red Algae

Laurencia papillosa, a red algae, exerts neuroprotective properties mainly through its antioxidant and anti-inflammatory bioactives, such as diterpenes, bromophenols, and polyphenols, which protect oxidative and inflammatory injury to neuron【154,155】. *Gracilaria edulis*, which shows AChE inhibitory and antioxidant activity, is indicative of possible cognitive advantages in AD and similar neurodegenerative conditions【156】. *Hypnea valentiae* was found to have both AChE and butyrylcholinesterase (BuChE) inhibitory activity as well as antioxidant activity. The fact that its inhibition mechanism is of mixed-type behavior advocates cholinergic therapeutic advantage in AD【157】. *Gelidiella acerosa* provides neuroprotection through free radical scavenging, anti-apoptotic activity, and inhibition of cholinesterase, among other mechanisms. Compounds of this nature, such as phytol, act to further bolster this activity of neuroprotection against amyloid beta toxicity and

neuronal degeneration 【158,159】. Inhibition of oxidative damage, inflammation, and AChE activity, all relevant to Alzheimer's and Parkinson's pathologies, by polyphenols and brominated metabolites found in *Asparagopsis taxiformis* also contributes to neuroprotection【160】. The carrageenophyte *Kappaphycus alvarezii* also possesses neurotrophic activity since it stimulates neurite outgrowth, a process fundamental for neuron development and regeneration. Surface samples incubated for 45 days presented even higher activity than those cultivated at a deeper level, as well as a higher neurotrophic potential when compared to *K. striatum* and *Eucheuma denticulatum*【161】.

7.2 Neuroprotective Activities of Brown Algae

Ample evidence has supported the neuroprotective efficacy of *Sargassum wightii* in Parkinson's disease, where the seaweed was shown to ameliorate dopamine levels, mitigate oxidative stress, and protect mitochondria from impairment in rats treated with rotenone 【162】. *Turbinaria ornata*'s myricetin and fucoidan are both capable of alleviating oxidative stress as well as the destruction of dopaminergic neurons and thus cell death, and making it a useful candidate in PD treatment【163】. The neuroprotective effects of *Padina tetrastromatica* are attributed to its rich content of fucoxanthin, sulfated polysaccharides, and phenolic compounds. These provide antioxidant and enzyme inhibitory properties, which may be valuable in mitigating neuroinflammatory and neurodegenerative processes. Diterpenes, phlorotannins, and sulfated polysaccharides found in *Dictyota dichotoma* support multiple mechanisms of antioxidant, anti-inflammatory, and cholinesterase-inhibiting activity that are important for neuroprotection and slowing neurodegeneration progression. 【164】.

8. Anti-Obesity Activities

Obesity is defined as a body mass index (BMI) greater than 30 kg/m 2, and is characterized by excessive fat accumulation affecting health, and is becoming a pandemic threat to global health. It is particularly associated with increased risk of type 2 diabetes, cardiovascular disease, dyslipidemia, non-alcoholic fatty liver disease (NAFLD), and hypertension, as well as certain cancers. Among them, genetic predisposition, hypothalamic dysfunction, psychogenic stress, and overconsumption of calories in childhood are major contributors. Based on data collected from over 200 countries, obesity is projected to affect 6% of the male and 9% of the female global population by 2025【165-167】. While anti-obesity medications do exist, their use is restricted due to side effects such as increased risk of stroke and cardiovascular conditions【168】. These facts led to growing interest in the use of marine-derived natural compounds as safer and more natural alternatives to the treatment of obesity. 【169】Molecules from seaweed, including alginates, fucoxanthin, fucoidan, and phlorotannins, have shown future possibilities for antiobesity action via mechanisms such as inhibition of enzymes involved in fat absorption, regulation of lipid and lipid metabolism, and appetite and satiety control.

8.1 Anti-Obesity Activities of Red Algae

Hypnea musciformis has also been found to ameliorate lipid metabolism, lower oxidative stress, and decrease levels of cholesterol. A diet rich in it could therefore be supportive in preventing the sequelae associated with obesity-related conditions【170-172】. *Gracilaria edulis* exhibits hypoglycemic and antioxidant activity that aid in the control of blood glucose

and oxidative stress, respectively, which can assist in the anti-obesity potential of this seaweed【173-175】.

