Journal of Advanced Zoology

ISSN: 0253-7214

Volume 45 Issue 1 Year 2024 Page 270:281

A Review on Seaweed Potential on Environmental Remediation and Biomedical Applications

Uddappanda Bopaiah Roy[1], Premalatha S.J.[2], Parimala B.[3], Sathish S.V.[4], Deekshitha M.B.[5], Renuka Jyothi S.[6], Pramod T.[7], Usha M.S.[7], and Sharangouda J. Patil[8*]

[1]*Department of Zoology and Genetics, Nrupathunga University, Bengaluru, Karnataka, India*
[2]*Department of Studies in Biochemistry, Government Science College, Chitradurga, Karnataka, India*
[3]*Department of Zoology, University College of Science, Tumkur University, Tumkuru, Karnataka, India*
[4]*Department of Zoology, Shri Mahadeshwara Government First Grade College, Kollegal, Chamrajnagar, Karnataka, India*
[5]*Department of Life Science, School of Sciences, Garden City University, Bengaluru, Karnataka, India*
[6]*Department of Life Science, School of Sciences, Jain (Deemed-to-be-University), Bengaluru, Karnataka, India*
[7]*Department of Microbiology, School of Sciences, Jain (Deemed-to-be-University), Bengaluru, Karnataka, India*
[8*]*Department of Zoology, NMKRV College for Women (Autonomous), Bengaluru, Karnataka, India*

***Corresponding Author:** Dr. Sharangouda J. Patil*
Department of Zoology, NMKRV College for Women (Autonomous), Bengaluru, Karnataka, India
E-mail: shajapatil@gmail.com

Received on 03 Oct 2023
Revised on 06 Dec 2023
Accepted on 09 Dec 2023

Abstract

Seaweeds exhibit a remarkable capacity for bioremediation, acting as natural filters that sequester pollutants like heavy metals, nutrients, and organic matter from waterways. This inherent ability translates into promising wastewater treatment technologies, offering a sustainable alternative to traditional chemical-intensive methods. Seaweeds perform bioremediation feats, drawing out toxins and paving the way for revitalized ecosystems. The environmental benefits of seaweeds extend beyond pollution mitigation. These efficient photosynthesizers act as potent carbon sinks, capturing atmospheric CO_2 and mitigating the effects of climate change. A vast number of bioactive compounds lies within their cellular walls, possessing a range of potential therapeutic properties. Seaweed extracts find their way into functional foods, enriching our diets with antioxidants, anti-inflammatory agents, and prebiotics. These nutritional powerhouses hold the potential to enhance immunity and overall well-being, offering a natural path towards improved health. Seaweed extracts are being investigated for their role in developing novel drugs and diagnostics. Imaging tools and biocompatible materials derived from these marine marvels could revolutionize personalized medicine. However, unlocking the full potential of seaweeds necessitates addressing challenges associated with large-scale cultivation and processing. Sustainable practices and cost-effective methods are crucial for ensuring the economic viability and ecological integrity of seaweed utilization. This review explores the

	multifaceted applications of seaweeds, highlighting their ability to remediate polluted environments and contribute to human health while acknowledging the challenges associated with their large-scale utilization.
	Keywords: *Seaweed, environmental remediation, wastewater treatment, bioremediation, carbon capture, nutraceuticals, functional foods, pharmaceuticals, medical applications*.

Introduction

Seaweeds, classified as macroalgae, stand as ubiquitous inhabitants of coastal regions worldwide, contributing significantly to the intricate tapestry of marine ecosystems (Delf, 1943). Their ecological significance extends far beyond their aesthetic appeal, encompassing vital roles in oxygen production through photosynthesis, provision of habitats for diverse marine organisms, and the stabilization of coastlines, effectively mitigating erosion. These ecological roles underscores the fundamental importance of seaweeds in maintaining the balance and vitality of coastal environments (Fleurence, 2016).

Despite their ecological contributions, coastal regions face escalating challenges due to rampant environmental pollution stemming from industrial activities and nutrient run-off from agricultural practices. This deleterious influence poses a substantial threat to coastal ecosystems, necessitating urgent and sustainable remediation strategies. In response, the imperative to develop effective and environmentally friendly approaches to cleanse industrial waste and excess nutrients from aquatic environments has never been more pressing (Lomartire & Gonçalves, 2022).

Simultaneously, the biomedical field is experiencing relentless advancements, marked by the continuous development of novel drugs, biomaterials, and therapeutic interventions. However, the current trajectory often relies on non-renewable resources and grapples with safety and sustainability concerns. The imperative to seek alternative sources from nature has become paramount, prompting a profound exploration of the vast potential harbored within the natural world (Lomartire et al., 2021).

Amidst this backdrop, seaweeds emerge as promising candidates, offering a myriad of possibilities to confront the challenges in both environmental remediation and biomedical applications. Their abundance across diverse coastal ecosystems, coupled with the presence of a rich array of bioactive compounds, positions seaweeds as versatile resources capable of addressing the intricate challenges of our times (Rao et al., 2018). Therefore, the objective of this review is to explore the potential of various seaweed species for applications like wastewater treatment, heavy metal removal, and use as antimicrobial, anticancer, or wound healing agents. The review aims to summarize recent research on seaweed-based techniques and products for environmental remediation and biomedicine.

Seaweed Characteristics and Bioactive Compounds

Seaweeds possess several advantageous biological characteristics that make them highly valuable for various applications. They exhibit rapid growth rates, often doubling their biomass in less than a month under optimal conditions, without requiring fertilizers or freshwater (Tseng, 1944). This is significantly faster than terrestrial plants. Some species of seaweeds like Kappaphycus and Eucheuma can renew their entire biomass in just 10-30 days (Carpena et al., 2021). This renewable biomass productivity enables harnessing seaweeds as a sustainable resource.

Additionally, seaweeds demonstrate remarkable resilience - they can thrive in diverse marine environments, adapting to wide ranges of salinity, temperature, sunlight and water conditions (Hentati et al., 2020). Different seaweed species inhabit rocky coasts, estuaries, tidal pools and coral reefs. This adaptability allows them to grow abundantly, making seaweed cultivation highly feasible. The characteristics of seaweeds are listed out in Table 1.