Table 2 Bioactivities of Indian Brown Algae

S.No	Algal Species	Type	Bioactive Compounds	Reported Bioactivities	Reference
1	*Turbinaria conoides*	Brown	Fucoxanthin, terpenes, fucoidans	Anticancer, Antioxidant, Anti-inflammatory, Anti-obesity, Antipyretic	【31,76,115】
2	*Sargassum wightii*	Brown	Fucoidan, polyphenols, alginates	Antioxidant, Antidiabetic, Antihypertensive, Anti-obesity, Antimicrobial	【112,118】
3	*Padina tetrastromatica*	Brown	Phlorotannins, sterols, sulfated polysaccharides	Antioxidant, Anti-inflammatory, Neuroprotective, Anti-obesity, Antipyretic	【78,79,110】
4	*Dictyota dichotoma*	Brown	Diterpenes, fucoxanthin	Antioxidant, Anti-obesity, Antithrombotic	【80,213】
5	*Hormophysa cuneiformis*	Brown	Alkaloids, phenolics, sulfated polysaccharides	Anticancer, Antioxidant	【32,33】
6	*Colpomenia sinuosa*	Brown	Polyphenols, diterpenes, carotenoids	Anticancer, Antioxidant, Antidiabetic	【35,62】
7	*Sargassum tenerrimum*	Brown	Fucoidans, flavonoids	Antioxidant, Antidiabetic, Anti-inflammatory	【36,73】
8	*Padina boergesenii*	Brown	Sterols, tannins	Anti-inflammatory, Antioxidant, Antibacterial	【37,99】
9	*Turbinaria ornate*	Brown	Phytosterols, polyphenols	Antioxidant, Antidiabetic	【38,120】
10	*Sargassum polycystum*	Brown	Fucoidan, mannitol	Antioxidant, Neuroprotective	【39,103】

Gracilaria dura inhibits the activity of α-amylase and α-glucosidase, leading to decreased carbohydrate absorption. It's polyphenols and flavonoids also help fight inflammation and oxidative stress associated with obesity【176,177】. *Hypnea cervicornis* has been shown to have enzyme-inhibitory, lipid-modulating, and antioxidant activity in preclinical models. Regulatory activity on appetite has also been suggested, although human studies are still

lacking【178-180】. Similar anti-obesity mechanisms, such as inhibition of enzymes or antioxidant activities, are also portrayed by *Gelidiella acerosa*. It could also be involved in appetite control and satiety【181,182】. *Kappaphycus alvarezii* is also promising via gut microbiota modulation, digestive enzyme inhibition, and lipid metabolism regulation. Plus, its anti-oxidative and anti-inflammatory effects also favor its employment in the control of obesity【183-185】.

8.2 Anti-Obesity Activities of Brown Algae

Sargassum wightii has been identified as a promising agent for functional foods in combating obesity due to the presence of polyphenols and fucoxanthin, which modulate lipid metabolism, promote insulin sensitivity, and mitigate inflammation【186-188】. In rats fed a high-fat diet, *Sargassum polycystum* decreased weight gain and fat storage, suggesting its use as a dietary supplement【189,190】.

In hypertrophied 3T3-L1 adipocytes, *Padina tetrastromatica* has been demonstrated to inhibit lipogenesis and to enhance thermogenesis. *Padina tetrastromatica* and barley combinations were safe and effective in mouse models 【191,192】. Fucoxanthin and fucoidan contained in *Turbinaria ornata* have been shown to affect adipocyte differentiation and lipid metabolism. It also shows potent protective effects in related scenarios associated with oxidative stress due to obesity【193,194】. From *Turbinaria conoides*, they have obtained a derivative of the oxygenated fucosterol with strong binding affinity for fat mass and obesity-associated protein (FTO). Sulfated polysaccharide bioactivity from this algae has also been related to antioxidant activity involved in obesity mitigation【195,196】.

Fucoxanthin and phenolic compounds are present in *Dictyota dichotoma* with significant antioxidant activity. They have been associated with their anti-obesity benefits as well as being a natural therapeutic agent 【197,198】. Fucus vesiculosus has been used medicinally for centuries. Its fucoxanthin and phlorotannins have anti-obesity, antidiabetic, and thermogenic effects. Extracts high in phlorotannins have also exhibited antihyperlipidemic effects, contributing to the prevention of atherosclerosis 【199,200】. *Lobophora variegata* is rich in sulfated polysaccharides and phlorotannins. Though the direct evidence of anti-obesity is limited, its antioxidant and anti-inflammatory activity suggests therapeutic potential【201,202】.