Table 1: Characteristics of seaweeds

Characteristic	Description
Growth Rates	High growth rates, varying by species
Adaptability	Thrives in diverse environmental conditions
Cultivation Potential	Varies based on species and cultivation methods
Reproductive Strategies	Utilizes both sexual and asexual reproduction

Size and Morphology	Ranges from microscopic phytoplankton to large kelp species
Temperature Tolerance	Exhibits a broad range of temperature tolerance
Salinity Range	Can adapt to a wide range of salinity levels
Light Requirements	Varies; some species thrive in low light conditions
Nutrient Preferences	Different species have specific nutrient requirements
Invasive Potential	Some species have invasive characteristics, impacting local ecosystems

The unparalleled combination of rapid growth and exceptional environmental resilience affords seaweeds a distinctive advantage over traditional land-based crops. Seaweed aquaculture has emerged as a highly efficient and sustainable practice, boasting the potential to produce biomass at yields estimated to be 5-30 times greater per hectare than terrestrial agriculture, all while requiring minimal inputs (Holdt & Kraan, 2011). This inherent efficiency positions seaweeds as an exceptionally promising candidate for the sustainable production of bioactive compounds, thereby contributing to the fields of biomedicine and environmental remediation.

Seaweeds represent prolific sources of an extensive array of bioactive molecules, encompassing polysaccharides, pigments, proteins, lipids, antioxidants, vitamins, and enzymes (Remya & Rajasree, 2016). Among these, polysaccharides such as alginates, carrageenans, and ulvans stand out for their multifaceted therapeutic properties, demonstrating antimicrobial, antiviral, anticoagulant, and anticancer effects (Rengasamy et al., 2020). For instance, alginates exhibit remarkable antimicrobial capabilities, carrageenans show promise as antiviral agents, and ulvans have demonstrated potent anticancer effects.

Extracts derived from brown seaweeds, such as fucoxanthin and phlorotannins, represent formidable sources of bioactive compounds. Fucoxanthin, a brown pigment, and phlorotannins, polyphenolic compounds, exhibit robust antioxidant properties, along with anti-inflammatory, antidiabetic, and anti-obesity effects (Sakthivel & Devi, 2019). These compounds exemplify the diverse therapeutic potential residing within seaweeds, showcasing their capacity to address multifaceted health challenges.

Moreover, enzymes isolated from seaweeds have garnered attention for their efficacy in bioremediation and wastewater treatment (Sapatinha et al., 2022). These enzymes exhibit catalytic prowess in breaking down pollutants and facilitating the removal of heavy metals from wastewater, underscoring the environmental applications of seaweed-derived enzymes. With advancing research, seaweeds are proving to be a versatile and sustainable resource that can provide solutions for food security, healthcare and environmental remediation. The actual role of compounds in the physiology of seaweeds and their sources are listed out in Table 2.

Table 2: Bioactive compounds from different seaweeds

Category of the bioactive compounds	**Role in seaweed physiology**	**Major compounds**	**Seaweed source**
Pigments	Chlorophyll for photosynthesis Carotenoids for photoprotection and color Phycobilins for light absorption in unique colors	Chlorophyll Fucoxanthin Phycoerythrin	Green Brown Red
Polysaccharides	Structural components, storage of energy, Modulation of immune responses	Alginates Carrageenan Agar Ulvans	Brown Red Red Green
Lipids	Structural components, storage of energy,	Omega-3 fatty acids Sterols	Brown Green
Phenolics	Scavenging reactive oxygen species (ROS) Protecting cells from oxidative stress Contributing to overall cellular health	Phlorotannins Halogenated furanones	Brown Red
Proteins	Facilitating metabolic processes Defense against pathogens and herbivores Role in nutrient acquisition and assimilation Modulation of seaweed's extracellular matrix	Lectins Phycobiliproteins	Green Red
Vitamins	Facilitating metabolic processes Defense against pathogens and herbivores	Vitamin A Vitamin B1, B2 Vitamin C Vitamin E	Brown Green
Minerals	Modulation of seaweed's extracellular matrix and aiding physiological homeostasis	Iodine Iron Calcium Magnesium Sodium	Brown Red Green

Environmental Remediation Applications

Seaweeds possess certain inherent biological capabilities that make them well-suited for remediating environmental pollutants and wastes. Their extensive surface area provided by complex branching thalli along with the presence of chemically active polysaccharides on their cell walls, enables seaweeds to effectively absorb dissolved nutrients, metals and organic matter (Baghour, 2017).

Treatment of Wastewater

The fast uptake of dissolved nutrients by seaweeds can be harnessed as an effective means of treating wastewater. Several studies have tested and validated the ability of seaweeds to remove excess nitrogen and phosphorus from aquaculture effluents. Species such as *Ulva lactuca* and *Gracilaria edulis* can take up inorganic nutrients and bring down total nitrogen and phosphorus concentrations significantly. Their nutrient removal rates matched and even exceeded standard chemical treatments in some cases (Bartucca et al., 2022). Capitalizing on this, commercial biofiltration systems using live seaweeds have been developed. The Sea Pure system uses Ulva sp., also known as Sea Lettuce, while Kelp Works utilizes the giant kelp *Macrocystis pyrifera*. As the nutrient-rich wastewater flows through tanks containing these seaweeds, they absorb the dissolved nitrates and phosphates, thereby purifying the water. These seaweed bioreactors have been successfully used to treat different industrial effluents, sewage water, agricultural runoffs and contaminated freshwater bodies (Luo et al., 2020).

In contrast to traditional physicochemical methods, seaweed biofilters emerge as a cutting-edge and environmentally sustainable alternative for wastewater treatment, presenting an energy-efficient and cost-effective solution. These biofilters stand out for their capacity to operate without the need for additional chemical inputs or aeration, reducing the environmental footprint associated with conventional treatment methods. This intrinsic eco-friendliness aligns with contemporary efforts towards sustainable and green technologies in wastewater management (Deniz & Ersanli, 2018).

One key advantage of seaweed biofilters lies in their simplified maintenance and operational processes. Unlike complex physicochemical treatments, seaweed biofilters require minimal intervention, and their periodic harvesting serves a dual purpose. Not only does it remove accumulated nutrients from the wastewater, preventing eutrophication and associated environmental issues, but it also offers a valuable biomass resource. This harvested seaweed biomass, enriched with nutrients, has been explored for its potential as a biofertilizer in agricultural applications. The processed water from seaweed biofilters exhibits high quality, making it suitable for reuse in irrigation or safe discharge into the environment. The versatility of seaweed biofilters in treating different types of contaminants, including heavy metals and organic pollutants, further underscores their potential as a versatile and efficient wastewater treatment technology (Mansour et al., 2022).

Scientific studies have delved into the specific mechanisms underlying the effectiveness of seaweed biofilters in wastewater treatment. The unique metabolic processes of seaweeds contribute to nutrient removal through adsorption, absorption, and assimilation, actively participating in the reduction of pollutants. Additionally, the role of specific bioactive compounds, such as polysaccharides and enzymes, in enhancing the bioremediation capabilities of seaweeds has been a subject of scientific investigation (Michalak, 2020).

Furthermore, the recognition of seaweed biofilters as a green technology extends beyond their immediate wastewater treatment applications. Phytoremediation with seaweeds is increasingly acknowledged for its broader environmental implications, highlighting the capacity of these marine organisms to play a pivotal role in ecosystem restoration and sustainability (Cotas et al., 2021).

Bioremediation and Phytoremediation

Several species of seaweeds have demonstrated promising potential for removing heavy metals and inorganic pollutants from contaminated marine environments through phytoremediation. Brown seaweeds like Sargassum have extensive root-like holdfast structures that firmly attach them to sediments. These holdfasts penetrate inside sediments and can absorb and accumulate heavy metals like lead, arsenic, chromium and cadmium. Sargassum also releases metal-chelating compounds such as alginates and fucoidan into the sediments which immobilize and detoxify heavy metals. Multiple studies have shown that cultivating Sargassum plantations helps extract heavy metals from contaminated estuarine and mangrove sediments (Varabih & Nofirman, 2023).

Other seaweeds like the brown alga *Fucus serratus* are intertidal, meaning they get exposed during low tides. Studies have tested Fucus serratus for reducing heavy metal mobility in sediments collected from zinc and copper mine tailing ponds. Periodic exposure to air enables Fucus to release oxidative compounds that alter

metal solubility in sediments. Thereby the mobility and toxicity of heavy metals like cadmium, copper and zinc can be mitigated (Wang et al., 2018, Singh et al., 2023, Mahishi and Patil, 2023).
In addition to direct metal uptake, seaweeds like kelps modify their chemical environment through release of compounds that change metal bioavailability. Thereby they can efficiently extract a broad range of toxic inorganic pollutants. Through rhizofiltration and bioaccumulation, seaweeds can purify marine and estuarine sediments contaminated by mining, industrial and harbor activities. Their metal removal efficiencies, ease of harvesting and environmentally benign nature makes seaweeds suitable for phytoremediation (Cotas et al., 2021). The seaweed species used in phytoremediation are listed out in Table 3 and the mechanisms involved in bioremediation mechanisms are illustrated in Figure 1

Table 3: Seaweed species used in phytoremediation

Species	Major Bioactives	Pollutants Removed	Mechanisms	Removal Efficiency
Sargassum sp.	Alginates, fucoidan	Cd, Cu, Pb, Zn	Biosorption, chelation	70-90%
Ascophyllum nodosum	Phlorotannins	Total Petroleum Hydrocarbons (TPHs) and Polycyclic Aromatic Hydrocarbons (PAHs)	Degradation	60%
Fucus vesiculosus	Fucoidan	Cu, Hg	Extracellular complexation	82%
Ulva lactuca	Ulvan	NH^{4+}, PO_4^{3-}	Cellular uptake	63%
Gracilaria sp.	Agar	Pb, Cr	Ion exchange	87%
Ecklonia sp.	Phlorotannins	Trinitrotoluene (TNT)	Enzymatic transformation	78%
Durvillaea antarctica	Sulfated polysaccharides	As, Mo, V	Chemisorption	83%
Lessonia nigrescens	Lessonia	Cu	Intracellular accumulation	71%

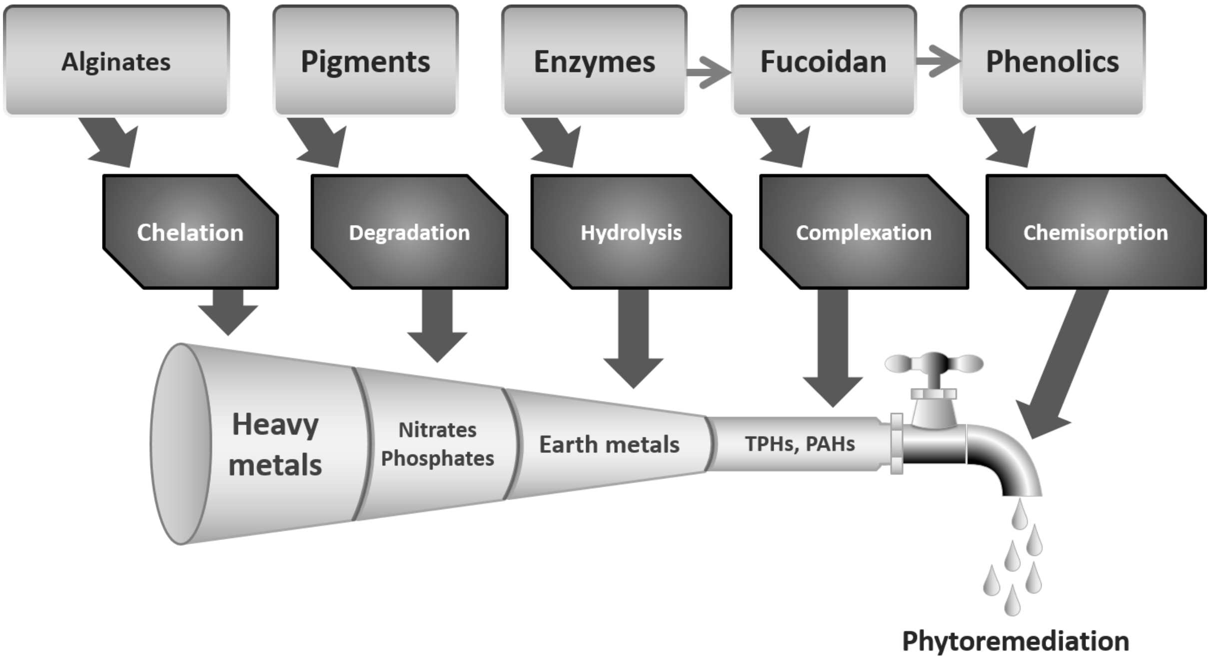

Figure 1: Bioremediation mechanisms of seaweed bioactives

Carbon Sequestration

As aquatic autotrophs that fix inorganic carbon through photosynthesis, seaweeds act as natural carbon sinks. Research estimates that kelps like the giant kelp *Macrocystis pyrifera* can sequester up to 200 grams of carbon per square meter per year. Other brown algae like Sargassum sp. fix 50-100 grams of carbon annually. This high carbon fixation rate makes seaweed farms potential tools for mitigating climate change through carbon sequestration (Cotas et al., 2020; Ganesan et al., 2019).