9. Antihypertensive Activity

High blood pressure is a major global health concern as well as one of the primary risk factors for cardiovascular diseases, stroke, and kidney failure. Mainly Red (Rhodophyta) and brown (Phaeophyceae) marine macroalgae are being increasingly recognized for their potential as natural sources of antihypertensive agents. Many have bioactive compounds, including sulfated polysaccharides, peptides, phlorotannins, polyphenols, and have beneficial angiotensin-converting enzyme (ACE) inhibition, vasodilation, and antioxidant effects, among other mechanisms of action【203,204】.

Among red algae, *Gracilaria* and *Hypnea* are known to contain inhibitory peptides and antioxidant compounds. The same applies to brown algae, as is the case for species of *Sargassum*, *Ecklonia*, and *Fucus*, which are rich in phlorotannins and other compounds that

protect the vascular tissues 【205】. These results indicate that marine algae are potential candidates for functional foods and drugs for the control of hypertension【206】.

9.1 Antihypertensive Activity of Red Algae

The high content of antihypertensive phenolics and carotenoids with ACE-inhibitory and antioxidant activity in *Hypnea musciformis* is of interest because it suggests a potential use for the seaweed as an antihypertensive agent. Though only limited in vivo documentation exists, its ethanolic extracts have been demonstrated to exert an antioxidant effect and to improve endothelial dysfunction【207】. *Gracilaria edulis* has been found to have ACE-inhibitory and antioxidant activities, which are presumably attributed to its sulfated polysaccharides. They decrease oxidative injury to vascular tissue and are proposed to play a role in blood pressure homeostasis【208】.*G.verrucosa* has been demonstrated to directly lower blood pressure in rats. Its ethanol extract also lowered systolic and diastolic blood pressure by about 14.6% and 15.1% at a dose of 125mg/kg, possibly due to inhibition of ACE【209】.

Gracilaria dura contains polyphenols and terpenoids known for their antioxidant and ACE-inhibitory activity, consistent with its proposed vascular protective and antihypertensive activity 【210】. *Gelidiella acerosa* has sulfate-rich polysaccharides and peptides, which are involved in the ACE-inhibiting and antioxidant mechanisms of action, highlighting its function in the ability to reduce hypertension. *Kappaphycus alvarezii*, which is rich in kappa-carrageenan, promotes blood pressure regulation indirectly by exerting anti-inflammatory and antioxidant activities on the vascular endothelium【211,212】.

9.2 Antihypertensive Activity of Brown Algae

Chloroform extract of *Sargassum wightii* has been reported to have a potential activity as an ACE-inhibitor with an IC_{50} of about 0.084 mg/mL. Its fractions also exhibit strong anti-inflammatory properties through COX and 5-LOX inhibition and have been noted to protect the vasculature【213】. Phlorotannins from *Ecklonia stolonifera*, such as eckol, dieckol, and phlorofucofuroeckol A, have shown ACE inhibitory activities with IC_{50} values of 70.82 μM, 34.25 μM, and 12.74 μM, respectively. Dieckol acts as a non-competitive inhibitor supporting the long-term regulation of the vascular tone【214】. *Ecklonia cava* has ACE inhibitory properties and also nitric oxide (NO) release from endothelial cells, resulting in vasodilation and reduction of blood pressure. The dieckol derived from this species is a strong ACE-inhibitor that stimulates the endothelium 【215】. Peptides from the enzymatic hydrolysis of *Undaria pinnatifida* (wakame) that inhibit ACE have been demonstrated to decrease systolic blood pressure in humans, confirming their potential for clinical application【216】. Phlorotannins and enzymatically hydrolyzed compounds derived from Fucus spiralis show important ACE-inhibitory effects (IC_{50}~0.5 mg/mL). These double-action molecules would implicate vascular protection and its importance in functional food development【214】.