Pilot projects are testing integration of seaweed aquaculture with carbon capture and storage technology. The Kelp Blue Carbon project in California cultivates *Macrocystis pyrifera* near offshore carbon dioxide emission sources to effectively capture and sequester the greenhouse gas. Similar efforts by Ocean Rainforest in the North Sea use steel structures to support large seaweed farms that absorb emissions from fossil fuel plants (Liu et al., 2020).

In addition to combating ocean acidification and rising emissions, the harvested seaweed biomass can serve as renewable biofuel, animal feed or fertilizer- thereby generating economic value. However, more research is required to quantify carbon sequestration potential across different seaweed species, oceanic conditions and cultivation systems. Efficient integrated systems that are economically feasible at large scales need development before the promise of seaweed carbon sequestration can be fully realized. Nevertheless, the combination of rapid growth, high carbon fixation ability and environmentally benign nature makes seaweeds a promising natural solution for mitigating climate change. The environmental applications of seaweeds are summarized in Table 4.

Table 4: Environmental applications

Application	Mechanism of Action
Wastewater Treatment	Adsorption of heavy metals and pollutants onto seaweed surfaces
	Absorption of dissolved organic compounds and nutrients
	Nutrient removal through uptake in seaweed biomass
Bioremediation and Phytoremediation	Breakdown of hydrocarbons through enzymatic activities
	Enhanced microbial degradation facilitated by seaweed root exudates
	Accumulation of heavy metals in seaweed tissues for pollutant removal
	Phytoremediation involving absorption and sequestration of pollutants
Carbon Sequestration	Photosynthetic carbon fixation, converting CO2 into biomass
	Incorporation of carbon into seaweed biomass for long-term storage
	Contribution to reducing atmospheric CO2 concentrations
	Enhanced carbon sequestration in coastal ecosystems
Mechanisms of Remediation	Desorption and release of adsorbed pollutants during regeneration
	Microbial activities in the rhizosphere promoting soil health
	Enhanced nutrient cycling through seaweed decomposition

Biomedical Applications

Seaweeds are increasingly being recognized as a valuable source of bioactive compounds that can be harnessed for human health and medical applications.

Nutraceuticals and Functional Foods

The rich nutritional profile and abundance of bioactive compounds make seaweeds an excellent source of nutraceuticals and functional foods (Sarella & Thammana, 2023). Seaweeds like kelps (Laminaria), nori (Porphyra), and dulse (Palmaria) contain a wide array of essential minerals like iodine, iron, zinc, calcium, potassium and beneficial vitamins A, B, C, E (Mangam et al., 2018). Edible seaweeds provide good dietary fiber content ranging from 33-50% dry weight, which promotes gut health (Okolie et al., 2022).

In addition, seaweeds contain diverse bioactive molecules. Fucoidans and laminarins from brown algae exhibit anticancer, antiviral, anticoagulant and immunomodulating effects (Sakthivel & Devi, 2019). Phlorotannins from brown seaweeds act as antioxidants and have antidiabetic and anti-inflammatory properties (Sohn et al., 2021). Polysaccharides from green and red seaweeds also display prebiotic and neuroprotective activities.

Multiple studies have demonstrated the ability of seaweed extracts and powders to reduce risk factors associated with obesity, hypertension, diabetes and cardiovascular diseases (Venkatesan et al., 2017). Seaweed polyphenols may also help prevent neurodegenerative disorders like Alzheimer's. Products containing seaweed powders, capsules and extracts are commercially marketed as superfoods and nutritional supplements owing to their medicinal properties and overall health benefits. The functional food industry has launched several products like snacks, seasonings, sauces, noodles, milkshakes and teas infused with seaweeds to meet growing consumer demand for such fortified foods (Vidanarachchi et al., 2013). Thus, ongoing research aims to further explore the diverse nutraceutical potentials of seaweeds for promoting human nutrition, medicinal uses and food security. The chemical constituents of seaweeds with physiological importance are depicted in Figure 1. The commercial nutraceutical products based on seaweeds are listed out in Table 5

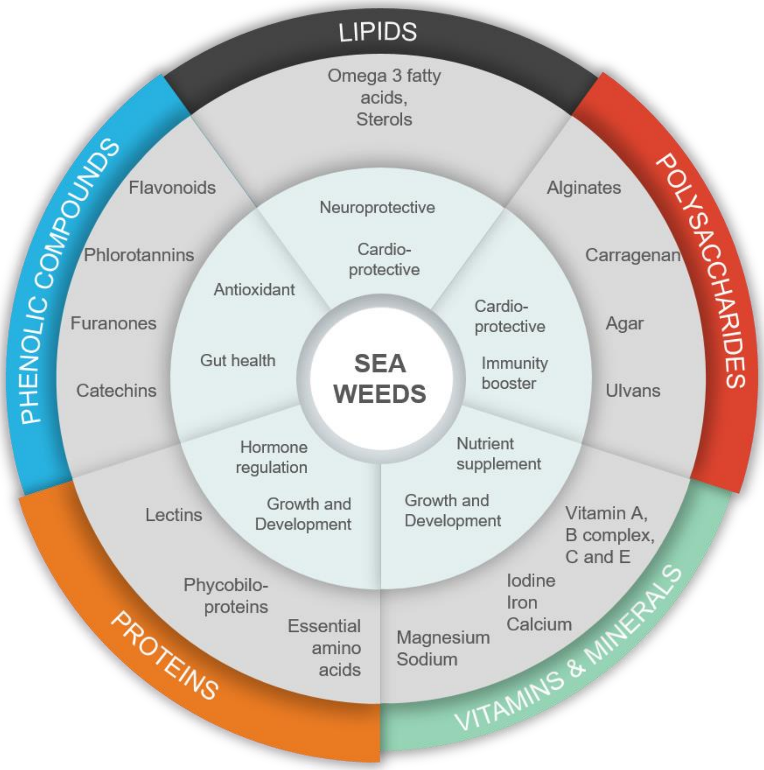

Figure 1: Chemical constituents of seaweeds with physiological importance

Table 5: Commercial nutraceutical products based on seaweeds

Product Name	Company	Seaweed Source	Bioactive Compounds	Health Benefits
OcéAlg	Océalg	*Laminaria digitata*	Polysaccharides	Immunity enhancer
Seagreens® capsules	Seagreens®	*Ascophyllum nodosum*	Fucoidan, phenolics	Antioxidant
Kombucha	GT Dave's	*Laminaria japonica*	Fucoidan	Gut health
Granola bars	Decathlon	*Kelpful Porphyra*	Polysaccharides	Heart health
Dulse flakes	Maine Coast Sea Vegetables	*Palmaria palmata*	Minerals, protein	Nutrient supplement
Ocean's Halo seaweed chips	Ocean's Halo Norilife	*Undaria pinnatifida*	Carotenoids, fiber	Weight management
Seaweed facial sheet masks	My Beauty Diary	*Undaria pinnatifida*	Amino acids	Anti-aging
Thrive Algae Oil	Simris Alg	*Ulva lactuca*	Omega-3	Brain health
Neptune krill oil	Neptune	*Schizochytrium sp*	Omega-3, astaxanthin	Heart health

Pharmaceuticals

Seaweeds produce a wealth of novel bioactive compounds that exhibit therapeutic pharmacology, indicating promise as drug leads for treating various diseases. Sulfated galactans like carrageenan from red algae such as Gracilaria have demonstrated anti-proliferative effects against lung, breast, liver and prostate cancer cells in preclinical studies (Sarella & Thammana, 2023). Based on this, the patented Gracilaria extract I-REX is currently undergoing Phase 2 clinical trials in Chile for treating advanced liver cancer and digestive tumors (Siahaan et al., 2018). Dieckol, a phlorotannin isolated from brown alga Ecklonia cava, showed potent inhibition of HIV-1 protease and influenza neuraminidase enzymes in vitro (Pereira & Costa-Lotufo, 2012). Dieckol is now formulated as an antiviral ingredient in some cosmetic products (Lomartire et al., 2021). Fucans are a group of sulfated polysaccharides from brown algae that exhibit anticoagulant and antithrombotic effects. Their mechanisms involve antithrombin activation and inhibition of procoagulant proteins like factor Xa (Baker, 1984). Fucans have shown potential as safer alternatives to heparin for thromboprophylaxis. Other brown algal phlorotannins like phlorofucofuroeckol-A indicate neuroprotective effects that may have applications against Alzheimer's disease. Some red and green seaweed extracts have also displayed anti-diabetic effects related to α-amylase and α-glucosidase enzyme inhibition (Afzal Rizvi & Shameel, 2005).

Medical Diagnostics and Devices

Unique compounds extracted from seaweeds are being widely researched for innovative applications in medical diagnostics, tissue engineering and drug delivery devices. The polysaccharide alginate can form hydrogels that are biocompatible, porous and mimic extracellular matrices. This enables their use in engineering bone, cartilage and cardiac tissue scaffolds. Injectable alginate gels are also being developed for wound healing and regeneration. Furthermore, alginate is used to encapsulate pancreatic islet cells for transplantation in diabetic patients. The capsules protect the islets from immune rejection while allowing diffusion of insulin (Jing Zhao et al., 2021). Clinical trials have demonstrated long-term reversal of diabetes in some alginate islet recipients. Fucoidan is a sulfated polysaccharide that has excellent metal ion chelating abilities. Based on this, fucoidan nanoparticles are being engineered for use as contrast enhancing agents in cancer diagnostic techniques like MRI imaging. Some sulfated polysaccharides from seaweeds have anti-adhesive properties that prevent bacterial biofilm formation on surfaces. Coating medical devices like catheters with these compounds can potentially reduce microbial infections. Thus, the diversity of seaweed polymers allows innovative applications in tissue engineering, drug delivery, medical diagnostics and antimicrobial coatings. Further research aim to develop seaweed-derived platforms that can improve personalized treatment and regeneration of tissues (Delf, 1943; Rao et al., 2018). The unique biomedical applications of seaweeds are listed out in Table 6

Table 6: Biomedical applications

Application	Therapeutic Mechanisms
Nutraceuticals and Functional Foods	Rich source of essential vitamins and minerals Dietary fiber for digestive health Omega-3 fatty acids for cardiovascular support Antioxidants combating oxidative stress Immunomodulatory effects supporting overall health
Pharmaceuticals	Antibacterial properties inhibiting microbial growth Antiviral activity against certain viral pathogens Anti-inflammatory effects reducing inflammation Anticancer properties impeding cancer cell proliferation
Medical Diagnostics and Devices	Bioimaging agents for non-invasive imaging Biosensors for rapid and sensitive detection of biomarkers Controlled drug delivery systems for targeted therapies Tissue engineering scaffolds for regenerative medicine
Therapeutic Mechanisms	Antimicrobial action disrupting pathogen cell membranes Anticancer effects inducing apoptosis in cancer cells Anti-inflammatory mechanisms modulating immune responses Wound healing properties promoting tissue regeneration

Limitations and Ongoing Research

While seaweeds possess diverse applications, there are some limitations that need addressing through ongoing research.

Cultivation Challenges

Expanding seaweed cultivation to meet growing demands faces certain constraints that need sustainable solutions. Onshore seaweed farms require suitable stretches of coastline providing optimal temperatures, sunlight, nutrients and water flow. Nearshore waters meeting these conditions are limited. Clearing coastal ecosystems like mangroves for farming may disrupt native species. Additional infrastructure needs like anchors, floated ropes and motorized barges may be expensive (Bartucca et al., 2022).

Offshore cultivation systems allow accessing more space and nutrients without competing for coastal land. But operating costs for equipment and maintenance are higher. Monitoring and harvesting offshore farms is also technologically challenging. Furthermore, large-scale seaweed monocultures could impact local biodiversity, change sedimentation rates, or lead to eutrophication from excess nutrients upon decomposition of unharvested seaweeds (Radulovich et al., 2015).