10. Anticoagulant and Antithrombotic Activities

Cardiovascular diseases are among the most prevalent causes of death in the world, and thrombosis and abnormal blood coagulation are key contributors to their pathogenesis. The risks of traditional anticoagulant and antithrombotic drugs, including bleeding, toxicity, etc., have prompted the search for safer natural alternatives. Red (Rhodophyta) and brown (Phaeophyceae) algae have been identified as rich sources of bioactive molecules with anticoagulant and antithrombotic potential. These algae are particularly rich in sulfated polysaccharides such as carrageenans, agarans, and fucoidans, which are thrombin inhibitors, retards coagulation, and increase fibrinolysis, acting like heparin but with less negative side effects 【217,218】.

10.1 Anticoagulant and Antithrombotic Activities of Red Algae

Several species of red algae are potent blood thinners. *Gracilaria corticata* has shown dose-dependent anticoagulant effects through thrombin and factor Xa inhibition, with a significant increase in aPTT that would indicate a heparin-like action 【219】. *Hypnea valentiae* also presented powerful antithrombotic activity by means of inhibiting platelet aggregation and fibrin formation; its sulfated galactans were successful in preventing thrombus formation in preclinical assays 【220】. The sulfated polysaccharides content of *Gelidiella acerosa* has been shown to have anticoagulant and anti-platelet effects, as it extends coagulation time and affects thrombin activity【221,222】. In the same way, *Grateloupia indica* exhibits aPTT and inhibits thrombin, so its galactans probably behave as low-MW heparins 【223】.

Portieria hornemannii, found in tropical waters in India, is the species that profiles the best anti-coagulant characteristics, since it increases protein C activity and also inhibits thrombin 【224】. *Acanthophora spicifera* is known to affect the intrinsic pathway of blood coagulation, exhibiting prolonged clotting times *in vitro* and *in vivo* 【225】. *Halymenia floresii* acts on intrinsic and extrinsic factors of the coagulation cascade, as its sulfated polysaccharides are also able to decrease the binding of fibrinogen and the ultimate strength of the clot 【226】.

10.2Anticoagulant and Antithrombotic Activities of brown algae

Fucoidans with anticoagulant potential are especially abundant in brown seaweeds. Another example is the fucoidan-rich extract from *Sargassum tenerrimum*, which showed a prominent effect on thrombin formation as well as fibrinolytic capabilities 【227】. *Turbinaria ornata* presented excellent anticoagulant and fibrinolytic action, as well as blocking platelet activation and enhancing the body's anticoagulant activity because of the high sulfation levels found in its fucoidans 【228】. *Sargassum wightii* has fucoidans that are active at both the thrombin and factor Xa level, capable of significantly extending PT and aPTT, suggesting their potent antithrombotic utility【229】. The sulfated fucans extracted from the tropical brown macroalga *Turbinaria conoides*, which is widely distributed, have also been shown to reduce the strength of fibrin clots and favor fibrinolysis 【230】.

Padina tetrastromatica demonstrates medium levels of anti-coagulation through the inhibition of thrombin and stimulation of tissue plasminogen activator (tPA) to support clot

breakdown【231】. *Dictyota dichotoma*, which has been shown to have dose-dependent anticoagulant properties owing to its polysaccharides of high fucosa content 【232】. Additionally, *Stoechospermum marginatum* also has anticoagulant effects by inhibiting the interactions between fibrinogen and thrombin, delaying the formation of clots 【233】.

11. Analgesic and Antipyretic Activities

Analgesic and antipyretic properties are necessary for the symptomatic management of inflammation and infection. Natural products remain a prominent source of these therapeutics, and red and brown taxa of marine macroalgae sourced from the Indian Ocean have received increasing attention as a source of such agents. The bioactive compounds of these seaweeds, including terpenoids, sulfated polysaccharides, flavonoids, and phenolics, have all been found to exert effects by influencing the synthesis of prostaglandins, levels of inflammatory mediators, or nociceptive signaling in animals. The metabolites derived from algae show low toxicity, thus being more biocompatible and eco-sustainable alternatives to chemical synthetic drugs, and thus represent a promising frontier in alternative medicine【234,235】.

11.1 Analgesic and Antipyretic Activities of Red Algae

Hypnea musciformis has shown significant analgesic and antipyretic activity in preclinical studies. Mice exhibiting less writhing in the acetic acid model and increased latency in hot-plate tests following methanolic extracts showed evidence of peripheral and central pain reduction. It also exhibited antipyretic activity in animal models of yeast-induced pyrexia, probably due to blocking the synthesis of prostaglandins. The analgesic and antipyretic activity of *Gracilaria dura* was found to be comparable to standard reference drugs. *In vivo* models have shown it to reduce pain and fever due to its high levels of terpenoids and phenolic compounds with known anti-inflammatory activity. *Kappaphycus alvarezii* showed moderate antipyretic activity and mild analgesic activity in rodents. These bioactivities have been related to the presence of sulfated galactans【234】.