Potential strategies to expand production sustainably include developing integrated multi-trophic aquaculture systems. Here seaweeds can be co-cultivated with finfish, mollusks and other organisms at appropriate densities to minimize environmental impacts. Such systems would also allow utilizing waste nutrients, thereby creating economic value. Advanced technologies like subsurface ocean farming models, biofouling resistant materials, and digital monitoring systems could also help scale-up seaweed farming in an eco-friendly manner (Hafting et al., 2015). But these solutions require further research and investment.

Harvesting and Processing

Harvesting and processing seaweed biomass into high-value products poses some technical and economic hurdles. Harvesting seaweeds manually is labor-intensive and time-sensitive. Seaweeds have high water content, so timely harvest and processing is crucial before spoilage. Farm machinery suited for marine environments is limited. Developing automated harvesters or robotic solutions can help, but involves high initial investment. Fresh seaweeds have short shelf-life. So drying methods like solar, freeze and spray drying are commonly used for preservation. But these are energy-intensive and can degrade sensitive compounds. Optimized drying protocols are needed. Conversion of seaweed biomass into value-added ingredients or products requires extraction using physical, chemical or enzymatic methods. Extraction efficiencies can vary widely based on solvents, time, temperatures and other factors (Buschmann et al., 2008). Standardizing optimized protocols for maximizing yields remains a challenge. Overall, the lack of specialized equipment, intensive manual labor needs, high energy requirements and variability in downstream processing results in high production and inventory costs. Advances in novel preservation techniques, automated harvest and extraction technologies can help enhance the commercial viability of seaweed-derived products.

Cost-Effectiveness

The utilization of seaweeds in environmental cleanup has exhibited remarkable remediation capacities, yet the practical implementation of these applications in a commercial context demands cost-competitive production for widespread adoption (Siahaan et al., 2018). The economic viability of seaweed-based technologies and products, particularly for single-use treatment of industrial waste or contaminated sites, is currently hindered by the elevated costs associated with seaweed biomass and extracts.

Comprehensive economic assessments encompassing every stage of seaweed utilization, from cultivation to processing, remain limited for most seaweed species. This critical gap includes the evaluation of costs related to establishment, maintenance, harvesting, and both pre- and post-harvest handling, as well as extraction methods. A thorough documentation of these costs across diverse scales, geographical locations, and commercial setups is imperative. Such an approach would not only facilitate the identification of the most efficient practices but also contribute to the realistic pricing of seaweed applications in the market.

The establishment of realistic cost structures is paramount for the successful integration of seaweed-based technologies into mainstream environmental remediation practices. Integrated multi-trophic aquaculture systems, which involve the co-cultivation of seaweeds with finfish or shellfish, present an innovative avenue to potentially offset production costs. The optimization of these symbiotic systems holds promise for generating additional revenue streams through the valorization of waste products. Seaweed residues and effluents can be utilized for the production of biofuels, animal feed, or fertilizers, thereby creating a closed-loop system with enhanced economic sustainability (Buschmann et al., 2017).

Scientific literature underscores the need for a comprehensive understanding of the factors influencing the cost-effectiveness of seaweed-based environmental remediation. Studies investigating the optimization of cultivation techniques, exploring novel extraction methods, and assessing the scalability of integrated aquaculture systems are critical to informing sustainable and economically viable practices. Moreover, the development of standardized economic models and frameworks for assessing the full life cycle costs of seaweed applications can significantly contribute to the adoption of these green technologies in commercial environmental cleanup initiatives. Optimizing such symbiotic systems can generate additional revenue streams through waste valorization like production of biofuels, animal feed or fertilizers from seaweed residues and effluents (Pereira & Costa-Lotufo, 2012).

Standardization

For commercial success and regulatory approvals of seaweed-based products, standardization of cultivation practices and biomass composition is important. However, this poses challenges due to the influence of environmental factors. Seaweed growth and biochemical makeup can vary significantly depending on conditions like temperature, salinity, light intensity, wave exposure and geographic location (Cotas et al., 2021). Even harvesting at different times of the year from the same area can lead to variations. Studies have documented changes in biomass yields, heavy metal uptake rates and bioactive compound concentrations across diverse seaweed species under changing natural conditions (Okolie et al., 2022). This lack of consistency can impact the scalability and reproducibility of applications. Thorough documentation of variations in seaweed characteristics like mentioned above is lacking for most commercially important species across their natural ranges and over different seasons. Systematically collecting such data will help develop control charts for cultivation standards. It can aid commercial production of seaweed biomass optimized for stability and targeted applications. Regulations also require baseline information on composition variability. Interplay between seaweed genetics and the growing environment shapes their traits. While genetics determine base characteristics, surrounding conditions induce phenotypic plasticity (Alberti et al., 2017). Elucidating these relationships through quantitative trait analysis and epigenetic profiling of seaweeds is an emerging research focus. It can enable developing varieties adapted to different environments through selective breeding.

Toxicity and Efficacy Testing

For any seaweed-derived product intended for pharmaceutical or cosmetic use, rigorous preclinical and clinical testing as per regulatory guidelines is mandatory to establish safety and efficacy (Sakthivel & Devi, 2019). However, the metabolic fate and mechanisms of biological action of many seaweed bioactives in humans remain unclear. Further studies on absorption, distribution, metabolism and excretion are needed to fully understand their toxicological profiles. Species-specific, geographical and seasonal variations in seaweed compositions also warrant studies for standardization (Hafting et al., 2015). Appropriately designed clinical trials with sufficient sample sizes are essential to demonstrate therapeutic efficacy for specific indications. More research on bioavailability enhancement and dose optimization can aid development of seaweed-based drugs and functional ingredients.

Exciting opportunities lie in interfacing seaweed materials science with cutting-edge technologies like tissue engineering, biosensors and medical imaging. For instance, tissue engineering approaches could develop novel seaweed biomaterial scaffolds for regenerative medicine. Diagnostic tools like implants and nanoparticles using seaweed compounds can be designed leveraging biosensor research. Medical imaging studies can uncover diagnostic and drug delivery applications of seaweed polysaccharides. Genetic enhancement of seaweeds can also tailor compositions and growth to meet specific biomedical needs (Sohn et al., 2021). Such interdisciplinary efforts can potentially extend the frontiers of seaweed-based therapeutics.

To improve commercial viability of high-value seaweed derived products, integrated biorefinery approaches are proposed (Varabih & Nofirman, 2023). Here, high-priority bioactives are extracted first, while the residues are processed to generate other value-added products. For example, fucoidan and alginates can be extracted, followed by extraction of remaining pigments, proteins and minerals from the biomass residue for use in cosmetics, food and agriculture respectively. This holistic utilization of total seaweed biomass can boost product yields along with profitability.

Conclusion

In conclusion, this review highlights the significant potential that seaweeds hold for environmental remediation and advancing biomedicine in a sustainable manner. Their unique biological traits and rich biochemical composition enables diverse applications in water treatment, bioremediation and carbon sequestration. Seaweed nutraceuticals and novel compounds also show promise to improve human health through functional foods, new drugs and diagnostics. However, more research is still required to address challenges pertaining to commercial scale cultivation, processing techniques and cost-effectiveness. Overall, seaweeds represent a versatile and largely untapped resource for environmental protection and biomedical progress. Further interdisciplinary efforts are encouraged to fully realize their immense capabilities and unlock innovative solutions from these remarkable marine organisms.

References

1. Afzal Rizvi, M., & Shameel, M. (2005). Pharmaceutical biology of seaweeds from the Karachi coast of Pakistan. *Pharmaceutical Biology*, *43*(2), 97–107. https://doi.org/10.1080/13880200590919366
2. Alberti, M., Correa, C., Marzluff, J. M., Hendry, A. P., Palkovacs, E. P., Gotanda, K. M., Hunt, V. M., Apgar, T. M., & Zhou, Y. (2017). Global urban signatures of phenotypic change in animal and plant populations. *Proceedings of the National Academy of Sciences*, *114*(34), 8951–8956. https://doi.org/10.1073/pnas.1606034114
3. Baghour, M. (2017). Effect of seaweeds in phyto-remediation. *Biotechnological Applications of Seaweeds; Nova Publishers Sciences: Hauppauge, NY, USA*, 47–83.
4. Baker, J. T. (1984). Seaweeds in pharmaceutical studies and applications. In C. J. Bird & M. A. Ragan (Eds.), *Eleventh International Seaweed Symposium* (pp. 29–40). Springer Netherlands. https://doi.org/10.1007/978-94-009-6560-7_4

5. Bartucca, M. L., Cerri, M., Del Buono, D., & Forni, C. (2022). Use of biostimulants as a new approach for the improvement of phytoremediation performance—A Review. *Plants*, *11*(15), 1946.
6. Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M. C., Pereda, S. V., Gomez-Pinchetti, J. L., Golberg, A., Tadmor-Shalev, N., & Critchley, A. T. (2017). Seaweed production: Overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology*, *52*(4), 391–406. https://doi.org/10.1080/09670262.2017.1365175
7. Buschmann, A. H., Gonzalez, M. D. C. H., & Varela, D. (2008). Seaweed future cultivation in Chile: Perspectives and challenges. *International Journal of Environment and Pollution*, *33*(4), 432. https://doi.org/10.1504/IJEP.2008.020571
8. Carpena, M., Caleja, C., Pereira, E., Pereira, C., Ćirić, A., Soković, M., Soria-Lopez, A., Fraga-Corral, M., Simal-Gandara, J., & Ferreira, I. C. (2021). Red seaweeds as a source of nutrients and bioactive compounds: Optimization of the extraction. *Chemosensors*, *9*(6), 132.
9. Cotas, J., Leandro, A., Pacheco, D., Gonçalves, A. M., & Pereira, L. (2020). A comprehensive review of the nutraceutical and therapeutic applications of red seaweeds (Rhodophyta). *Life*, *10*(3), 19.
10. Cotas, J., Pacheco, D., Gonçalves, A. M., Silva, P., Carvalho, L. G., & Pereira, L. (2021). Seaweeds' nutraceutical and biomedical potential in cancer therapy: A concise review. *J. Cancer Metastasis Treat*, *7*, 13.
11. Delf, E. M. (1943). The nature and uses of seaweeds. *Journal of the Royal Society of Arts*, *91*(4646), 505–514.
12. Deniz, F., & Ersanli, E. T. (2018). An ecofriendly approach for bioremediation of contaminated water environment: Potential contribution of a coastal seaweed community to environmental improvement. *International Journal of Phytoremediation*, *20*(3), 256–263. https://doi.org/10.1080/15226514.2017.1374335
13. Fleurence, J. (2016). Seaweeds as food. *Seaweed in Health and Disease Prevention*, 149–167.
14. Ganesan, A. R., Tiwari, U., & Rajauria, G. (2019). Seaweed nutraceuticals and their therapeutic role in disease prevention. *Food Science and Human Wellness*, *8*(3), 252–263.
15. Hafting, J. T., Craigie, J. S., Stengel, D. B., Loureiro, R. R., Buschmann, A. H., Yarish, C., Edwards, M. D., & Critchley, A. T. (2015). Prospects and challenges for industrial production of seaweed bioactives. *Journal of Phycology*, *51*(5), 821–837. https://doi.org/10.1111/jpy.12326
16. Hentati, F., Tounsi, L., Djomdi, D., Pierre, G., Delattre, C., Ursu, A. V., Fendri, I., Abdelkafi, S., & Michaud, P. (2020). Bioactive polysaccharides from seaweeds. *Molecules*, *25*(14), 3152.
17. Holdt, S. L., & Kraan, S. (2011). Bioactive compounds in seaweed: Functional food applications and legislation. *Journal of Applied Phycology*, *23*(3), 543–597. https://doi.org/10.1007/s10811-010-9632-5
18. Jing Zhao, Genying Xu, Xin Yao, Huirui Zhou, Boyang Lyu, Shuangshuang Pei, & Ping Wen. (2021). Microneedle-based insulin transdermal delivery system: Current status and translation challenges. *Drug Delivery and Translational Research*, 1–25. https://doi.org/10.1007/s13346-021-01077-3
19. Liu, J., Luthuli, S., Wu, Q., Wu, M., Choi, J., & Tong, H. (2020). Pharmaceutical and nutraceutical potential applications of *Sargassum fulvellum*. *BioMed Research International*, *2020*. https://www.hindawi.com/journals/bmri/2020/2417410/
20. Lomartire, S., & Gonçalves, A. M. (2022). An overview of potential seaweed-derived bioactive compounds for pharmaceutical applications. *Marine Drugs*, *20*(2), 141.
21. Lomartire, S., Marques, J. C., & Gonçalves, A. M. (2021). An overview to the health benefits of seaweeds consumption. *Marine Drugs*, *19*(6), 341.
22. Luo, H., Wang, Q., Liu, Z., Wang, S., Long, A., & Yang, Y. (2020). Potential bioremediation effects of seaweed *Gracilaria lemaneiformis* on heavy metals in coastal sediment from a typical mariculture zone. *Chemosphere*, *245*, 125636.
23. Mangam, V. T., Nallam, V. R., Anitha, A., Devi, P. R., & Sanisha, M. (2018). Dengue-An Overview. *International Journal of Pharma Research*, *9*(1). 01-06.
24. Mansour, A. T., Alprol, A. E., Ashour, M., Ramadan, K. M., Alhajji, A. H., & Abualnaja, K. M. (2022). Do Red Seaweed Nanoparticles Enhance Bioremediation Capacity of Toxic Dyes from Aqueous Solution? *Gels*, *8*(5), 310.
25. Michalak, I. (2020). The application of seaweeds in environmental biotechnology. In *Advances in Botanical Research*, 95, 85–111.
26. Okolie, J. A., Savage, S., Ogbaga, C. C., & Gunes, B. (2022). Assessing the potential of machine learning methods to study the removal of pharmaceuticals from wastewater using biochar or activated carbon. *Total Environment Research Themes*, *1*, 100001.