The seaweed *Gracilaria corticata* collected from the coast of Tamil Nadu has been shown to exhibit antipyretic activity in rats with induced pyrexia. Its methanolic extract was shown to have an antipyretic, similar to paracetamol, activity that is dose dependent, a property that indicates this plant as a possible febrifuge【236】.

11.2 Analgesic and Antipyretic Activities of brown algae

Both acetic acid-induced writhing and hot-plate tests have demonstrated potent dose-dependent analgesic activity of *Sargassum ilicifolium*. This extract also exhibited central and peripheral antinociceptive and antipyretic activity, as demonstrated by reduced paw edema induced by carrageenan as well as fever by yeast 【235】. *Sargassum wightii* showed notable anti-inflammatory and antipyretic activity. Fucoidan fractions obtained from the algae were able to impede prostaglandin-mediated hyperthermia and decrease nociceptive measures in rodents【237】.

The presence of flavonoids and sterols in *Padina tetrastromatica* is suggestive of its traditional use as a remedy for fever and pain. These active constituents were also identified by phytochemical screening, supporting interest in the plant as a potential pharmacological

development 【238】. *Turbinaria conoides* has traditionally been employed as a febrifuge in children. Inhibition of pro-inflammatory mediators has been supported experimentally by models that show a significant reduction in body temperature by cyclohexane extracts ($P<0.01$) 【239】. The anti-inflammatory activity of *Stoechospermum marginatum* might be responsible, at least in part, for the analgesic and antipyretic activity. GC-MS screening shows the presence of some bioactive compounds that have the potential to modulate pain and fever pathways 【240】.

Conclusion

Macroalgae have been identified as a good collection of bioactive compounds such as sulfated polysaccharides, phlorotannins, polyphenols, carotenoids, sterols, and peptides with structural diversity, including Indian red and brown macroalgae. A broad spectrum of pharmacological properties has been observed in *vitro* and *in vivo*, including anticancer, antidiabetic, antioxidant, anti-inflammatory, antimicrobial, and neuroprotective. Anti-obesity, antihypertensive, anticoagulant, analgesic, and antipyretic activities. These bioactive compounds work through different mechanisms on molecular levels that include redox modulation, inhibition of enzymes or other biologically relevant ligands, triggering anti- and pro-apoptotic responses, inhibition of the inflammatory pathway, and metabolic regulation.

Most importantly, these marine resources are sustainably available along the Indian coast and can provide biocompatibility and wide-ranging therapeutic and, underscoring their promise as auspicious candidates for pharmaceutical, nutraceutical, and cosmeceutical development. Unfortunately, translating these results into clinical practice is constrained by limitations such as variability in bioactive compound yield, the absence of standardized extraction protocols, low bioavailability, and a lack of human trials.

Future Prospects

Recent challenges that hinder the clinical and commercial translation of Indian red and brown macroalgae demand inclusion in future studies. To improve reproducibility and consistency in the yield of bioactives by season and location, extraction and purification protocols must be standardized. Development of formulation technology, including nanoencapsulation and targeted delivery systems, could significantly increase stability and bioavailability of algal derivatives, enhancing their therapeutic potential. By employing a combinatorial approach using omics-based approaches such as genomics, metabolomics, and proteomics, the identification of new compounds and their mechanisms of action is likely feasible. Further studies incorporating *in vivo* verification coupled with methodical clinical studies for determining the effectiveness, safety, and proper dosing in humans are warranted, and work is already in progress. Future industrial needs for these compounds will require large-scale aquaculture or sustainable methods of biotechnological growth, while minimizing depletion of natural resources. Furthermore, the application of these bioactive-rich seaweeds in the preparation of functional foods, nutraceuticals, and cosmeceuticals could represent a preventive healthcare model. Thus, Indian red and brown algae have the potential to emerge as vital contributors to marine-based drug discovery and global health solutions by bridging the current gap between laboratory research and applied product development.

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