27. Pereira, R. C., & Costa-Lotufo, L. V. (2012). Bioprospecting for bioactives from seaweeds: Potential, obstacles and alternatives. *Revista Brasileira de Farmacognosia*, *22*, 894–905.
28. Radulovich, R., Neori, A., Valderrama, D., Reddy, C. R. K., Cronin, H., & Forster, J. (2015). Farming of seaweeds. In *Seaweed sustainability* (pp. 27–59). Elsevier. https://www.sciencedirect.com/science/article/pii/B9780124186972000039
29. Rao, P. S., Periyasamy, C., Kumar, K. S., Rao, A. S., & Anantharaman, P. (2018). Seaweeds: Distribution, production and uses. *Bioprospecting of Algae. Society for Plant Research*, 59–78.
30. Remya, R. R., & Rajasree, S. R. (2016). A study on bioactive compounds derived from brown seaweeds and their therapeutic applications towards various diseases. *Research Journal of Pharmacy and Technology*, *9*(4), 369–372.
31. Rengasamy, K. R., Mahomoodally, M. F., Aumeeruddy, M. Z., Zengin, G., Xiao, J., & Kim, D. H. (2020). Bioactive compounds in seaweeds: An overview of their biological properties and safety. *Food and Chemical Toxicology*, *135*, 111013.
32. Sakthivel, R., & Devi, K. P. (2019). Antioxidant, anti-inflammatory and anticancer potential of natural bioactive compounds from seaweeds. *Studies in Natural Products Chemistry*, *63*, 113–160.
33. Sapatinha, M., Oliveira, A., Costa, S., Pedro, S., Gonçalves, A., Mendes, R., Bandarra, N. M., & Pires, C. (2022). Red and brown seaweeds extracts: A source of biologically active compounds. *Food Chemistry*, *393*, 133453.
34. Sarella, P. N. K., & Thammana, P. K. (2023). Potential applications of Folate-conjugated Chitosan Nanoparticles for Targeted delivery of Anticancer drugs. *Research Journal of Pharmaceutical Dosage Forms and Technology*, *15*(4), 281–288.
35. Siahaan, E. A., Pangestuti, R., & Kim, S.-K. (2018). Seaweeds: Valuable Ingredients for the Pharmaceutical Industries. In P. H. Rampelotto & A. Trincone (Eds.), *Grand Challenges in Marine Biotechnology* (pp. 49–95). Springer International Publishing. https://doi.org/10.1007/978-3-319-69075-9_2
36. Sohn, S.-I., Rathinapriya, P., Balaji, S., Jaya Balan, D., Swetha, T. K., Durgadevi, R., Alagulakshmi, S., Singaraj, P., & Pandian, S. (2021). Phytosterols in seaweeds: An overview on biosynthesis to biomedical applications. *International Journal of Molecular Sciences*, *22*(23), 12691.
37. Tseng, C. K. (1944). Utilization of seaweeds. *The Scientific Monthly*, *59*(1), 37–46.
38. Varabih, C. A., & Nofirman, N. (2023). The importance of seaweed as bioremediation natural agent: The importance of seaweed as bioremediation natural agent. *Journal of Oceanography and Aquatic Science*, *1*(2), 48–53.
39. Venkatesan, J., Anil, S., & Kim, S.-K. (2017). *Seaweed Polysaccharides: Isolation, biological and biomedical applications*. Elsevier. https://books.google.com/books?hl=en&lr=&id=BZ2pDQAAQBAJ&oi=fnd&pg=PP1&dq=seaweeds+and+nutraceuticals,+pharmaceuticals,+biomedical+applications&ots=JwvwBNkRDm&sig=bLErhnr_0RQFIu8FUIB9cHXEAHY
40. Vidanarachchi, J. K., Kurukulasuriya, M. S., & Wijesundara, W. (2013). Biological and biomedical applications of marine nutraceuticals. *Marine Nutraceuticals: Prospects and Perspectives*, 345.
41. Wang, X., Shan, T., & Pang, S. (2018). Phytoremediation Potential of *Saccharina japonica* and *Sargassum horneri* (Phaeophyceae): Biosorption Study of Strontium. *Bulletin of Environmental Contamination and Toxicology*, *101*(4), 501–505. https://doi.org/10.1007/s00128-018-2435-0
42. Singh, S. R., Bhadra, A., Malathi, H., Madhu, Kademane, A., Shrivastava R., & Patil, S. J. (2023). Phytoremediation - A promising approach for pollution management. *European Chemical Bulletin*, *12*(Spl Iss -10), 416-421.
43. Mahishi P., & Patil, S. J. (2023). Emerging pollutants in back water (estuaries) and their phytoremediation and conservation. In: The Handbook of Plant Genomics & Nano Biology. (ISBN: 978-93-93636-56-0). Integrity Media – The Publisher, New Delhi, p. 01-09.